

Selective Recovery of Valuable Chemicals from Tire Pyrolysis Oil: A Sustainable Approach

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Abstract

The generation of waste/scrap/end-of-life tires (ELTs) poses severe environmental challenges globally. For the disposal of huge numbers of ELTs (generated every year) using conventional recycling methods, like as landfill or incineration, are not preferred due to their adverse environmental impacts. To overcome this problem, an alternative and promising technology is developed -the pyrolysis of waste tires. Pyrolysis is a thermochemical process that decomposes organic materials (Rubber Hydrocarbons) in the absence of air at elevated temperatures. This process yields industrially valuable products like tire pyrolysis oil (TPO), pyro gas, and char (crude carbon black). Tire pyrolysis oil (TPO) is found to be a versatile and valuable feedstock with rich in hydrocarbons content, including aromatic compounds and terpenes, which can be further processed to recover precious chemicals. Tire pyrolysis oil is a heavy oil or crude oil which is extracted from waste tires through the pyrolysis process and considered as Green Fuel. Tire pyrolysis oil can be successfully converted into diesel by refining, and it can be used in large automobile vehicles like trucks, trailers, tractors & generators, and heavy machinery etc. Tire pyrolysis oil is being developed as an alternative to conventional fossil fuel because it has more or less similar physicochemical properties to diesel fuel. The physicochemical properties of tire pyrolysis oil will have similar impact on the combustion, performance, and emission comparable to diesel engines. Tire pyrolysis oil obtained by pyrolyzing end-of-life tires also contains valuable chemicals such as toluene, benzene, ethylbenzene, xylene (BTEX), and limonene. This review article briefly explores the composition of TPO, the key chemicals that can be extracted, and various technologies and methods currently employed or being developed to recover these precious chemicals efficiently and sustainably.

Keywords: Tire pyrolysis oil, end of life tires, benzene, xylene, ethyl benzene, BTEX

INTRODUCTION

The exponential growth in the number of automobile vehicles globally has led to huge generation of end-of-life tires (ELTs) [1-2], which are a severe environmental and waste management problems globally. Tires are produced using natural & non-bio degradable synthetic rubbers, carbon black, steel, rubber processing oil and chemical additives etc. Thus, making their disposal very difficult using conventional methods like landfilling or incineration. To overcome, these concerns, pyrolysis is emerged as a promising thermochemical technology that not only mitigates the environmental impact of waste tires but also recovers valuable energy resources [3-4]. Generally, tire pyrolysis involves the thermal decomposition of tires in an oxygen-free environment, resulting in the production of three major products: solid residue (primarily carbon black and steel), non-condensable gases (pyro gas), and a liquid fraction known as tire pyrolysis oil (TPO).

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Tire pyrolysis oil accounts for approx..35–45% of the total output by weight, is a complex mixture of hydrocarbons, oxygenated compounds, and aromatic chemicals. TPO initially explored as an alternative fuel due to its high calorific value, TPO has garnered growing attention for its potential as a source of high-value chemicals. Among the Chemicals present in TPO, aromatic hydrocarbons

such as benzene, toluene, ethylbenzene, xylene (collectively known as BTEX), and specialty chemicals like limonene getting special attention due to their extensive industrial applications and commercial value. These chemicals are key raw materials in the production of polymers, solvents, pharmaceuticals, agrochemicals, and fragrances, making their recovery a subject of growing interest for both economic as well as environmental reasons.[5-7]

The extraction and purification of these precious chemicals from TPO need a thorough and detailed understanding of the TPO's composition and require advanced separation techniques. TPO typically contains around 10–20% aromatic hydrocarbons, depending on the pyrolysis conditions and input feedstock composition. Benzene and toluene are normally found in significant quantities and xylene and ethylbenzene in relatively smaller but commercially relevant amounts. Limonene, which is a renewable monoterpene hydrocarbon with a citrus-like aroma, is derived from the thermal degradation of natural rubber and found predominantly in the lighter fraction of the pyro oil. Its recovery not only adds commercial value to the process but also aligns with the growing demand for bio-based and sustainable chemicals.

The real challenge lies in effectively isolating these compounds from a complex mixture that also includes heavier hydrocarbons, sulphur compounds, and reactive intermediates [7-9]. Conventional separation techniques like fractional distillation, solvent extraction, adsorption, and advanced chromatographic methods are being employed and developed to separate and purify desired chemicals from TPO. Recent R&D efforts in development of catalysis and membrane-based technologies have further improved the selectivity and efficiency of recovery processes, opening new opportunities for industrial-scale applications of these improved separation technologies.

This article provides a comprehensive review of the recovery of precious chemicals such as benzene, ethylbenzene, xylene, and limonene from tire pyrolysis oil. It explores the chemical composition of TPO, identifies factors influencing the yield and quality of target compounds, and discusses the latest developments in extraction and purification technologies. By highlighting the economic and environmental benefits of chemical recovery from TPO, this work highlights the potential of tire pyrolysis as a key feedstock of sustainable waste management and resource recovery strategies.

Literature Survey on Recovery of Chemicals from Tire Pyrolysis Oil

Typically, Tire pyrolysis oil (TPO) is a mixture of hydrocarbons and pose serious processing problems due to high sulphur content (around 0.8-1.4 wt%), heterogeneous composition, & presence of unwanted contaminants. Current methods achieve oil yields up to 45-50% by weight, however, resulting products always need upgrading steps prior to its commercialization.

One of the big tasks is in efficiently converting a complex and contaminated mixture of hydrocarbons into standard fuel products as well as maintaining economic feasibility at commercial scale up. A summary of literature survey is as follows,

As per this patent chemical products and carbides obtained from end-of-life tires were successfully recycled by multi-step process involving pyrolysis, hydrogenolysis, and steam cracking. As a first step, process involves pyrolysis of crushed tire scrap to get Pyro gas (gas fraction), Pyro Oil (oil fraction), and Crude Carbon Black (residual fraction). The carbide is thereafter recovered from the residual fraction. Hydrogenolysis of the oil fraction results into formation of light & heavy fractions. The heavy fraction is steam cracked to obtain precious chemical products along with new carbide feedstock. The process allows efficient conversion of used tire waste into value-added chemicals along with recovery of carbide as a by-product. [10]

Hydrotreatment process is generally used to reduce undesirable high diolefin, high sulphur, nitrogen, and chlorine contents in TPO. The process is carried out following a specific sequence and catalyst for hydrogenation of tire pyrolysis oil (TPO). The process involves mixing the pyrolysis oil and hydrogen

under high pressure (~15 MPa or more) for hydrogenation of TPO. Further processing involves a second mixing stage with hydrogen at relatively lower pressure (around 5 MPa or more) with a different hydrogenation catalyst. The two-step hydrogenation process yields effective hydrogenation of the oil without deactivation of the catalyst due to sulphur and nitrogen present in the TPO. [11]

A patent reports economical method for recovering desulfurized fuel oil & fuel gas from scrap tires using hydro processing and distillation processes. The method involves hydro processing of the pyrolysis oil from tires for its desulfurization. The resulting hydro processed oil is then distilled to produce multiple fuel products like kerosene, naphtha, fuel oil, fuel, and diesel. The amount of hydrogen necessary for hydro processing is met by recirculating hydrogenated material. The excess pyro fuel gas is used to produce power. The power production from pyrolysis by-products and electrolytic production by hydrogen through the low-cost power co-produced reduces the overall costs [12]

A patented method reported simultaneous processing of mixture of pyrolysis oil from plastic waste and renewable resource oils for the removal of impurities and use them for further refining steps. The process involves several steps such as selective hydrogenation, hydrodemetalation, and hydrotreating. Process allows converting the contaminated feedstocks with various impurities into cleaner fuel products suitable for further refining into existing refineries. Typically, these steps are carried out at elevated temperatures and hydrogen pressures to minimize and avoid excessive gum formation during the operations. This allows handling and transportation of the pyrolysis oil without clogging issues. This process also reduces impurities such as dienes, metals, metalloids, chlorine, and sulfur to levels meeting the speculations required for further processing in existing refinery units [13]

A Chinese defines method for refining high-quality light oil obtained from pyrolysis oil to upgrade it as a versatile fuel. The method involves pre-treating the pyrolysis oil to minimize various impurities, stripping heavy oil, cracking of the remaining hydrocarbons, fractional distillation of the cracked oil, and filtering the final light oil to significantly improve its purity. This method allows crude pyrolysis oil into high-quality light oil which can be used as a general-purpose fuel [14].

A patent outline method for upgrading pyrolysis oil obtained from plastic and rubber waste to produce a higher quality fuel with much reduced impurities i.e. olefins, solid residues, and heteroatoms. Typically, the process involves treating the pyrolysis oil with an aqueous solution or optionally a hydrocarbon fluid to separate into phases. The organic phase is subsequently separated and filtered to produce the upgraded version of pyrolysis oil containing reduced impurities as compared to the untreated original oil. Treated TPO can be used as upgraded oil -a substitute for transportation fuel, blending with other conventional fuels, or as a chemical feedstock. The aqueous solution extract impurities from the pyrolysis oil into the water phase and hydrocarbon fluid assists separation and reduction of solid residues [15].

A process is reported for the disposal of end-of-life tires (ELT) that allows complete recycling without creating environmental problems. This process involves pyrolyzing to convert the scrap tires into pyrolysis oil. The pyrolysis oil is thereafter subjected to hydro refining to improve its quality and make it as substitute of fossil fuels for industrial processes. This process therefore allows converting the end of life tires into a valuable industrial product instead of burning them or landfilling them. The hydro refining removes impurities such as rubber fines and other impurities to produce a cleaner, and more useful oil [16]

A method to co-pyrolyze waste tires and waste polyolefin plastics in an anaerobic environment to produce low-oxygen high-quality pyrolysis oil. The method involves mixing the waste tire and waste polyolefin plastics in a 1:1-10 mass ratio, heating them at 400-800°C for 10-60 seconds, and collecting the liquid phase pyrolysis product. The co-pyrolysis of waste tires and waste polyolefin plastics significantly reduces the oxygen content in the pyrolysis oil, improves the yield and quality of the

pyrolysis oil, and expands the relationship between waste tires and waste plastics. It provides a coordinated recycling solution for harmless treatment of waste tires and waste plastics while reducing carbon emissions [17].

Upgradation of pyrolysis oil from organic waste cracking improves quality of oil and enable its usage as fossil fuel in industrial applications. Generally, process involves secondary cracking of the crude pyrolysis oil and water mixture to separate and upgrade the pyrolysis oil. The secondary cracking steps involves flashing, washing, condensation, and separation to minimise impurities and produce refined oil. This improves the quality of the pyrolysis oil as compared to the crude mixed condensate [18].

A method is reported for producing high-quality oil from waste tires obtained by pyrolysis, separation, and refining. The method covers crushing the waste tires, pyrolysis under an ammonia atmosphere under pressure and separating the liquid mixture, and further refining the crude pyro oil. The pyrolysis step is carried out at 425°C for 2 hours. The separation process is done using cooling and extraction by dichloromethane solvent. The refining of crude pyro oil involves hydrogenation with a combination of catalyst and tetrahydronaphthalene. This method results into high-quality oil with properties matching to commercial grade oil [19]

Pyrolysis process of scrap tires has been reported to make fuel products that can be used in marine applications. The fuel having specific properties like flash point, boiling range, density, acid number, styrene content, and halogen content similar to existing fuel. The fuel is derived from pyrolyzing scrap/waste rubber and subsequently separating the oil fraction. The pyrolysis of scrap tires is carried out between 400 to 550°C temperature and 1 to 4 hours residence time with negative pressure during processing. The oil thus obtained is centrifuged to remove solids before separation. The fuel so obtained has a flash point > 40°C, boiling point > 140°C, density < 990 kg/m³, acid number < 12, styrene, < 7000 ppm, and halogen < 50 mg/kg [20]

A Process developed for recycling rubber shavings from end-of-life tires (ELTs) into resins and used in virgin tire production without deteriorating tire performance. The process is based on pyrolysis of the rubber shavings to generate pyrolysis oil containing olefinic monomers. The oil is subsequently separated into various fractions and the intermediate fraction containing the desired monomers. This monomer containing fraction is polymerized to obtain the resins. The process conditions are so optimized to get highest monomer yield from the shavings. Detailed studies exhibited that the resulting resins for ELTs shaving can be used in fresh tire production without affecting tire performance [21-22]

Extracting fuel from scrap tires through pyrolysis process and separation of different by-products of the process can produce valuable added industrial fuel compositions. The pyrolysis of waste rubber generate oil having high levels of black carbon. This oil is separated into two fuel components. One product is low-density fraction, low-sulfur fuel with low halogen content and low aromatic content. The second fraction is high-density fuel containing high aromatic content. The low-density fuel has found to be suitable for commercial use as a fuel meeting requirement like low flash point, low sulfur, low halogen, and low aromatic content. This allows its usage in tanks, vessels, and equipment without the post-use cleaning step due to the black colour. The high-density fraction has high aromatic content and can be used as a high temperature heating media for industrial applications [23]

Composition of Tire Pyrolysis Oil

Tire pyrolysis oil is a complex mixture of hydrocarbons, containing both aliphatic and aromatic hydrocarbons. Typically, significant portion (about 62.4%) of TPO contains aromatic hydrocarbons like benzene, toluene, xylene, and styrene (23), as well as their alkylated homologues and polycyclic aromatic hydrocarbons (PAHs). Other components include heteroatom and polar compounds. The exact composition of TPO dependent on several factors such as temperature, residence time, and the type of tires used in pyrolysis process. The composition of TPO varies based on several factors like feedstock

type (crumbs of scrap tyres), particle size of scrap tires, pyrolysis conditions (temperature and feed rate), reactor design and continuous or batch pyrolysis process. Typically, TPO comprises:

- *Aromatic hydrocarbons*: Aromatic compounds like benzene, toluene, xylene (BTX), ethyl benzene, and styrene, which are very valuable for further processing in petrochemical industry.
- *Aliphatic hydrocarbons*: Mixture of Paraffins and olefins, which can be utilized as solvents or fuel additives.
- *Terpenes*: Like limonene, which have wide applications in fragrances manufacturing and also as green solvents.
- *Polycyclic aromatic hydrocarbons (PAHs)*: High molecular weight compounds that can be very well used in carbon black production.
- *Sulfur and nitrogen compounds*: These compounds have to be removed by the process of desulfurization and denitrogenating prior to further processing before utilization commercially.

The type of tires used, pyrolysis temperature, and residence time all play a role in the final composition of the pyrolysis oil. For example, at higher temperatures and longer residence times, more char (solid residue) and less oil may be produced[24].

Recovery Techniques for Precious Chemicals

Distillation

In the distillation process, TPO is heated in a distillation column under controlled temperature conditions and as the temperature rises, different components of the oil vaporize at their respective boiling points. BTEX compounds, are light aromatics with relatively low boiling points (Benzene ~80°C, Toluene ~110°C, Xylene ~140°C), are distilled off in the light fraction of the process (24).

The distillate containing BTEX is then condensed and collected separately. Further refining or purification is used to isolate BTEX compounds individually. This recovery process adds significant economic value to tyre pyrolysis by enabling the extraction of high-demand petrochemicals.

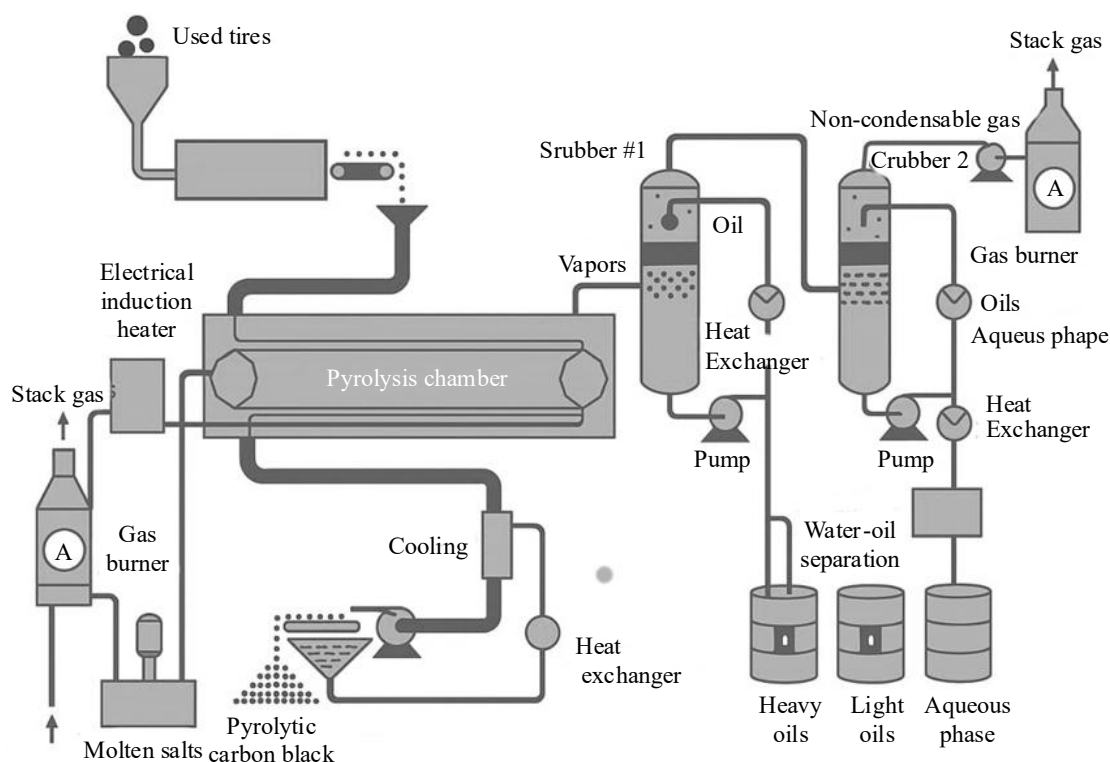


Figure1. Recovery of chemicals from tire pyrolysis process (25).

Fractional distillation is a primary method for separating components in TPO based on their boiling points. This process as shown in the Figure 1. involves:

- *Initial distillation*: TPO is heated to separate lighter fractions (boiling below 204°C) from heavier ones
- *Further separation*: The lighter fraction is subjected to additional distillation to isolate specific compounds.

This technique yields valuable chemicals such as BTX compounds, styrene, and limonene, which are essential in various industrial applications. [25]

Flow Diagram as shown in Figure: Distillation of TPO to Recover BTEX

1. *TPO feedstock*: Crude TPO is pumped into the distillation unit.
2. *Heating*: The TPO is heated in a reactor under controlled conditions to vaporize its components.
3. *Fractional distillation column*: The vaporized mixture enters a distillation column equipped with a reflux system.
4. *Condensation*: Vapor rises through the column, condensing at various trays based on boiling points.
5. *Collection of fractions*: Light Fraction (LF): Contains BTEX compounds and lighter hydrocarbons.
Heavy fraction (HF): Comprises heavier hydrocarbons and polycyclic aromatic hydrocarbons (PAHs).
6. *Cooling system*: The condensed fractions are cooled and collected in separate tanks.
7. *Purification*: The light fraction undergoes further purification to remove impurities and enhance quality.
8. *Final products*
 - *BTEX*: Recovered for use in various industrial applications.
 - *Heavy Oil*: Can be used as fuel or can be further processed.
 - This distillation process allows for the efficient recovery of valuable BTEX compounds from TPO, contributing to the circular economy and reducing reliance on fossil fuels.[26]

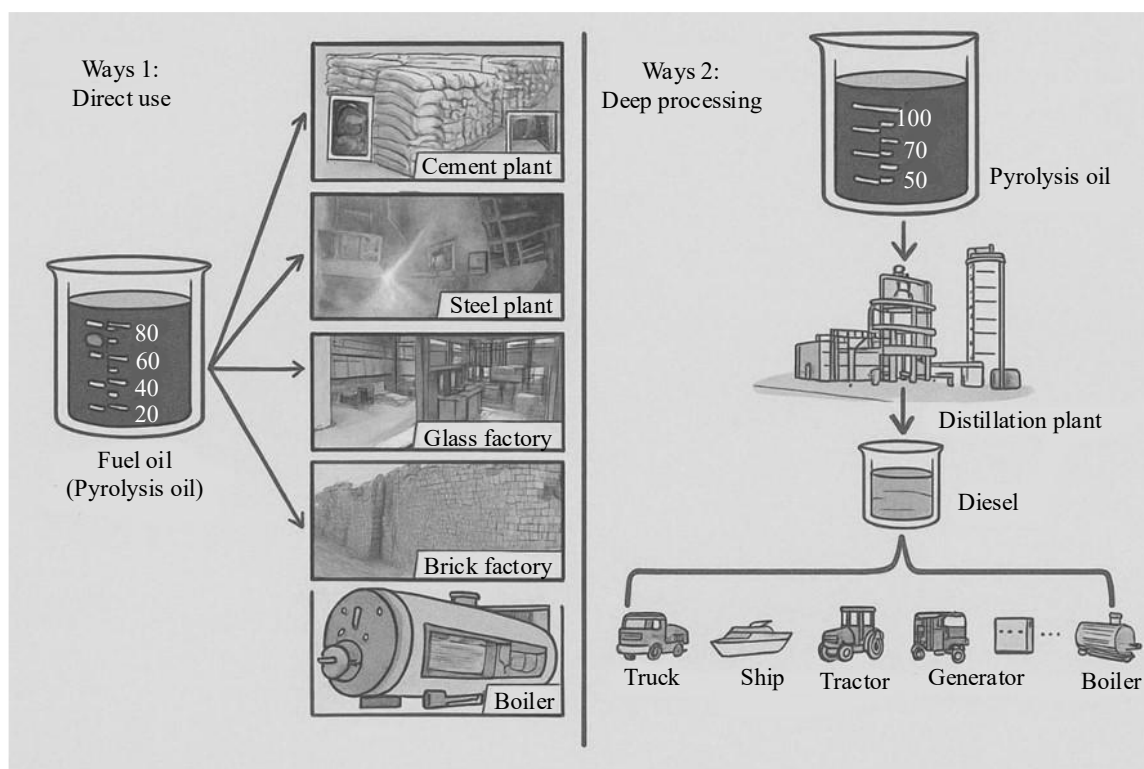


Figure 2. Industrial uses of tire pyrolysis Oil (26).

CATALYTIC UPGRADING

Catalytic upgrading involves using catalysts to enhance the quality of TPO by promoting desirable chemical reactions:

- *Hydrotreating*: Utilizes hydrogen and catalysts to remove sulfur and nitrogen impurities, improving the oil's quality for use as a fuel or chemical feedstock.
- *Hydrocracking*: Breaks down larger hydrocarbons into lighter, more valuable fractions.
- *Selective hydrogenation*: Targets specific compounds, such as PAHs, converting them into more useful chemicals. [27]

These processes enhance the economic value of TPO by producing high-quality fuels and chemicals. Catalytic Upgrading of Tyre Pyrolysis Oil (TPO):

1. Feedstock Preparation:
 - Waste tyres are shredded and fed into the pyrolysis reactor.
2. Pyrolysis Reaction:
 - The reactor is heated to temperatures between 400–600°C in the absence of oxygen.
 - This process breaks down the tyres into gaseous and liquid products, including TPO.
3. Catalytic Upgrading:
 - The TPO is then passed over a catalyst bed (e.g., Ni/HZSM-5 zeolite) at temperatures around 350°C.
 - This step reduces sulfur content, enhances aromatic compound production, and improves fuel quality.
4. Product Separation:
 - The upgraded oil is condensed and separated into various fractions based on boiling points.
 - Light fractions may be used as gasoline-like fuels, while heavier fractions can be further processed or used in industrial applications.
5. By-product Management:
 - Gaseous by-products are collected and can be used as fuel for the pyrolysis process.
 - Solid residues, including carbon black and steel wire, are separated and can be recycled or disposed of appropriately Figure 2.

This catalytic upgrading process enhances the quality of TPO, making it a more viable alternative fuel source.[28]

STEAM DISTILLATION

Steam distillation is particularly effective for extracting volatile compounds like terpenes:

- *Process*: Steam is introduced to TPO, causing the volatile compounds to evaporate and then condense into a separate phase.
- *Advantages*: This method is gentle and helps preserve the integrity of sensitive compounds like limonene, which are valuable in the fragrance and flavour industries.

Following are the advantages of steam distillation over traditional distillation methods for upgrading Tire Pyrolysis Oil (TPO):

1. Lower Operating Temperatures
 - Steam distillation allows separation of various components at relatively lower temperatures than their actual boiling points.
 - This minimise thermal cracking or degradation of valuable light hydrocarbons and preserving fuel quality.
2. Reduced Energy Consumption
 - Because steam distillation is carried out at lower temperatures, it requires less energy than conventional high-temperature distillation process.
3. Minimization of Tar Formation
 - High temperatures in traditional distillation often lead to the formation of heavy tars and coke as residue.[29]

- Steam distillation being carried out at a relatively lower temperature, helps in reducing formation of these unwanted by-products and improving overall efficiency.
- 4. Improved Product Quality
 - Generally, lighter fractions obtained by steam distillation contains lower sulphur content and better combustion properties.
 - This results in cleaner and more stable fuel suitable for industrial applications or engine use.
- 5. Better Environmental Performance
 - Lower sulphur & impurity levels in the finished product reduces the toxic emissions when the fuel is burned.
- 6. Equipment Longevity
 - Less thermal stress & tar formation during steam distillation results reduced fouling and wear of distillation equipment and extending its service life.[30]

ADSORPTION AND EXTRACTION TECHNIQUES

Advanced materials such as activated carbon, zeolites, and alumina are often used to selectively adsorb, separate or extract specific components from TPO:

- *Desulfurization*: For this purpose, normally, adsorbents such as alumina removes sulphur compounds and making the oil more suitable for use in engines or as a chemical feedstock.
- *Selective extraction*: Solvents or ionic liquids are used to extract specific compounds, such as BTX, from TPO and enhancing the purity and yield of the desired chemicals.

CARBON BLACK PRODUCTION

The heavy fractions of TPO, which is rich in PAHs content, are ideal feedstocks for carbon black production:

- *Process*: In this process, heavy oil is subjected to partial oxidation at high temperatures, resulting in the formation of carbon black
- *Applications*: Carbon black is widely used as a reinforcing agent in rubber products, especially tires, and as a black pigment in inks and coatings.

Applications of Recovered Chemicals

The precious chemicals recovered from TPO have diverse applications across various industries:

- *Petrochemical industry*: BTX compounds used as feedstocks for the commercial production of plastics, synthetic fibres, and resins.
- *Energy sector*: Upgraded TPO is being developed to be used as a fuel or blended with conventional fuels to reduce dependency on fossil resources.
- *Fragrance and flavour industries*: Recovered limonene from TPO may be utilized in the production of perfumes, cleaning agents, and flavouring substances.
- *Rubber and plastics manufacturing*: Carbon black produced from TPO is a key ingredient in reinforcing and commercial production of tire and non-tire rubber products and as a black pigment in plastics. [31]

Environmental and Economic Implications

The recovery of precious chemicals from TPO can have several environmental and economic benefits (27): such as

- *Waste reduction*: Pyrolysis of scrap tires convert waste tires into value added products and significantly reducing landfill usage of scrap tires and thus minimizing environmental pollution.
- *Resource conservation*: Recovering chemicals from TPO will lead to the reduced reliance on virgin fossil resources and will contribute to resource conservation.
- *Economic value*: The production of high-value chemicals from TPO is expected to stimulate economic growth by new markets development and creating job opportunities in recycling and chemical processing related industries.

Challenges and Future Directions in the Recovery of Precious Chemicals from Tire Pyrolysis Oil (28)

Challenges

Recovery of valuable chemicals from TPO holds immense potential, however, it is not possible without significant technical, economic, and environmental challenges. These obstacles must be addressed and overcome for making the process commercially viable and environmentally sustainable.

Complexity of TPO Composition

TPO is a highly complex mixture of hundreds of chemical species, including aromatics, aliphatic, oxygenated compounds, sulphur- and nitrogen-containing species. This complexity makes:

- *Selective separation difficult*: It requires sophisticated analytical equipment and system capable of multiple stages of distillation or chemical treatment.
- *Analytical challenges*: Accurate characterization of TPO components require advanced instrumentation like GC-MS, FTIR, and NMR, which will increase overall operational costs.[32]

Presence of Contaminants

The presence of undesirable compounds like:

- Sulfur compounds (e.g., thiophenes, mercaptans)
- Nitrogenous compounds
- Heavy metals

Makes the downstream processing of TPO more difficult and complicated. These contaminants can:

- Poison catalysts used in upgradation of TPO processes like hydrotreating.
- Lead to environmental issues when the oil is combusted or disposed of improperly which will result in release of toxic vapours.
- Increase the cost of refining due to additional treatment steps.

Catalyst Deactivation and Regeneration Issues

In catalytic regenerating/upgrading processes:

- Catalysts activity may suffer from coke formation (deposition of carbonaceous residues).
- The high temperature and heavy oil fractions may damage catalyst structure.
- Frequent regeneration or replacement may be required, which will increase operational downtime and cost.

Economic Viability

Despite the potential value of recovered chemicals:

- High capital investment is required for setting up advanced and sophisticated distillation, upgradation, and purification facilities.
- Low yield of high-value chemicals may not justify the cost without subsidies or value-added integration.
- Volatile oil markets can significantly influence the profitability of producing fuels or chemicals from TPO.

Regulatory and Environmental Compliance

Operating a pyrolysis facility involves:

- Strict adherence to stringent environmental regulations for emissions (e.g., VOCs, SO_x, NO_x) (29).
- Safe handling and storage of flammable and toxic chemicals.
- Disposal and salvaging of solid and liquid waste streams responsibly.

Inconsistencies in regulations across regions may also hinder large-scale adoption of TPO chemical recovery plants globally.

Lack of Standardization

Currently, there is:

- No standard unified verified classification or quality standard for TPO (30).
- Variability in feedstock composition (tires vary by brand, type, and age).
- Difficulties in process reproducibility and scalability across different setups.

This lack of standardization may severely affect consistency in product quality and deters its adoption on commercial scale.

Future Directions

Despite these above-mentioned challenges, there are several promising directions and innovations that can lead to unlocking the full potential of TPO valorisation (30).

Advanced Catalytic Materials

Next-generation catalysts are under development to:

- Improve adsorption and selectivity toward desired chemicals (e.g., BTX, limonene).
- Development of catalysts with improved resistance for poisoning from sulphur and nitrogen compounds.
- Catalysts capable of in-situ regeneration and reducing process downtime.

Examples include

- Zeolite-based catalysts with tailored pore sizes.
- Metal-organic frameworks (MOFs) for selective adsorption and reaction.
- Nano-structured metal oxides for enhanced surface area and activity.

Process Integration and Intensification

Integrating and synchronising TPO recovery processes into current industrial ecosystems (e.g., refineries, chemical plants) can:

- Reduce transport and handling costs.
- Enable the use of shared common infrastructure.
- Capable of handling combined product streams and will lead to greater value recovery.

Following Process Intensification Techniques Such as:

- Reactive distillation
- Microwave-assisted pyrolysis
- Supercritical extraction can enhance efficiency, reduce energy usage, and improve product yield.

Bio- and Green Chemistry Approaches

Enzyme-catalyzed processes and green solvents (e.g., ionic liquids, supercritical CO₂) are currently being developed for:

- Mild and selective extraction of desired value-added chemicals like limonene or phenolics.
- Environmentally friendly desulfurization processes.
- Significantly reducing the air pollution of the recovery process.

Machine Learning and Data-Driven Optimization

Using artificial intelligence (AI) and machine learning models can help:

- Predict precise and optimal pyrolysis conditions to achieve maximum yield of target compounds.
- Measure, Monitor and effectively control real-time processing parameters.
- Automated quality control system for consistent product quality.

Smart modelling techniques can also be used for the selection of tires and determining optimum operating conditions and processing parameters for achieving optimized outputs.

Policy Support and Economic Incentives

Governments can accelerate and motivate adoption of the technologies through:

- Subsidies or tax credits for recycling and chemical recovery sectors.
- Setting up carbon credits for emissions saved.
- Establishing dedicated standards and certification schemes for promoting commercial usage of recovered pyrolysis chemicals.

Public-private partnerships can facilitate the faster adoption of technology and commercialization to foster innovation ecosystems.

Circular Economy and Sustainability Integration

Tire pyrolysis process can be aligning with circular economy principles by:

- Reintroducing recovered chemicals into manufacturing loops (e.g., recovered BTX into tire production).
- Developing and commercially implementing closed-loop recycling models.
- Partnership of automotive and chemical sectors to develop adequate and best end-to-end solutions.

As backward integration, sustainable tire design (produced using recyclable materials or fewer additives) will also improve the quality of TPO and its downstream utility and adoptability.

CONCLUSION

As per the global market report for recovered chemicals from tire pyrolysis oil will experience exponential growth, due to the demand for sustainable waste management and alternative green energy and fuel sources. The global market for recovered chemicals from TPO is estimated to be increased from approx. \$776.66 million in 2023 to \$1275.83 million by 2032, with a Combined Annual Growth Rate of approx..6.0% (32). This significant growth is attributed to the stringent environmental as well as stricter waste management regulations, and the increasing attention to adopt circular economy practices globally.

The recovery of precious chemicals from tire pyrolysis oil represents a compelling and mandatory opportunity to transform an environmental liability into an economic asset. Through advance R&D in new catalysis, state of the art process engineering practices, AI based optimization, and sustainability practices, the challenge of solving TPO component complexity, its contamination and removal as well as economic viability can be sorted out for hassle free commercialization.

It can be concluded based on above details that, collaborative efforts of academia, industry, and policymakers will be crucial for successful implementation of commercial implementation of recovery of chemicals from TPO. It is therefore need of the hour to develop innovative recovery technologies and full support from policy frameworks, to fully reap of this recycling technology which will only reduce waste but also pave a way forward to more sustainable and circular chemical economy and therefore discarded tire waste/scrap has the potential to high-value creation by recovering precious chemicals as a bonus

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