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Breaking the Cycle of Waste: A Comprehensive Review of ELT Repurposing with a Special Emphasis on Pyrolysis Technology in India

Aanya Chand and Dr. Piyali Das
aanya@chand.in

ABSTRACT

End of life tyres (ELTs) pose a serious environmental threat globally. Presently, incineration, open burning, stockpiling, and disposal in landfills account for nearly 3–4 billion ELTs. It is estimated that one ton of tyres incinerated could generate as high as ~2,270 kg CO2-eqv (GHG emissions) which translates to nearly 3.178 million metric tons (MMT) of emissions from the Indian annual domestic ELT production.

This paper highlights the importance of choosing technologies like pyrolysis to treat ELTs into energy products, thereby providing the dual benefit of avoiding emissions while reducing India's dependence on imported crude oil to meet the energy requirements for India.

Authors
Aanya Chand, Dr. Piyali Das

The Energy and Resources Institute
Creating Innovative Solutions for a Sustainable Future

From Waste to Wealth: Scrap Tyres & Their Benefits -

"Tyres produce the same amount of energy as oil & 25% more than coal."

Context

- 217.5 million units of tyres produced approximately each year
- Tyres have a very high energy content (32 GJ/ton), more than coal (27 GJ/ton)
- Valued at $164.9 billion in 2023
- The burning of scrap tyres is hazardous, and common.
- The open burning of tyres produces carbon monoxide, sulphur dioxide and nitrogen dioxide.
- The incomplete combustion of scrap tyres = Polycyclic Aromatic Hydrocarbons (PAHs) that are carcinogenic, mutagenic and toxic for reproduction.
- The storage of scrap tyres in landfills creates breeding grounds for mosquitos and rodents which carry diseases.



Car Tyres

Uses, Types, Properties, Production



Emissions

The burning of tyres give rise to gaseous pollutants (CO, NO2, and SO2)
Exposure to these gases could lead to -

1. Carbon Monoxide: Fatigue, dizziness and headaches due to the lack of oxygen in the brain.
2. Nitrogen Dioxide: Respiratory diseases and lung failure.
3. Sulphur Dioxide: Bronchitis, and irritation in the throat, lungs and nose.



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Solutions

The reusage of scrap tyres can be acted upon by executing the following points -

1. Pyrolysis - oil, carbon black and gas
2. Ground Rubber - cushioning and cement
3. Manufacturing - home products
4. Recycling - dock bumpers and highway barriers
5. Manufacturing medical products from the rubber
6. Creating anti-vibration, acoustic insulations with tyres

Composition of Virgin Tyres: -

S. No.	Components	Types of Tyres		Comments
		Passenger Tyre	Heavy Vehicle Tyre	
1.	Rubber	41-47%	42-48%	As seen in the table, most components do not have a vast difference in percentage, besides silica (6-8%, 1-5%) and metal (10-16%, 22-27%)
2.	Carbon Black	19-28%	20-28%	
3.	Metals	10-16%	22-27%	
4.	Textile	4-6%	0-9%	
5.	Silica	6-8%	1-5%	
6.	Additives	3-8%	3-9%	



Conclusion

Since scrap tyres have an energy content of 32GJ/ton, almost twice of the energy content of coal and oil, we should find a sustainable way to make use of this resource. Scrap tyres shouldn't be seen as a waste, but more as an asset to produce new products, and re-gain important materials.
One's waste is another's gold, and tyres could be India's new gold.

INTRODUCTION

Tyres play an immensely important role in modern transportation; without them, efficient transportation would not be possible. Unfortunately, the end-of-life tyre (ELT) management is often overlooked by even industry stakeholders unaware of evolving technological and environmental concerns.

India generates approximately 1 million tons of ELTs annually, a figure predicted to increase with the expanding automotive sector. In 2024, India domestically produced approximately 1.6 million tons of ELTs while also importing a nearly equivalent amount of 1.4 million tons of ELTs.[1] The global annual ELT generation is reported to be approximately 1 billion tyres, according to the World Business Council for Sustainable Development.[2] Therefore, tyres are among the most significant products globally. In recent years, growing environmental concern around the topic of tyres has highlighted the issue of disposal of ELTs. At the same time India is a net importer of crude petroleum oil which is refined to make transport fuels like diesel and gasoline to support the fuel needs of the transport sector. This fossil-fuel demand in the transport sector could be partially met by tyre-derived oil produced through the pyrolysis of ELTs in a controlled environment, followed by appropriate upgrading of the oil.

It is reported that as much as 60% of the rubber used in the tyre industry is synthetic and derived from petroleum sources thus substantially contributing to the depletion of nonrenewable resources. The disposal of ELTs, on the other hand, remains a challenge, with many ending up in landfills or being incinerated, releasing harmful pollutants into the atmosphere. In addition, multiple studies have reported the release of carcinogens and polycyclic aromatic hydrocarbons during open burning of ELTs.[3,4,5]

Even with the emergence of viable sustainable solutions, most consumers are still unaware of the complete life-cycle of tyres and how they affect our environment. This lack of awareness underscores the need for advanced research and information on how tyres can be made more sustainable through ELT repurposing and the implementation of technologies for effective ELT valorisation, while ensuring a low life-cycle footprint across value chains.

Additionally, there is a rising interest in developing more sustainable tyres by incorporating bio-based materials, improving recycling processes and designing tyres that enhance vehicle fuel efficiency. By reducing the dependency on petroleum-based products and improving the longevity and recyclability of tyres, the industry can play a crucial role in combating carbon and greenhouse gas emissions and advancing towards a more circular economy.

This paper seeks to review the current status of ELT disposal and its associated environmental threats. Additionally, this paper also depicts the potential of ELTs in paving the way forward towards a more sustainable future. By bridging these gaps in knowledge, this literature review paper aims to provide a clearer roadmap for understanding how tyres and their proper disposal can impact our economies, environment and daily lives.

This paper comprises six sections, which includes types of ELTs versus their composition, review methodology, current practices of ELT management, emissions and environmental impact from tyre incineration, pyrolysis of ELTs as the foremost technology for valorisation of ELTs and final conclusions.

REVIEW METHODOLOGY

In this review paper, the literature search was conducted systematically, with data collected from authentic sources, including peer-reviewed journals, government institute and research centre websites, published newspaper articles, and other credible sources. Initially, statistical data related to ELT generation, both globally and in India, were collected from peer-reviewed journals and government websites. Next, relevant literature on current global practices in ELT management and conversion was collected. To make a quantitative assessment of the overall environmental impact and associated risks, the literature was reviewed for experimental investigations into ELT landfilling, open burning, and the associated release of gaseous and particulate pollutants. In the search for widely practised and emerging processes, pyrolysis technology was identified as one of the promising options with future potential for the effective valorisation of ELTs for the generation of alternative energy and fuels. Technology-related data and current regulatory issues were examined through the websites and reports of Indian national and state government institutions. In this regard, reports and gazette notifications from the National Institution for Transforming India (NITI Aayog),[1] which serves as the Government of India's apex public policy think tank; the Central Pollution Control Board (CPCB), an apex statutory organisation in India under the Ministry of Environment, Forest and Climate Change (MoEFCC),[26] and other relevant sources were reviewed. Tyre composition and characteristics were referenced from peer-reviewed journals and industrial websites.

Keywords: ELT generation and management, ELT pyrolysis, environmental impact of ELT burning, ELT valorisation.

COMPOSITION OF ELTs

The Basel Convention, originally adopted in 1989 and currently accepted by 180 parties, is an important international treaty governing the transboundary movement of hazardous waste. ELTs are presently referenced under Annex IX (Entry B3140) of the Basel Convention and are not classified as hazardous waste under Annexes I and III, which specify hazardous characteristics. As ELTs are considered non-hazardous waste, they are therefore excluded from strict control procedures when undergoing

recovery operations and may be traded relatively freely from developed countries, with a significant proportion ultimately ending up in developing countries such as India.[31]

Nonetheless, individual member states retain the right, under their national legislation, to ban or restrict the import of waste tyres. ELTs, however, are also listed under Basel Convention Annex II, which pertains to wastes requiring special consideration, and Annex VIII,[31] which concerns hazardous waste, more precisely in the context of their intended direct reuse rather than material recovery. Besides posing a potent fire hazard, toxic leachates from tyres discarded in landfills can contaminate water bodies and pose a risk to both human health and the environment.[5]

The following **Table 1** provides a glimpse of the comparative composition of both virgin passenger and heavy vehicle/truck tyres. It is seen that most components do not have a vast difference in percentage, with the exception of their silica and metal contents (6-8 wt.% for passenger tyre, 1-5 wt.% for heavy vehicle tyre) and metal (10-16 wt.% for passenger tyre, 22-27 wt.% for heavy vehicle tyre) content.[6]

Additionally, with regard to the composition of rubber, passenger cars contain 14-15 wt.% of natural rubber whereas for the heavy vehicles, this is almost double that of the passenger tyre, ranging from 27-30 wt. %.[6,7] The global data also shows that the tyre industry is the largest consumer of natural rubber, which exceeds 70% of the world's natural rubber production.[8] Synthetic rubber, on the other hand, constitutes a higher percentage in heavy vehicle tyres as compared to passenger vehicles. Interestingly, it is observed that Asian tyres consist of a higher proportion of natural rubber than their global counterparts due to its easy availability and abundance in the region.[9]

It is worth noting that natural rubber originates from *Hevea brasiliensis* trees, which contributes to stiffness and abrasion resistance. Synthetic rubber, in turn, is derived from fossil polymers like styrene-butadiene rubber (SBR) and polybutadiene which provide heat resistance, wear and traction performance. In tyres, carbon black and silica are used as fillers to reinforce the rubber, enhancing its strength. The structural integrity is achieved through the inclusion of steel, polyester, rayon or nylon to build the outer rim of the tyre. Additives and chemicals, vulcanizing agents like sulfur and plasticizers are also key components in tyres.

Table 1: Comparison of the Composition of Virgin Passenger and Heavy Vehicle Tyres [6,7]

S. No.	Components (wt. %)	Types of Tyres	
		Passenger Tyre	Heavy Vehicle Tyre
1.	Rubber (added materials)	41-47%	42-48%
2.	Carbon black	19-28%	20-28%
3.	Metals	10-16%	22-27%
4.	Textile	4-6%	0-9%

5.	Silica	6-8%	1-5%
6.	Additives	3-8%	3-9%

With respect to the textile content, the major components are polyester cord fabric, rayon cord fabric, nylon cord fabric, and aramid cord fabric. In addition, the main metals typically used include copper, zinc, tin and cobalt.

CURRENT PRACTICES OF ELT MANAGEMENT

The global tyre industry produces approximately 1.5 billion tyres annually and over 1 billion tyres are discarded each year globally. Recycling efforts remain limited, with a majority of tyres being landfilled or incinerated. According to some estimates, 5-23% of ELTs are reused, 20-30% are landfilled or stockpiled, and 25-60% are incinerated or used for energy recovery.[10] In general, ELT management is handled in many different ways, with some methods being more environmentally friendly, while others are more commonly used. Many widely used processes are unsustainable and lead to the release of harmful chemicals, such as polycyclic aromatic hydrocarbons and carcinogens.

Mechanical recycling processes like cryogenic grinding of recovered ground tyre rubber are also essential for the upcycling of these ELTs. Additionally, retreading, used mostly for truck tyres, extends the tyre's lifespan significantly and makes it an eco-friendly alternative in circular tyre management. Thermochemical treatments such as pyrolysis and gasification are also proving to be reliable alternatives to traditional management methods, by producing essential byproducts like gas, char, oil, carbon black and syngas. The following information is expanded on in **Table 2.**[22]

Table 2: Alternative uses of ELTs

S. No.	Uses	Products	Comments
1.	Pyrolysis	Oil, Char, Gas	Pyrolysis is an expensive method, so very few institutions are investing in it.
2.	Civil Engineering Materials	Lightweight Construction Material	This method is also used by a very small pool of companies.
3.	Ground Rubber	Cushioning Material	Tyres are significantly being used for cushioning materials in India.
4.	Home Products	Doormats, chairs, etc.	Home products remain a niche, largely informal market in India.
5.	Retreading	Tyres that can be reused	Retreading is one of the most prominently used methods of utilising scrap tyres.

S. No.	Uses	Products	Comments
6.	Recycling	Shoe soles, dock bumpers, highway crash barriers etc.	Recycling of tyres is currently the most popular method of utilising scrap tyres.

EMISSIONS FROM OPEN BURNING ELTs

The open burning of scrap tyres (OBST), whether through accidental combustion or intentional incineration, poses a grave environmental and health risk due to the wide array of harmful chemicals released when tyres are combusted. As mentioned above, tyres are primarily composed of rubber, synthetic polymers, steel, and other additives that when combusted break down into various toxic compounds. This process releases pollutants such as polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), heavy metals and particulate matter which pose significant risks to human health and the environment.[11,12] The combustion of tyres leads to the release of carcinogens and mutagenic compounds that persist in the environment for long periods of time, and therefore bioaccumulate in ecosystems resulting in long-term environmental contamination. The release of these pollutants increases the risk of respiratory and cardiovascular diseases, cancer, and increased infant mortality. The National Institutes of Health results showed that an increase of 10 $\mu g/m^3$ in PM_{10} during the early period of exposure was associated with a significant increase in the risk of mortality, due to elevated levels of pollutants in the atmosphere, of which tyre burning is one of the contributing sources.[13]

Open burning of scrap tyres (OBST) which is recognised as a major source of gaseous pollutants and contributes particularly to the generation of CO, NO_2 and SO_2.[14] In addition, aerosols with aerodynamic diameters of less than 10 μm, including $PM_{2.5}$ and PM_{10}, are of particular significance, along with total suspended particulate matter (TSP) and heavy metals. PM_{10} or $PM_{2.5}$ are reported to have a greater effect on humans over other pollutants. These primarily consist of a complex mixture of both solid and liquid particles of organic and inorganic nature suspended in air as a result of tyre combustion.[15] Globally a large number of countries are increasingly studying the impact of open burning of tyres on local air quality. Overall, health challenges like nervous system disorder, dermal and eye irritation, respiratory problems are linked to the length and degree of exposure to emissions generated through tyre burning.[16]

Particulate matter has recently received increasing attention in pollution studies owing to its substantial effects on human health. Research reports show strong evidential proof that coarse dust particles (D_P) (2.5 μm < D_P< 10 μm) are effectively removed in the upper part of the respiratory tract while small particles (D_P < 2.5 μm) get deposited on the bronchi walls in the bronchi tree.[16,3]

A research study was carried out to investigate the potential emission of particulate pollutants ($PM_{2.5}$ and PM_{10}) from combustion of scrap tyres and their possible impacts on human health and environment.[19] In this study, the toxicity potential (TP) of aerosols is calculated as the ratio of the measured ambient PM

concentration to the corresponding standard ambient concentration limits, as presented in **Table 3.** [14,16,17,18,19,20,21]

Table 3: 24-Hour Standard Limits For Particulate Matter (PM)[18,19,20,21]

Particle Type	**WHO (2006) (µg/m^3)**	**ASHRAE (2010) (µg/m^3)**	**NAAQS (µg/m^3)**
$PM_{2.5}$	25	15	65
PM_{10}	50	50	150

The toxicity potential value of any pollutant greater than unity signifies that the concentration has the potential to cause harm to people in sensitive categories (young people, older adults, and people with respiratory diseases) and poses significant threats to the environment.

This study has shown that OBST could contribute to elevation in concentration of aerosols in the environment. People could be exposed to significant concentration levels of aerosols due to OBST in the environment as the toxicity potential levels were above unity in some of the tyre samples investigated. The most breached limits are ASHRAE and WHO limits of 50 µg/m^3 for PM_{10} where three motorcycle, car and truck tyre samples have the TP values above unity. These are followed by ASHRAE standard for $PM_{2.5}$ and WHO standard for $PM_{2.5}$. The NAAQS limit was exceeded least frequently.[19,20,21]

Gaseous pollutants from 20 types of Tyre samples representing five from each of the bicycle, motorcycle, car, and truck categories are analysed and reported. The AQI values of CO, NO_2, and SO_2 emissions from OBST, based on the EPA AQI categories, are shown in **Table 4.**[21,27,28]

About 75%, 31.8%, and 75% of the CO, NO_2, and SO_2 emissions from OBST fall within the AQI range of 51-100 and are classified as 'moderate' levels of health concern.[15,18] Only NO_2 (43.2%) falls within the AQI range of 0-50, which is categorised as 'good' levels of health concern.[18] Also 25% each of the three pollutants CO, NO_2 and SO_2 is within the AQI range of 101-150.[25] These are regarded as ' unhealthy for Sensitive Groups', of health concern[18], thus people with heart disease, asthma or other respiratory diseases, the elderly, and children are the groups most at risk of exposure to these gaseous emissions from OBST.[18,24]

Table 4: AQI of Gaseous Emissions from OBST and their Health Concerns.[21,25,27,28]

AQI Values	Levels of Health Concern	Frequency (%)		
		CO (ppm)	SO_2 (ppm)	NO_2 (ppm)
0-50	Good	0.0	0.0	43.2
51-100	Moderate	75.0	75.0	31.8
101-150	Unhealthy (Sensitive Groups)	25.0	25.0	25.0
151-200	Unhealthy	0.0	0.0	0.0
201-300	Very Unhealthy	0.0	0.0	0.0
301-500	Hazardous	0.0	0.0	0.0

Research by the U.S. The Environment Protection Agency (EPA) noted that tyre burning is a significant source of heavy metal emissions, including lead, cadmium, and zinc.[11] These metals can leach into the soil and water systems, resulting in contamination that can affect both terrestrial and aquatic life. The dispersion of these metals could lead to the degradation of air quality and affect the quality of life of all organisms living near burning sites.

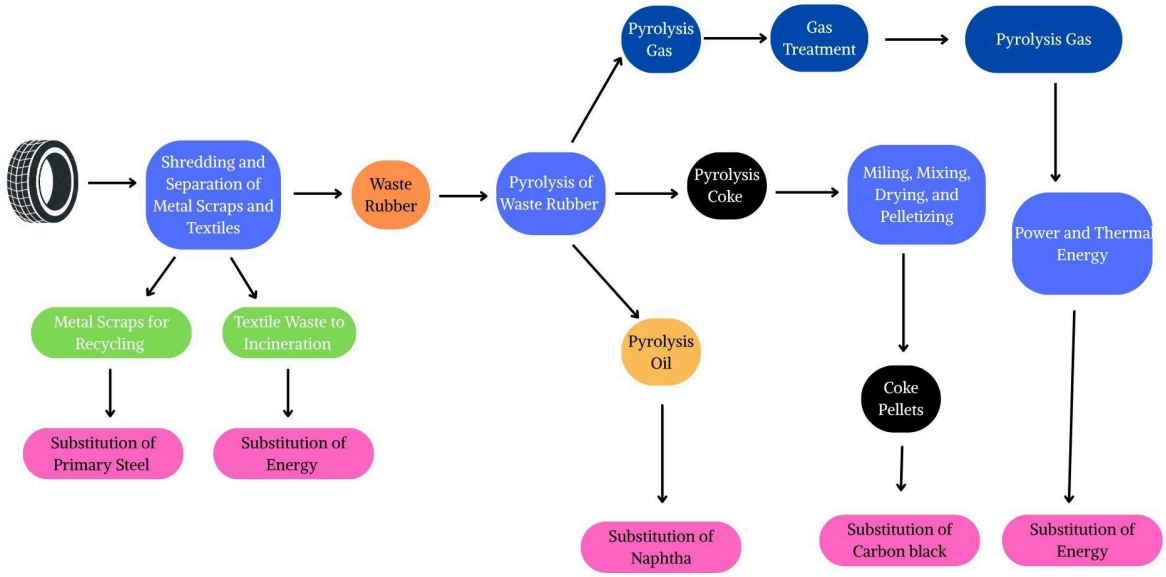
PYROLYSIS FOR TYRE VALORISATION

Pyrolysis is a thermochemical process in which ELTs are heated in the absence of air to break down the material into three major products: tyre pyrolysis oil (TPO), pyrolytic carbon/char, and non-condensable gases such as CO, CO_2, H_2, and methane. The ELT valorisation process through pyrolysis is illustrated in Figure 1.[28,29] Tyre pyrolysis reactors operate in both batch and continuous modes. Globally advanced technologies such as plasma pyrolysis have commercial applications in Singapore and Italy although the high cost of this technology is a limiting factor in India. Catalytic pyrolysis can produce high-grade hydrocarbon products along with carbon black as a by-product, as reported by many researchers. Thus, it is worth mentioning that pyrolysis technology is potentially sustainable only when the process is operated under controlled conditions, maintaining precise emission control, product standards and necessary regulatory compliance.

Presently, there are no pyrolysis product standards available in India which restricts the widespread adoption of the tyre pyrolysis process. India has so far instituted an SOP to achieve environmental compliance through advanced batch automated pyrolysis technologies. However, for large-scale deployment and sustainable continuous pyrolysis processes India needs to develop standards and regulations for the pyrolysis process and products.

As per India's Central Pollution Control Board, in India, there are over 750 tyre pyrolysis plants across 17 states - Uttar Pradesh, Haryana, Rajasthan and Maharashtra are particularly spearheading the process of tyre pyrolysis, which are largely batch processes. Presently the pyrolysis oil in particular is used for heating applications in industrial boilers. In 2022, of these 757 units, more than half were non-compliant with the standards/norms set by State Pollution Control Boards (SPCBs). Bureau of Indian Standards (BIS), the regulatory authority of India is developing standards of ELT pyrolysis products.[26,29,30]

Figure: 1 : The ELT valorisation process Through pyrolysis



Treatment of ELTS by pyrolysis; Reproduced from: Maga Daniel et al, 2023

CONCLUSION

Conventional disposal methods of ELTs such as landfilling and incineration are unsustainable and pose long-term ecological risks. Hence, the adoption of sound scrap tyre management practices is necessary along with strict compliance with both national and international laws and regulations. Pyrolysis of ELTs offers an eco-friendly alternative, converting rubber into pyrolysis oil, gas, and char. The oil fraction, which accounts for 40-45 wt.% of the product, has a high calorific value (40-45 MJ/kg) and can serve as an industrial fuel after appropriate desulfurization and refining to remove heavy fractions. Carbon black also has significant potential for industrial applications. Pyrolysis technology offers a sustainable long-term solution for tyre waste valorisation while tyre pyrolysis oil could be used in industrial heating applications or further refined to advanced transport fuels. All these applications also necessitate the development of standards for tyre-derived pyrolysis products and government policy support to scale up such technologies in India.

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