

Study of Impact Over Environment Air Quality and Side Products Due to Recycling of Tyres

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Abstract: The exponential increase in the global vehicle population has led to an alarming rise in the generation of waste tyres, also known as end-of-life tyres (ELTs). Tyres are designed to be durable and resistant to wear, which makes them difficult to degrade naturally, posing significant environmental challenges if not managed properly. As traditional disposal methods such as landfilling and open burning are increasingly discouraged due to their harmful environmental effects, tyre recycling has emerged as a preferred strategy for sustainable waste management. However, while recycling conserves resources and reduces landfill volume, it is not free from adverse impacts—particularly concerning the degradation of ambient air quality and the generation of hazardous by-products.

This research paper presents a comprehensive study of the environmental implications of tyre recycling with a focused investigation into the effects on ambient air quality and the nature of side products released during different recycling processes. Field data were collected from three distinct types of tyre recycling facilities in India employing mechanical shredding, cryogenic grinding, and pyrolysis technologies. Using a combination of on-site air sampling, laboratory-based chemical analysis, and data modeling, we examined key pollutants such as particulate matter (PM_{2.5} and PM₁₀), volatile organic compounds (VOCs), sulfur oxides (SO_x), nitrogen oxides (NO_x), and polycyclic aromatic hydrocarbons (PAHs). In addition, by-products including carbon black, pyrolytic oil, steel residues, and gaseous emissions were qualitatively and quantitatively assessed for environmental risks and usability.

The findings indicate that mechanical and cryogenic processes are relatively benign with minimal emissions, while pyrolysis-based recycling poses considerable risks due to elevated emissions of VOCs and carcinogenic compounds. Specifically, pyrolysis operations recorded PM_{2.5} and PM₁₀ levels exceeding National Ambient Air Quality Standards (NAAQS) by 65–90%, and VOC concentrations that surpassed WHO guidelines. The study also found that some of the generated by-products, though recoverable, contain impurities that can render them unsuitable for direct reuse without further treatment.

This research underscores the need for stringent monitoring protocols, environmentally-sound recycling technologies, and policy frameworks to mitigate the environmental impacts of tyre recycling operations. It advocates for the adoption of clean technologies, emissions control systems, and lifecycle assessments to ensure tyre recycling contributes positively to sustainable development without compromising public health or environmental integrity.

Keywords: Tyre Recycling, End-of-Life Tyres (ELTs), Ambient Air Quality, Pyrolysis, Mechanical Shredding, Cryogenic Grinding, Particulate Matter (PM_{2.5}, PM₁₀), Volatile Organic Compounds (VOCs), Polycyclic Aromatic Hydrocarbons (PAHs), Carbon Black, Pyrolytic Oil, Environmental Impact, Recycling Emissions, Sustainable Waste Management, Airborne Toxins.

Introduction - The global rise in automobile usage has contributed significantly to an unprecedented increase in the generation of end-of-life tyres (ELTs). According to estimates by the World Business Council for Sustainable Development (WBCSD), over one billion tyres reach the end of their useful life each year globally. In India alone, the annual generation of waste tyres exceeds 275,000 tonnes, and this figure is expected to rise with the expansion of the automotive sector. Tyres, made primarily of synthetic rubber, natural rubber, carbon black, steel, nylon, and

various additives, are highly durable, making their decomposition in the natural environment extremely slow—taking up to hundreds of years. Consequently, managing tyre waste has become a critical environmental issue.

Traditionally, waste tyres have been disposed of through landfilling, stockpiling, and open burning. However, these methods are increasingly recognized as environmentally hazardous. Landfilled tyres create breeding grounds for disease vectors such as mosquitoes and pose fire hazards. Open burning releases toxic gases, including

dioxins and furans, into the atmosphere, contributing to air and soil contamination. These environmental and public health risks have prompted a global shift toward recycling as a sustainable alternative for managing waste tyres.

Tyre recycling offers several benefits: it reduces landfill space, conserves natural resources, recovers valuable materials, and supports the circular economy. However, recycling is not without its challenges. Depending on the method employed—mechanical shredding, cryogenic grinding, or pyrolysis—the process can release harmful emissions into the environment. Particularly concerning are the effects on ambient air quality, which have not been comprehensively studied across different recycling technologies, especially in developing countries like India where emission control mechanisms are often limited or absent.

Mechanical shredding involves cutting tyres into smaller chips that can be reused in civil engineering applications or as fuel. This method produces negligible emissions but is limited in material recovery value. Cryogenic grinding freezes tyres using liquid nitrogen and then shatters them into fine rubber powder. It is clean but cost-intensive. Pyrolysis, a thermal decomposition process conducted in the absence of oxygen, is increasingly popular for its ability to produce valuable by-products such as pyrolytic oil, gas, carbon black, and steel. However, it is also the most emission-intensive method. Studies have reported the release of polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), sulfur oxides (SO_x), nitrogen oxides (NO_x), and other airborne toxins during pyrolysis.

Despite the growing number of recycling plants, especially in industrial belts of India, there is limited field-level research on the actual environmental impact of these facilities. Most studies have been either laboratory simulations or theoretical evaluations, lacking empirical data from real-world operations. Moreover, there is insufficient understanding of the nature and quality of the by-products generated—many of which may be hazardous if improperly handled.

This paper seeks to bridge that knowledge gap by conducting a comparative environmental impact assessment of three distinct tyre recycling technologies. The study evaluates their effects on ambient air quality and characterizes the side products generated. Field sampling from operational recycling units, followed by laboratory analysis and data interpretation, forms the core methodology. The research also examines the alignment of emissions with established environmental standards such as those by the National Ambient Air Quality Standards (NAAQS) and the World Health Organization (WHO).

The ultimate goal of this research is to provide a scientific foundation for policymakers, industrial stakeholders, and environmental agencies to make informed decisions about the adoption, regulation, and

improvement of tyre recycling technologies. It emphasizes the need for an environmentally responsible approach to tyre recycling—one that maximizes material recovery while minimizing ecological harm.

Methods: To comprehensively assess the impact of tyre recycling on ambient air quality and to identify the nature and potential environmental risks of the by-products generated, a mixed-methods research approach was employed. This included site selection and sampling, analytical procedures, laboratory testing, and statistical evaluation. The methodology was designed to ensure a comparative analysis across multiple recycling techniques with a focus on real-world industrial practices in India.

A. Site Selection and Description: Three tyre recycling facilities were selected based on their operational scale, geographical diversity, and the type of recycling process they employed.

All three facilities were located in industrial zones of India and had received local environmental clearance. The selected sites were:

Facility A: Mechanical Shredding Unit (Ahmedabad, Gujarat): This unit employs industrial-grade shredders to reduce waste tyres into rubber chips and strips for use in rubber mats, sports turfs, and road fillers.

Facility B: Cryogenic Grinding Plant (Pune, Maharashtra): This facility uses liquid nitrogen to freeze tyres before pulverizing them into fine rubber granules suitable for reprocessing into new rubber products.

Facility C: Pyrolysis Plant (Panipat, Haryana): The most emission-intensive facility, it utilizes batch-mode pyrolysis reactors to thermally decompose tyres and recover pyrolytic oil, carbon black, and steel wires.

Each facility was visited twice over a 4-week period for data collection during peak operational hours.

B. Air Quality Sampling and Monitoring: Ambient air quality was monitored using high-volume samplers and portable real-time monitors positioned 10 meters downwind and 10 meters upwind of each facility's main emission outlet. Sampling was conducted for 8-hour intervals to capture diurnal variations.

Measured Pollutants Included:

Particulate Matter (PM_{2.5}, PM₁₀) — Measured using Gravimetric Sampler (Envirotech APM 550)

Volatile Organic Compounds (VOCs) — Captured using sorbent tubes and analyzed via GC-MS (Gas Chromatography-Mass Spectrometry)

Sulfur Oxides (SO_x) and Nitrogen Oxides (NO_x) — Monitored using portable gas analyzers (Testo 350XL)

Carbon Monoxide (CO) and Carbon Dioxide (CO₂) — Measured with NDIR-based multi-gas meters (Aeroqual Series 500)

Meteorological data such as wind speed, direction, temperature, and humidity were also recorded to contextualize air dispersion behavior.

C. Sampling of By-Products: In addition to air

monitoring, samples of solid and liquid by-products were collected from each facility:

Mechanical Facility: Shredded rubber chips and extracted steel wires.

Cryogenic Facility: Fine rubber granules and residual frost-contaminated waste.

Pyrolysis Facility: Pyrolytic oil, carbon black powder, condensed gases, and steel wire residues.

Each sample was labeled, sealed, and transported under standardized conditions to a certified environmental laboratory for further analysis.

D. Laboratory Analysis of By-Products: By-products were tested for their physical and chemical properties to evaluate their usability and potential hazards:

Carbon Black was analyzed for heavy metal contamination using Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Pyrolytic Oil underwent flash point, viscosity, and hydrocarbon content tests using ASTM D86 and ASTM D445 protocols.

Rubber Granules and Chips were checked for leachable toxic compounds using the Toxicity Characteristic Leaching Procedure (TCLP).

Steel Residues were magnetically separated and tested for structural integrity and coating contamination.

E. Data Analysis and Comparison

All collected data were digitized and processed using statistical software tools:

SPSS 27.0 for descriptive statistics and standard deviation analysis.

MATLAB R2022b for trend plotting and regression modeling.

GIS Tools for spatial air pollution mapping near each facility. The pollutant concentrations were compared against benchmark standards from:

1. National Ambient Air Quality Standards (NAAQS – CPCB, India)
2. World Health Organization (WHO) Ambient Air Quality Guidelines
3. US EPA Hazardous Air Pollutants (HAPs) thresholds

The data were further analyzed to determine emission intensity per tonne of tyre processed, enabling a direct comparison between recycling methods.

E. Ethical and Environmental Compliance: Prior permissions were obtained from the facility operators and local environmental boards. All sampling was conducted in accordance with CPCB protocols, ensuring minimal disruption to ongoing operations and safety for researchers. Laboratory testing followed ISO/IEC 17025 standards.

Results And Discussion: This section presents the comparative analysis of data collected from three tyre recycling facilities employing mechanical shredding, cryogenic grinding, and pyrolysis. The results are discussed under two primary themes: (i) Impact on Ambient Air Quality, and (ii) Nature and Environmental Implications of By-

products. Data trends are compared with national and international standards to determine environmental compliance and sustainability.

A. Ambient Air Quality Impact: Air sampling near all three facilities revealed significant differences in pollution levels corresponding to the recycling method used.

Particulate Matter (PM_{2.5} and PM₁₀)

Mechanical Shredding (Facility A): PM_{2.5} and PM₁₀ concentrations were recorded at 45 µg/m³ and 75 µg/m³, respectively—within acceptable NAAQS limits (60 µg/m³ for PM_{2.5} and 100 µg/m³ for PM₁₀). These values were only marginally higher than upwind baseline levels, indicating minimal air quality disruption.

Cryogenic Grinding (Facility B): PM concentrations were slightly lower than Facility A, attributed to the enclosed freezing process. PM_{2.5} was 38 µg/m³, and PM₁₀ was 66 µg/m³, showing efficient dust containment.

Pyrolysis (Facility C): Exhibited significantly elevated PM levels. PM_{2.5} was 102 µg/m³ and PM₁₀ reached 190 µg/m³, both exceeding NAAQS thresholds by 70–90%. This suggests ineffective emission capture and higher fugitive dust release during unloading and reactor cooling phases.

2. Volatile Organic Compounds (VOCs)

Facility A & B: VOC levels remained below 0.5 ppm, well within the WHO safe limit of 1 ppm. The absence of high-temperature processes contributed to lower emissions.

Facility C (Pyrolysis): VOC levels averaged 2.4 ppm, with peaks up to 3.8 ppm during reactor venting, particularly benzene, toluene, and styrene—known carcinogens. These results highlight inadequate condensation systems or leakages in the exhaust mechanism.

3. Other Gaseous Emissions (SO_x, NO_x, CO)

Pollutant	Facility A	Facility B	Facility C	NAAQS Limit
SO _x	8 µg/m ³	6 µg/m ³	48 µg/m ³	80 µg/m ³
NO _x	14 µg/m ³	12 µg/m ³	60 µg/m ³	80 µg/m ³
CO	0.3 ppm	0.2 ppm	1.5 ppm	2.0 ppm

While all facilities remained within NAAQS limits, the pyrolysis unit approached critical thresholds. The elevated SO_x and NO_x emissions can be traced to incomplete combustion and feedstock contamination. These emissions, though not acutely hazardous, pose chronic respiratory risks with sustained exposure.

Polycyclic Aromatic Hydrocarbons (PAHs): PAHs were detectable **only at Facility C**, with concentrations of benzo[a]pyrene (BaP) reaching **2.1 ng/m³**, which exceeds the European guideline value of 1.0 ng/m³. These results are concerning given BaP's strong association with cancer risks and endocrine disruption.

Analysis of By-products Mechanical and Cryogenic Outputs

1. Shredded Rubber and Granules: Both were found free from hazardous leachates as per TCLP testing. Their reuse in rubberized asphalt, sports turf, and moulded products is environmentally viable.

2. Steel Wires (Facility A): Magnetically separated steel wires were ~95% pure and suitable for re-smelting.

3. Cryogenic Waste Residue: Minimal in volume and chemically inert, posing no disposal risk.

Pyrolysis By-products

1. Pyrolytic Oil: High in calorific value (~9800 kcal/kg) but contained 1.3% sulfur by weight and traces of benzene, making it unsuitable for direct use as industrial fuel without desulfurization. Flash point tests (ASTM D92) revealed a low safety margin (~42°C).

2. Carbon Black: Contained up to 900 ppm of zinc and 120 ppm of lead, surpassing the acceptable limits for use in non-automotive rubber products. Requires purification before reuse.

3. Condensed Gases: Consisted largely of methane, ethane, and traces of hydrogen sulfide (H₂S). Although energetically valuable, the toxicity of raw gas poses handling risks.

4. Steel Residues: Often coated with oily carbon black, rendering them unsuitable for direct recycling without extensive cleaning.

Comparative Environmental Risk Assessment: A lifecycle impact analysis (LCA)-based risk index was developed to numerically compare the environmental footprint of each method:

Method	Air Pollution Index (0–10)	By-product Hazard Index(0–10)	Overall Risk Score
Mechanical	2.1	1.5	3.6(Low)
Cryogenic	1.7	2.0	3.7(Low)
Pyrolysis	7.8	6.5	14.3(High)

The pyrolysis process, while material-efficient, presents significant environmental and health hazards due to air pollution and toxic by-products, warranting stricter regulation and technology upgrades.

Discussion and Interpretation: The results validate that while tyre recycling is a necessary strategy for waste management, the choice of recycling technology critically determines the environmental outcomes. Mechanical and cryogenic methods are safer, though limited in value recovery. Pyrolysis offers higher resource recovery but at the cost of air quality and public health risks.

Key gaps identified include:

1. Lack of emission control technologies in small-scale pyrolysis units.
2. Absence of quality standards for secondary products like pyrolytic oil and carbon black.
3. Inadequate regulatory oversight and environmental auditing.

These findings point to a pressing need for integrated environmental planning, mandatory emissions treatment systems, and market certification for by-products.

Conclusion: This study systematically investigated the environmental implications of three predominant tyre

recycling techniques—mechanical shredding, cryogenic grinding, and pyrolysis—with a particular focus on their impact on ambient air quality and the nature of their by-products. The findings clearly establish that while tyre recycling plays a crucial role in sustainable waste management and resource recovery, the process employed significantly affects its environmental footprint.

Among the methods evaluated, mechanical shredding and cryogenic grinding demonstrated comparatively minimal adverse impacts on air quality. Emissions of particulate matter, volatile organic compounds (VOCs), and gaseous pollutants remained well within regulatory limits, and the by-products generated—such as shredded rubber, fine rubber granules, and reclaimed steel—were found to be non-hazardous and readily reusable. These processes, although less efficient in terms of material recovery, present a safer and more environmentally viable option for tyre waste handling, particularly in urban or sensitive ecological zones.

In contrast, pyrolysis, while technologically advanced and efficient in extracting valuable secondary resources such as pyrolytic oil, carbon black, and steel, posed considerable environmental concerns. The process emitted elevated levels of PM_{2.5}, PM₁₀, VOCs, and polycyclic aromatic hydrocarbons (PAHs), often exceeding national and international air quality standards. Moreover, the by-products—though economically attractive—contained hazardous constituents such as heavy metals and carcinogenic hydrocarbons, raising red flags over their unregulated use and disposal.

The environmental risk assessment matrix developed in this study revealed pyrolysis to have the highest cumulative risk score, indicating a strong need for improved emissions control, process optimization, and regulatory oversight. In its current state, pyrolysis, especially when implemented without adequate pollution control mechanisms, can negate the environmental benefits of recycling by introducing new forms of air and soil contamination.

From a policy and implementation perspective, the following recommendations emerge from this research:

- 1. Mandatory Installation of Emission Control Devices:** All pyrolysis units must be equipped with advanced scrubbers, condensers, and real-time emission monitoring systems to mitigate the release of hazardous pollutants.
- 2. Standardization of By-products:** Quality certification protocols must be established for pyrolytic oil, carbon black, and recycled steel to ensure their safe use in downstream industries.
- 3. Preference for Low-Impact Recycling Methods:** Government incentives and subsidies should promote mechanical and cryogenic recycling technologies, particularly in densely populated or environmentally sensitive regions.

4. Integrated Environmental Auditing: Regular field-based audits by pollution control boards should be enforced to assess compliance with air quality standards and waste handling norms.

5. Public Awareness and Industry Training: Stakeholders in the recycling sector must be educated on the environmental and occupational risks associated with unregulated recycling practices and trained in safe handling techniques.

In conclusion, the sustainable management of end-of-life tyres requires a balanced approach that combines technological innovation with environmental responsibility. This research underscores the need to transition from unregulated pyrolysis to cleaner, controlled recycling operations, supported by robust policy frameworks, monitoring systems, and industry best practices. Only then can tyre recycling truly become a pillar of the circular economy, contributing to resource conservation without compromising ecological and public health.

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