



Turning tire green: examine waste tire pyrolysis as a green solution.

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Abstract: The world is moving forward; industries and populations have rapidly grown by increasing energy demands and releasing degradable and non-degradable wastes into the neighborhoods. When it is directed to global tire waste, billions of tires are produced, eventually becoming waste. Waste tires are excellent for energy production with high heating value, high volatile, and medium sulfur content. With the help of developing technology, the primary energy forms such as gases, liquid, and solid phases can be extracted from the waste tires to meet the energy demand while minimizing environmental and health issues. This paper reviews the previous research on Pyrolysis, the type of Pyrolysis with working principles, and why it is needed in detail to further the steps of Pyrolysis. Eventually, the composition of the tire and the effecting factors for the products percentages along with their applications and market.

Keywords: Tire pyrolysis, the composition of the tire, factors affecting Pyrolysis, alternative energy.

1 INTRODUCTION

Public concern and a top worry in policy discussions surround managing trash from end-of-life items. End-of-life scrap tires have serious environmental and public health consequences [1],[2]. Tires mainly comprise rubber, carbon black, steel, and textile components as reinforcing materials. The most commonly used tire is rubberstyrene-butadiene copolymer (SBR). Natural rubber and polybutadiene are also included in the manufacture of tires. Moreover, their chemical and physical properties make them a precious resource[3],[4]. Due to the booming economy and the burgeoning car sector, an increasing amount of used tires are creating "black pollution," which is endangering the quality of life for people[5],[6]. The number of tires produced worldwide is estimated to be 3.0 billion, with an annual growth rate of at least 1.0 billion tires, according to figures provided by Wang et al. [7]. Li et al. [8] Nearly 90% of the world's tire production is produced in North America, Europe, and Asia, which produce a lot of trash tires. In the EU, the European Tire and Rubber Manufacturers Association reported 3.57 million tons in 2018 and 3.42 million tons of waste tires collected in 2017. Each year, waste tire disposal is quantified between 1 and 1.8 billion pieces globally [9]. Over 1 billion tires are manufactured yearly for passenger cars, utility vehicles, trucks, off-road vehicles, etc. Every year, an almost equal number of tires is permanently removed from vehicles and defined as waste. Disposal of scrap tires is no longer an acceptable management practice because of the risks of tire fires, and tire piles can provide

habitats for diseases. EPA outlines the following principles: reuse, reduction, recycling, waste-to-energy, and proper disposal in a suitable facility [10]. Since the life period of tires in a landfill ranges between 80 and 100 years[11], landfilling increases community concerns and becomes a less acceptable choice[12]. Furthermore, the European Landfill Directive strictly prohibits the disposal of rubber tires on landfill sites. Tire rubber has a high calorific value and can be used as fuel, although some problems may arise due to the emission of hazardous compounds and metals[13]

According to the Industrial Information Network 2018 and China Rubber Association, statistics have summarised comprehensive data on recycling waste tires since 2011. The primary information comprises the production of tires and waste tires and the value and volume of the recovery, as presented in Fig. 1. It may be noted that the total production of tires from 2011 to 2018, in terms of weight, was around 172.82 million tons. New tires weighed 4.493 billion, while the waste tires weighed 96.41 million tons. But only 37.2 %, i.e., 35.87 million tons, recovery of waste tires was made due to which waste tires accumulated and caused severe environmental problems. Hence, there is a need to devise innovative techniques to recycle these waste tires for environmental protection[14], as shown in Fig. 2.



Fig. 1. Production and recycling of tires from 2011 to 2018 [14]

Major concerning issues of the current world are energy shortage and the destruction of the environment. Explosive population growth, increasing industrial development, and unorganized solid waste management are responsible for these issues. Energy recovery from diverse waste materials using adequate technology can minimize energy shortage and environmental damage. Therefore, as a solution, scientists have carried out extensive studies to find appropriate methods for energy recovery from non-biodegradable solid waste materials like rubbers and plastics[15] by the name of Pyrolysis which decomposes waste tires into gas, pyrolytic oil, and char, all of which are beneficial products[16],[17]. It is emerging as the safe, efficient, green option for recycling end-of-life tires. It's a circular solution that can solve the tire waste problem and simultaneously provide in-demand inputs for several industries. By enabling circularity, tire pyrolysis replaces fossil-based raw materials with sustainable alternatives to reduce the associated environmental impact[18].

2 WHY PYROLYSIS IS IMPORTANT

Pyrolysis may be used to create products from waste materials such as biomass, coal, lubricating oil, plastic, and tire trash that are both economically and environmentally advantageous[19],[20],[21].pyrolysis is one method of transforming waste tires into valuable products. It is becoming the preferred technology to recycle ELTs due to the allowance of tire industries to meet their sustainability plus climate change commitments[18]. Pyrolysis processes will make an impact on our environment and will be a significant investment to eliminate landfills, piles of used tires, asbestos, and toxic material by converting the waste into electricity, fuel, steam, construction/highway aggregate, and superior insulation and create new jobs by dealing with waste tire problem up to a great extent.100% wastage tire recycling environmental friendly process (No chemicals and Intermediates are used in operation) hence no soil, water or air pollution is observed During and after the process[22].

Tire debris should no longer be improperly disposed of thanks to the development of Pyrolysis, which stands out as a sustainable method for creating alternative fuels[23]—the world's most cost-effective waste tire recycling technology. Raw material (wastage tire) is cheap and easy to provide. It is a 100 % pollution-free process, thus creating an eco-friendly environment. Pyrolysis Creates an economically viable alternate source of energy to replace natural gas and petroleum products out of waste tires. The process can be applied to all rubber-based materials [22].

Fuel oil from tire pyrolysis is a good fuel, with more than 10,000 kcal of heat, which can be used in many industries, such as fuel for cement factories, glass factories, boiler factories, and heating centers, as shown in Fig. 3. Plus, the Fuel oil can be further processed into diesel by a distillation machine. Some countries, such as Africa, used as fuel for cars, trucks, and other fuels. It is also a good fuel for ships. Diesel is more widely used and has a higher price [24]. Pyrolytic oil is a complex mixture of paraffin, olefins, and aromatic compounds that can be used as fuels or added to petroleum refinery feedstock [10]. The fuel oil has no strict requirements on the storage environment. Worrying about oxidation, oil deterioration, and other issues is unnecessary. You only need to use a heavy oil burner when using it [24].



Fig. 2. fuel oil application [25]

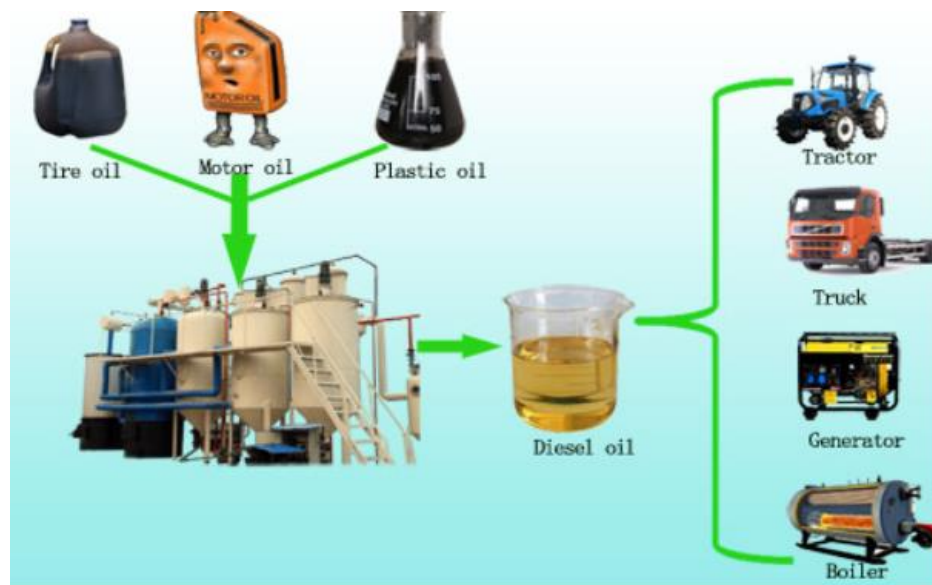


Fig. 3. Waste oil distilled uses [26]

The solid pyrolysis product, pyrolysis char, is a raw material for active carbon production. Solid fuels and carbon black are used in tire production[27],[28]. The pyrolysis gas can be used as fuel in the pyrolysis process for heat generation or other heat generation purposes [10]. Eventually, The procedure can reduce the external reliance on fossil fuels by recovering from local wastes and also promote circularity in the tire industry. The tire industry can improve its corporate ESG (environmental, social, and governance) goals by joining the circular economy and using safe pyrolysis products. [18].countries like Canada use tires as a source of energy and valuable chemical products through the thermal decomposition of rubber in a pilot plan [29]. The Whole tires have a low bulk density; around 75 % of their volume is space; hence, it take up a large volume in a landfill. The tire lifetime in a landfill is considered to be between 80 and 100 years[30]. Tires are thermoset polymers, which means that they cannot be melted and separated into their chemical components[11] such that the better way of managing tire waste is Pyrolysis.

3 COMPOSITION OF TIRE

Tires contain vulcanized rubber (60-65 wt.%) and carbon black(25-35 wt.%). The remaining comprises accelerators, fillers, reinforcing textile cords, fabric belts, steel wire reinforcing beads, etc., added during manufacturing [11]. The compositions vary depending on the application, manufacturer, etc. For example, the rolling friction is high in vehicles, so additives that reduce the rolling friction are added to the components used to prepare tires. The essential parts of tires are synthetic rubber or natural rubber, wire, fabric, tread, carcass, sidewall, shoulder, bead, bead wire, bead filler, and liner [31], as shown in Fig. 4 and the continent, the material of them is in table 2 [32]. And they are considered thermoset polymers. Vehicle tires (both passenger and truck) are mainly a blend of natural (NR) and synthetic rubber (SR), such as butyl rubber (BR) and styrene–butadiene copolymer (SBR) [33].

Rubber comprises elastomeric polymers characterized by a network structure that can temporarily be deformed when subjected to external forces. According to the International Rubber Study Group, in 2010, 24.37 million tons of rubber were produced. From this amount, 10.38 million tons (42%) were NR, and the remaining 13.99 million tons (58%) were SR[11]. Usually, the sulfur content of rubber from tires is around or up to 1.5 wt% [34]. An organic-sulfur compound accelerator is added with ZnO and stearic acid as a catalyst to control the vulcanization process and enhance the rubber's physical properties Other inorganic compounds include clay

fillers, calcium and magnesium carbonates, silicates, and various inorganic pigment materials [11]. Truck tires (TT) generally contain more natural rubber content than passenger car tires (PCT), and the amount of added compound can vary from region to region, as shown in Table 1 [32].

Table 1. shows the typical composition of passenger and truck tires [32]

Material(wt.%)	PCT		TT	
	USA	EU	USA	EU
Natural rubber	14	22	27	30
Synthetic rubber	27	23	14	15
Carbon black	28	28	28	20
Steel	14-15	13	14-15	25
others ^a	16-17	14	16-17	10

Fillers, accelerators, Nylon, and sulfur, among others.

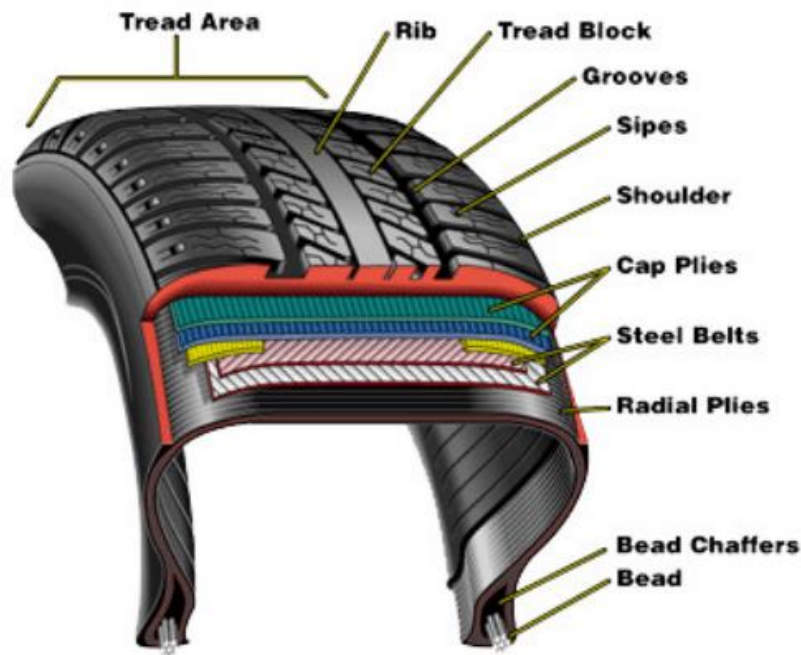


Fig. 4. Components that make up a tire [32]

Table 2. Typical elements of a tire and their constituent materials [32]

Element	Composition
Liner	Inner coating of synthetic rubber
Plies	Layers of rubber, Nylon, and metal-reinforced rubber piled together.
Bead heel	Ringed steel wires surrounded by hard rubber
Sidewall	Natural and synthetic rubber mixed with small amounts of carbon black and additives.
tread	Natural and synthetic rubber

Tires are characterized using proximate and ultimate (elemental) analyses. Depending on the specific literature's intention, the tire's calorific values can also be included[32]. The proximal and final analyses of several tires in the literature are shown in Tables 3 and Table 4.

Table 3. typical approximate analysis of a waste tire

Component (wt.%)	Literature source		
	Qiang Yao et al. [35]	Choi et al. [36] ^a	Williams et al. [37]
Moisture	1.14		0.8
Volatile matter	62.24	73.9± 0.66	66.5
Fixed carbon	32.28	21.8± 0.6	30.3
Ash	4.35	4.3± 0.07	2.4
Steel			
Calorific value (MJ/Kg)	34.9		40.0

^adry basis

Table 4. Typical ultimate analysis of a waste tire

Element (wt.%)	Literature source			
	Qiang Yao et al. [35]	Choi et al. [36] ^a	Williams et al. [37]	Isabel et al.[38]
C	84.08	89.2±0.00	85.9	86.5± 0.7
H	6.71	7.7± 0.01	8.0	10.7± 0.2
N	0.49	0.5± 0.02	0.4	0.3 ±0.04
S	1.51	2.6± 0.08	1.0	1.0 ±0.2
O	1.73		2.3	1.4 ±0.8
ASH			2.4	

^adry and ash-free basis

4 TIRE PYROLYSIS

Waste Tire Pyrolysis is a recycling technique that involves tire waste into industrial fuels (pyrolysis oil, monomers, steel wire, carbon black, tire oil, and gases)by thermal and catalytic cracking processes [22],[6]. As shown in Fig. 5. Pyrolysis has been referred to as reverse polymerization, thermal depolymerization, or polymer cracking [11].

Tire pyrolysis oil (TPO) is similar to Diesel fuels (DF) with some properties, such as calorific value and density, while others, such as viscosity and the composition of each fraction obtained in the tire pyrolysis, can vary depending on the precise characteristics of the process adopted (i.e., temperature, pressure, type of reactors) [39],[40],[41]. However, TPO's utilization in energy conversion devices, such as internal combustion engines, needs some preventative measures that depend on the specific application. In the case of Diesel engines, TPO must be mixed with Diesel fuel or complemented by a cetane improver (diethyl ether, etc.). Furthermore, the high sulfur content in TPO can require desulphurization methods to meet stringent exhaust SO₂ limits [10].



Fig. 5. waste tire pyrolysis products and their applications [42]

The thermochemical breakdown of tires without oxygen at high temperatures is known as Pyrolysis. Pyrolysis happens at high temperatures (300°C-900°C) and low pressure[43]. Since only a finite amount of oxygen in the reactor and a certain amount of oxidation can occur, Pyrolysis cannot be carried out practically without oxygen. Scrap steel (10–15 wt%), pyrolysis black carbon (PCB) (30–35 wt%), crude tire pyrolysis oil (TPO), and pyrolysis gas (Pyro-Gas) (10–15 wt%) are all byproducts of the Pyrolysis of used tires[44]. The typical waste tire pyrolysis system is shown in Fig. 6. In the process, the organic volatile matter of tires is decomposed to low molecular weight products, liquids, or gases. The inorganic components and the non-volatile carbon black remain as a solid residue that is relatively unaltered and, therefore, can be recycled in worthwhile applications [45]. The Pyrolysis of scrap tires has received increasing attention due to the optimized process conditions to produce oil, gas, and residual char, plus the steel is recycled back into the related industry. The other three products are used as energy (fuel) or/and chemical resources [43].

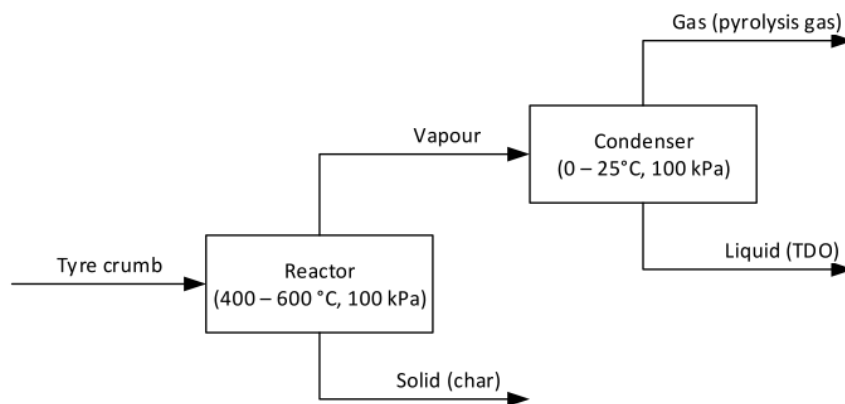


Fig. 6. schematic of a typical waste tire pyrolysis system [32]

4.1 Critical steps in tire pyrolysis

Phase 1(Feedstock Preparation): The processes before actual Pyrolysis are crucial and influence the quality of the pyrolytic products. The ELTs are shredded to separate steel and fabric from the rubber components. This

may involve a two or three-step process. For example, it is first extracting the steel/fiber from the tire rim, cutting the tires into relatively large pieces, and then, as a second stage, cutting the tires into smaller pieces to a size generally between 20 and 50mm. Shredding tires leads to better quality products than entire tires, as they can be heated faster and more evenly. The separated steel can be recycled. Our process at Contac involves sourcing and using the best quality feedstock during this phase.

Phase 2(initiation): Before the rubber granules are fed into the pyrolysis reactor, the chamber undergoes initiation to protect the process and staff from combustion. The oxygen content of air is reduced from 21 percent by volume to less than 13 percent by pumping in nitrogen, an inert gas. Not all pyrolysis processes use this step, and by not opting for this step, they risk explosions. Initiation is crucial to the safety of the process.

Phase 3(Pyrolysis Process): Granulated pretreated rubber is fed into the reactor and heated by an electric furnace outside. As a carrier gas to temperatures between 400 and 700 °C with no or little oxygen, nitrogen or another inert gas is utilized. In addition, some pyrolysis techniques employ high pressure and catalysts to speed up the process. Every pyrolysis plant will proceed according to how it heats up. The heat leads to various decomposition and volatilization reactions like cracking, dehydration, isomerization, aromatization, dehydrogenation, and condensation. The solid tire waste is converted to volatile gases, steel, and char. More liquid products are produced at lower temperatures, and more gaseous products are made at higher temperatures.

Phase 4(Post-Processing): In the end, four main products are produced: carbon black, oil, gas, and steel. Most of the vaporized compounds liquify when cooled to give pyrolytic oil rich in aromatic compounds, and the uncondensed gas is used as fuel in the pyrolytic plants and makes them energy self-sufficient. The char comes out mixed with finer steel bits and inorganic salts. The solids go under a magnetic separator to remove all traces of steel, which is recyclable. The solid portion is recovered carbon black (RCB). The RCB is a unique grade that can be used as a semi-reinforcement filler to produce new tires and other rubber products and as a coloring agent, pelletized to meet market demand. Pyrolytic products (oil, gas, and RCB) are high-value raw materials in many industries with high demand[46],[47],[48],[49],[18]. System boundaries for the process are shown in Fig. 7.

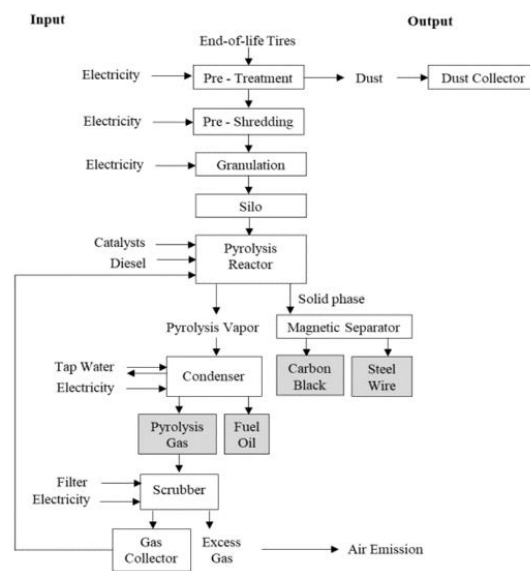


Fig. 7. system boundaries for the tire pyrolysis [50]

5 TYPES OF PYROLYSIS

this review only goes through some common types of Pyrolysis used for waste tires [51]. One of the methods is based on supplying thermal energy, where the source of this energy is:

- the heat of combustion of raw materials or pyrolysis products inside the reactor,
- heat supplied by flue gases or electricity through the external walls
- heat supplied to the interior by an inert gas or material or from internal radiators.
- under atmospheric pressure, a vacuum [52],[53] or overpressure
- periodic (fixed bed) or continuous (fluidized bed),
- Another criterion is the reactor mode of operation, which can be Of inert gas in the absence or presence of a catalyst [54],[51]
- currently, pyrolizers are classified as shown in Fig. 8, depending on how the raw material (powder, granules, pieces, scraps, or whole worn tires) is forced to move inside them pneumatically, mechanically, and gravitationally.
- The types of pyrolizers have a key influence on oil and gas yields and the composition and quality of the third major product, carbon black or activated carbon. Pyrolysis oil is chemically a highly complex mixture, especially from tires containing aliphatic, aromatic, hetero-atomic, and polar fractions. The gases are a mixture of H₂, C1–C₄ hydrocarbons, CO₂, CO, and H₂S. Using catalysts during Pyrolysis increases the proportion of hydrogen in the gas and the number of aromatic compounds in the oil [51].

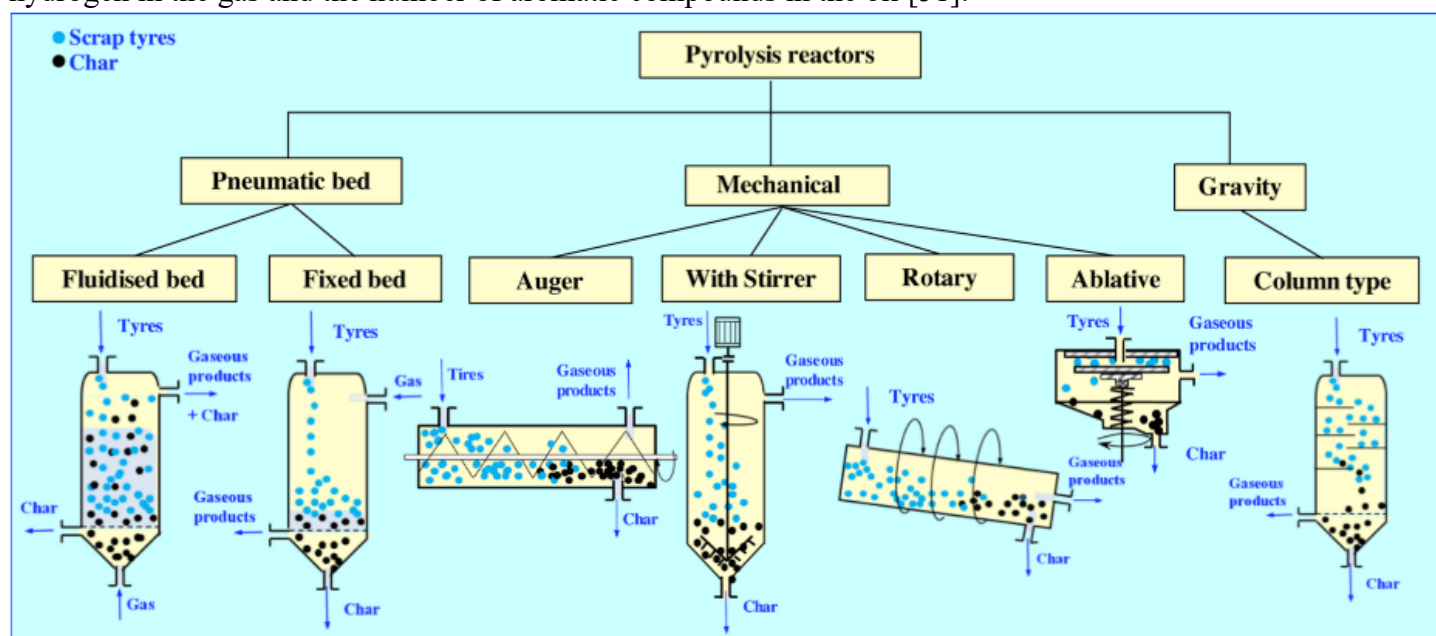


Fig. 8. types of waste tire pyrolizers [51]

As shown in Table 5, the mass yields of the three primary products (oil, char, and gas) under different pyrolysis conditions (residence times of volatiles RT_v and solids RT_s in the pyrolyzer, waste tire heating rates HR) and, if the tires are shredded, particle size and the thermal decomposition temperature [51].

Product yields depend on the thermal decomposition temperature, the heating rate, and the residence time of oil vapours and solids in the reactor. The power supplied, particle size, and thermal conductivity of the pyrolyzed material influence the heating rate. The temperature impacts the varieties of primary thermal decomposition reactions exhibited by organic materials, leading to an extension in the residence time within the reactor. And increases the probability of secondary reactions. Due to the decomposition of molecules within the liquid and the remaining solid mass, smaller molecules are generated, thereby enhancing the gas fraction. From the point of view of oil production, tire pyrolysis can be classified into three main categories, depending on operating conditions: flash, fast, and conventional Pyrolysis. Flash pyrolysis of organic materials, involving high temperatures and rapid heating rates, is promising. Still, in the case of waste, tires remain a future-oriented

process for producing biofuels. The significance of conventional Pyrolysis, which takes place at low temperatures and low heating rates, can now be treated as historical: it has been used for centuries to produce charcoal. However, being technologically limited, it cannot efficiently produce good quality oil. In this situation, ignoring torrefaction as these processes are unrelated to oil production, we now focus on the fast pyrolysis process. Essential characteristics of fast Pyrolysis include the precise adjustment of the reaction temperature specific to a rough material, a rapid heat transfer and heating rate, a short vapour residence time, and the rapid cooling of vapours and aerosols for a high oil yield [51],[55],[56].

Table 5. typical operating parameters and products during pyrolysis [51]

Pyrolysis	Hot vapour residence time(RTv) s	Solid residence time (RT _s) s	Heating rate (HR) k/s	Particle size mm	Temperature	Product yield		
						oil	char	gas
Flash	>1	<0.5	>1000	<0.2	450-1000	75	12	35
Fast	~1	~1	-	-	~500	75	12	35
	-	0.5-10	10 -200	<1	600-1000	50	20	30
Intermediate	10-30	Modarate	-	-	~500	50(in 2 phase)	25	25
Conventional	-	450-550	0.1-1	5-50	300-700	30	35	35
Slow	Long	Very long	-	-	~400	35	35	30
Torrefaction	Long	Long	-	-	~300	Vapour	85	15
Gasification	short	Short	-	-	800-900	1-5	Solid <1%(all burned)	Vapour 95-99

6 FACTORS AFFECTING PYROLYSIS

Waste tire pyrolysis is influenced by various parameters, with some having direct and indirect effects [32]. The Preparation of the feedstock, the kind of reactor, and the pyrolysis reaction conditions all affect the pyrolysis output yields (temperature, pressure, how long volatiles stay in the hot reaction zone, how quickly things heat up, etc.) However, the configuration of the pyrolysis process is mostly influenced by temperature[57], even though The type and configuration of reactors also influence the products of waste tire pyrolysis. Reactors like autoclave, entrained bed, kiln, rotating cone, auger type, fluidized bed, fixed bed, spouted bed, vacuum pyrolyzer, free fall, vortex type, plasma type, and ablative type should be studied [58].In recent years, different pyrolysis reactors have been developed and examined to produce waste tires for oil, char, and gas [57].

6.1 Reactor types

The liquid is an interesting fraction due to its energetic and economic value, so the most suitable reactor must be designed to obtain a higher liquid yield. Calorimeters, fast-heating microreactors, or commercial thermogravimetric equipment are frequently used for kinetic measurements (pyro probe-type pyrolyzers)[59]. A certain type of reactor should preferably be selected from the assortment of reactors depending on the purpose of the Pyrolysis (heat generation, fuel obtention, etc.), such as fixed-bed (batch), screw kiln, rotary kiln, vacuum, and fluidized-bed waste tire pyrolyzers. The variety of pyrolysis reactors used to study the Pyrolysis of old tires and the yields of oil, char, and gas from the procedure are shown in Table 6. A small portion of the time, the data also includes the steel belt and cord recovery, which normally accounts for 10-15 weight percent of the waste tire. To study the Pyrolysis of old tires, fixed-bed batch reactors have been routinely employed[49]. Plus, inert gas is important in pyrolysis processes, and it acts as a shield protecting the organic material from oxidation. Secondly, its flow mixes the reaction environment, evens the temperature and concentration distribution, and discharges volatile pyrolysis products. Sometimes, it is also a carrier of thermal energy [51]. Each reactor type will be covered in greater detail due to its distinct properties.[59].

Table 6. the variety of pyrolysis reactors utilized in studies on the yields of oil, char, and gas from the Pyrolysis of waste tires.

Reactor	Tire characteristics		Experimental condition						Maximum oil yield				Reference
	Tire type	Size (m)	Temperature °C	Heating rate (°C OR K/min)	Mass (kg)	Pressure (Kpa)	Flow rate	Flow rate (kg/h)	Temperature (°C)	Oil (wt.%)	Char (wt.%)	Gas (wt.%)	
Fixed bed batch			400-700						500	40.26	47.88	11.86	Aydin et al. [44]
Fixed bed batch	Steel free tire	1-4	350-600	5&35°C	0.01				400	38.8	34.0	27.2	Banar et al. [60]
Fixed bed batch			300-720	5-80°C	0.05				720	58.8	26.4	14.8	Williams et al. [37]
Fixed bed batch		6	400-460		0.025-0.045		0.45(m ³ /h)		420	57.0	35.7	7.3	Arabiourrutia et al [61]
		16					0.25(m ³ /h)		420	36.0	51.0	13.0	
		16					0.45(m ³ /h)		450	62.0	35.2	2.8	
		2					0.35(m ³ /h)		430	58.52	31.5	9.9	
Fixed bed batch		< 3		5 K	0.006-0.008				850	58.0	38.0	4.0	Acevedo et al[62]
Fixed bed batch			375-500	10°C	0.01				425	60.0	~30	~10	Y. Ka [63]
Fixed, wire mesh, fast reactor			390-890		0.002				860	~5	~22	~73	Zabaniotou et al. [64]
Batch pyrolysis	LVT	1-3	550-800	20°C	0.2		N ₂ ,100 (ml/min)		650	51.0	9.1		Kumar Singh et al. [65]
	MVT								750	45.5	12.5	42.3	
	HVT								750	63.5	10.0	28.5	
Vacuum, conical spouted bed			425-500					25&50	500	~60	~34	~4	Lopez et al [53]
Vacuum			500						500	56.5	33.4	10.1	Pakdel et al. [66]
Fluidized bed			450-600					~0.22	450	55.0	42.5	2.5	Williams et al.[67]
Circulating fluidized bed			360-810					5	450	~52	~28	~15	Dai et al.[68]
Rotary kiln			450-650					12-15	500	45.1	41.3	13.6	Li et al. [69]
Rotary kiln			550-680					4.8	550	38.12	49.09	2.39	Galvagno et al[70]

*LVT-light vehicle tire ,*MVT-medium vehicle tire,*HVT-heavy vehicle tire

6.1.1 Fixed bed reactor

The behaviour of the bed in the pyrolizer depends on the inert gas flow rate and the size and specific gravity of tire particles. When the inert gas flow is slow, the solid particles remain stationary in the bed in fixed-bed Pyrolysis [51]. Fixed bed pyrolysis reactors, as shown in Fig. 9, are relatively simple to construct and efficient at producing clean fuel, plus generally perform at 450–700 °C[59]. These reactors are mostly used in batch-mode Pyrolysis of waste tires [58].

This reactor's waste tire is fed into a fixed bed inside a cylindrical steel pyrolizer. Heat is supplied to the waste tire via the pyrolizer wall by an electrical heater or furnace mounted around the reactor. Purging pressurized nitrogen (N₂) from the external cylinder eliminates all the oxygen inside the pyrolyzer. When used tire waste decomposes, solid char collects at the bottom of the Pyrolysis while vapour (both condensable and non-condensable) escapes to the top. The oil is then kept and collected in a liquid storage container after the vapour has been cooled by a condenser, which condenses the condensable vapour into oil. Syngas are created when non-condensable vapour is collected. [71],[3]. There are different types of fixed bed reactors: Vertical fixed bed

reactors, Horizontal fixed bed reactors, Two-stage catalytic fixed bed reactors, Microwave fixed bed reactors, and Solar fixed bed reactors[51].

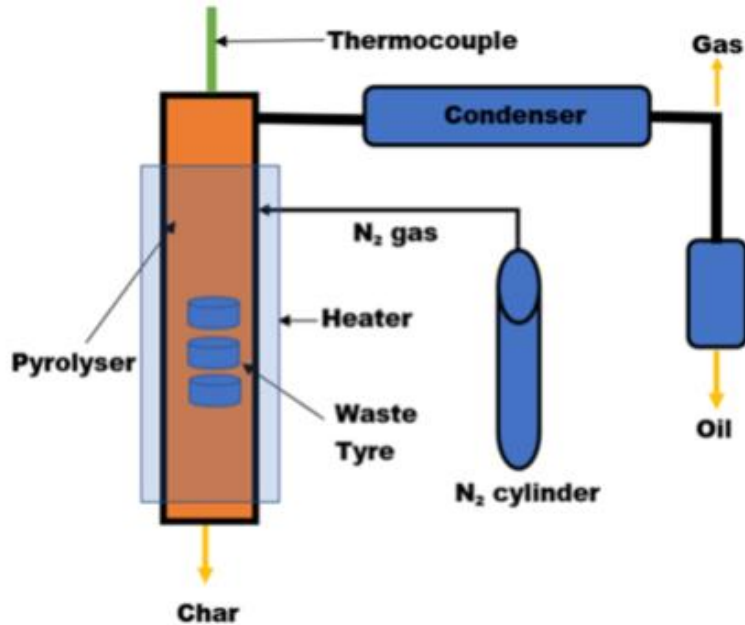


Fig. 9. Diagram of a generally fixed bed pyrolysis reactor [57]

Fig. 10 illustrates tire pyrolysis in a tubular stainless steel batch reactor of diameter $D=0.48\text{m}$ and height $H=0.99\text{m}$. The overall size of the reactor was 2.49m , and the length of the shield was 0.61m [50]. The process was carried out with maximum liquid production. The reactor wall was made from two 0.002m stainless steel sheets, with a 0.04m thick insulation layer (glass wool) between them. At the bottom of the reactor, a 0.20m diameter tube was attached to remove char. Five spiral tubes of 0.019m diameter (three U-shaped and two semi-hexagonal ones, not shown in Fig. 10) were placed inside the chamber to improve fast heating. However, the main heat flux is supplied to the reactor by means of a fuel burner. This furnace has a hole where the reactor was placed, two openings for providing solid fuel, and four ports for removing ash. Two businesses that dispose of fixed bed reactors on an industrial scale that have a capacity of 16 and 4 T per day, respectively, are Kouei Industries (Vancouver, Canada) and NoWaste Technology (Reinach, Germany)[59]. The product distribution obtained by other authors using fixed bed reactors is shown in the maximum oil yield conditions of their works in Fig. 11. Still, the results vary significantly because they are, to a different extent dependent on the experimental conditions, such as reactor size, variables like temperature, heating rate, and feeding rate effect. Increasing temperature and heating rates often increase gas yields[59].

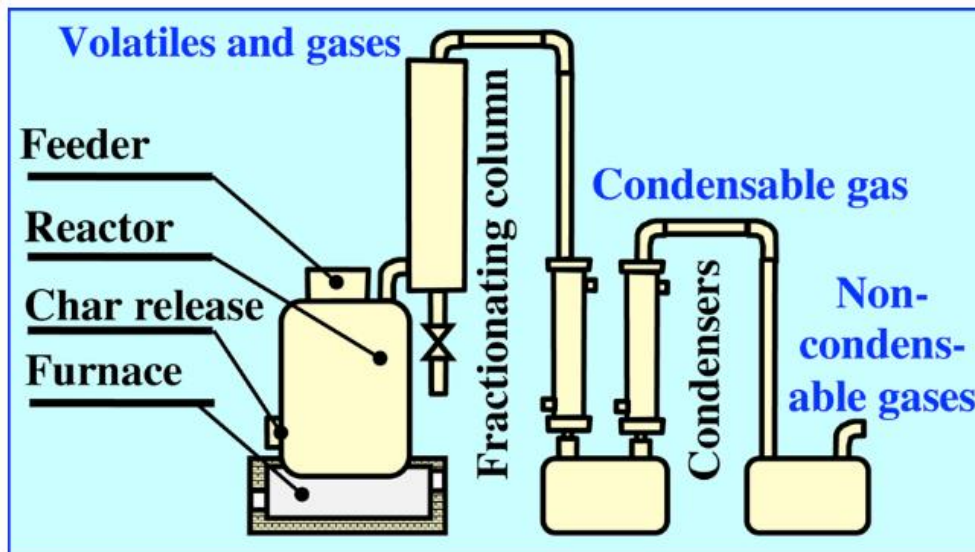


Fig. 10. flow diagram of a vertical fixed bed reactor at pilot scale [72],[51]

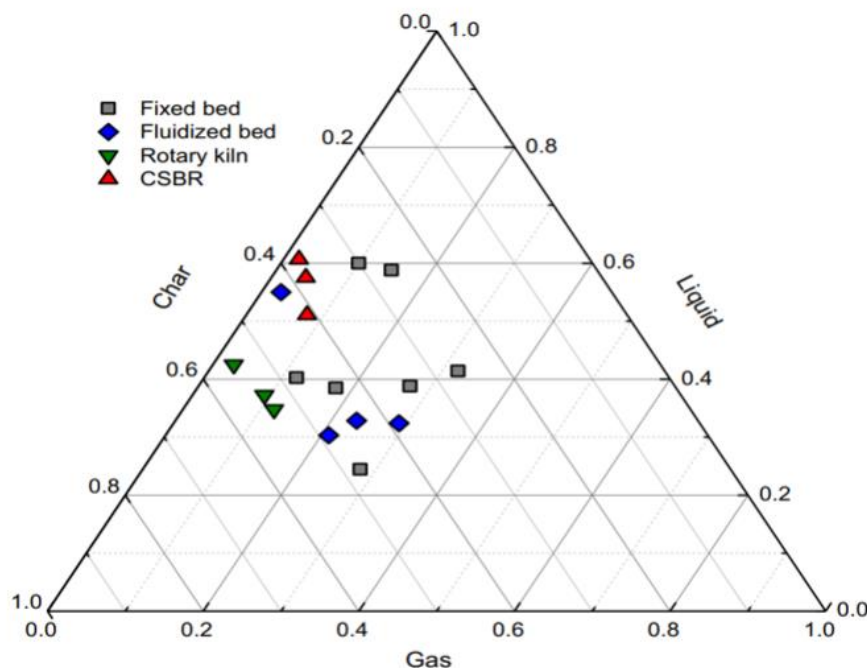


Fig. 11. product lump(wt.%) in different types of reactors at different temperatures [59]

The main features of fixed bed reactors are a high carbon conservation rate, a low gas velocity, a low gas carryover rate, and a prolonged solid residence time. These reactors are often thought of for small-scale heat and electricity applications. There is a serious difficulty with tar removal from fixed-bed reactors, but recent advancements in thermal and catalytic tar conversion have offered a potential remedy.[57]. Another issue is this reactor's low heat transfer rate and difficulties in continuous operation and scale-up, hence the limited economic interest in full-scale applications of the fixed bed reactor [58].

In a 1.15-litre fixed bed reactor with nitrogen at temperatures between 400 and 700 °C, Aydin and Ilkilic [44] studied the Pyrolysis of scrap tires with the steel and fabric removed. The oil output increased from 31 wt% at 400 °C to 40 wt% at 500 °C, with no change in yield at higher temperatures, they discovered. The production of gas, therefore, increased. Additionally, they looked at how nitrogen flow rate affected product production and

discovered hardly any differences. In a small-scale, fixed bed, batch reactor, Williams et al. [37] studied the impact of pyrolysis temperatures between 300 and 720 °C and heating rates between 5 and 80 °C per minute on product yield. There was hardly any thermal degradation of the tires at the low temperature of 300 °C. Pyrolysis temperatures between 600 and 720 °C were necessary to enhance oil production of 54 and 58.8 wt%. It should be noted that oil and gas production only slightly rises in a fixed bed reactor system when the temperature is raised above the point at which the rubber has thermally deteriorated. The feedstock loading was 1.5 kg, the pyrolysis temperature was 475 °C, and the heating rate was 5 °C min⁻¹. Oil, char, and gas yields were measured by Cunliffe and Williams [73] and were 58.2 wt% oil, 37.3 weight percent char, and 4.5 weight percent gas.

Islam et al. [74] pyrolyzed 750 g batches of waste tires in a fixed bed reactor and found that the oil output was high at 475 °C 55 wt% pyrolysis temperature with matching char and gas yields of 36 wt% and 9 wt%. According to Banar et al. [60], at a pyrolysis temperature of 400 °C and a heating rate of 5 °C min⁻¹, the greatest oil production for the Pyrolysis of tire-derived fuel (steel removed) was only 38.8 wt%, with char yield at 34 wt% and a high gas yield at 27.2 wt. %

6.1.2 Fluidized bed reactor

If the bed increases its gas flow rate, it begins to swell, and once a certain threshold velocity has been exceeded, a fluidized bed forms. Initially, this is a bubbling fluidized bed BFB. Still, the further acceleration of the gas flow rate transforms the process into a circulating fluidized bed CFB. Depending on the gas flow rate, there may be two types of CFB: the first mode (a), in which the inert material remains in the bed, and the second mode (b), in which the inert gas forces circular fluidization of all solid particles (inert material, batch, char, and ash) in the bed. A faster gas velocity gives rise to the pneumatic transport of the solid substance in the CFB [51], as shown in Fig. 12.

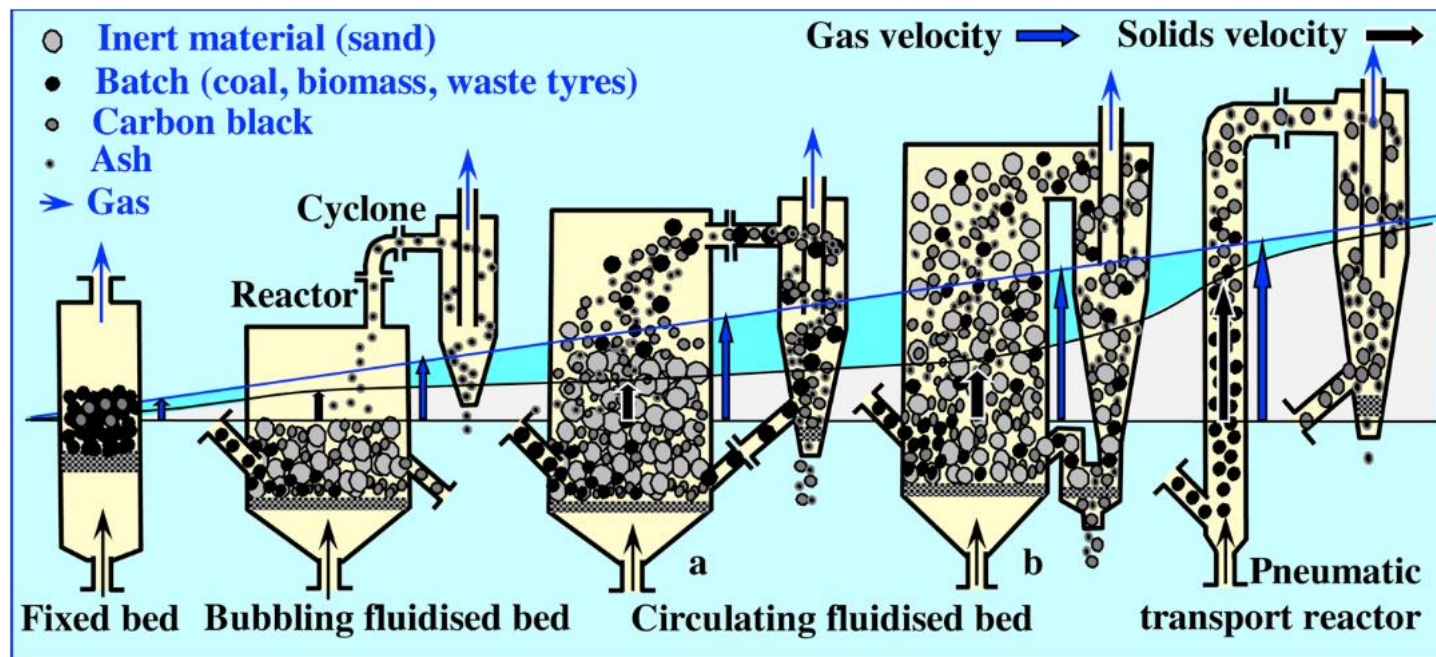


Fig. 12. Classification of reactor beds depending on the gas flow rate [51]

Reactors for fluidized bed pyrolysis are often employed in the chemical and oil sectors. Fluidized bed reactors are far more efficient and economical than fixed bed reactors since they can handle waste tires constantly. This is especially true in industrial enterprises[75]. Using this kind of reactor, high-quality oil may be produced with a liquid yield of 50–60% of the dry weight of the used tire. After shredding into smaller pieces, waste is continually fed into a pyrolizer's hot sand or other stable solid beds. For the Pyrolysis to occur without needing

oxygen, the solid bed is fluidized with N_2 or other inert gases. The shredded tire quickly heated up on the solid hotbed and decomposed into vapour, char, and aerosols [57]. As seen in Fig. 13, once the char has been eliminated using a cyclone separator, the residual vapour is promptly transformed into bio-oil and stored using a quench cooler. Burning some of the produced gas in the bed or transmitting heat to the solid bed by burning char created in another chamber are two ways to generate the heat needed to operate this sort of reactor [76]. Shredded tire particle sizes of less than 2-3 mm are required in the fluidizing bed reactor to achieve the optimum heating rate [57].

Since 1970, many plants have been constructed at laboratory size (0.6-3.0 kg/h), pilot-plant scale (10-40 kg/h), and industrial scale (120-200 kg/h) to study the fluidized bed reactor. Figure 11 (blue legend) shows the product yields produced utilizing fluidized bed reactors with various features at various scales, from a laboratory size to a technical scale to a pilot plant scale, resulting in multiple results. Vacuum pyrolysis using fluidized beds demands lower temperatures and boosts product yield [59]. The Hamburg method is a technique created based on fluidized bed pyrolysis of various materials, including ST, to produce essential compounds and carbon black [77].

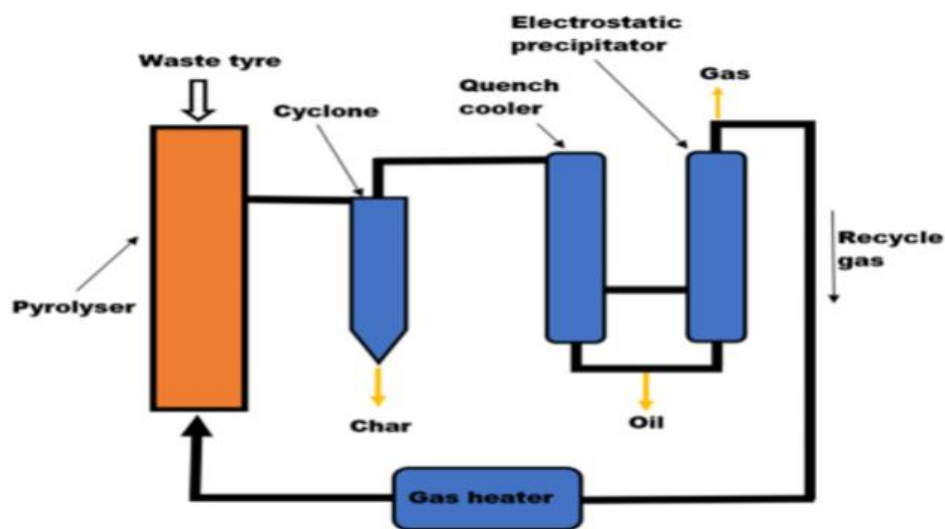


Fig. 13. diagram of a fluidized bed pyrolysis reactor [57]

fluidized bed reactors have been investigated at a laboratory scale with 1 kg h⁻¹ throughput, a technical scale with 30 kg h⁻¹ throughput, and a pilot scale with 200 kg h⁻¹ throughput. Large-scale pilot plant studies were able to process the whole 9 tires. Through radiant heat tubes embedded in the quartz sand bed, where the pyrolysis gas produced during the process is burned to provide heat, the fluidized bed is indirectly heated to average temperatures of between 500 and 780 °C. The fluidizing gas, which doubles as the product gas, is warmed to 400 degrees [78]. According to Kaminsky et al. [79] the laboratory scale 1 kg h⁻¹ fluidized bed reactor produces oil at a rate of 30.2 wt% at 740 °C. The 200 kg h⁻¹ pilot scale reactor processes whole tires at a rate of 26.8 wt% at 700 °C, but on a steel-free basis, it produces oil at a rate similar to the laboratory reactor's 30.9 wt% at 740 °C.

6.1.3 Stirred tank

These reactors are based on an autoclave-type configuration, As shown in Fig. 14, where ST is fed discontinuously. In contrast, the inert gas required for the Pyrolysis and products flows continuously [59]. De Marco et al. [38] investigation on the 30-minute Pyrolysis of tires in the 300-700 °C range under a N_2

atmosphere. Char had the largest yield under these circumstances, reaching up to 87.6 wt% at 300 °C. However, at 700 °C, the yields of liquid and gas rose to 38.5 and 17.8 wt%, respectively.

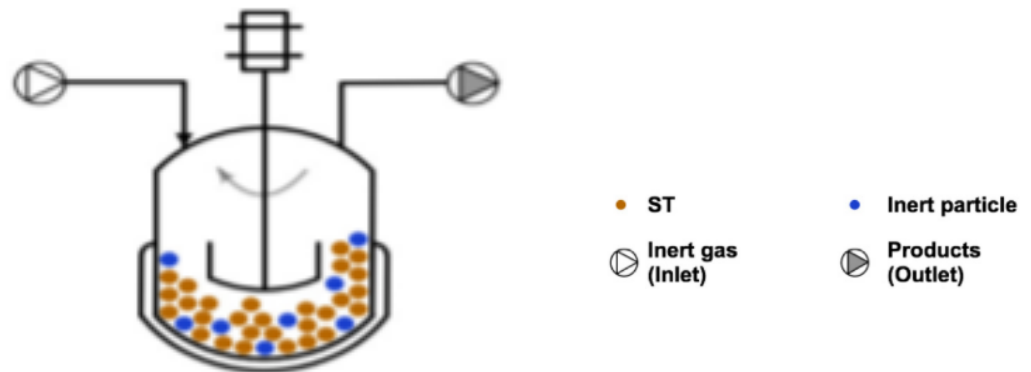


Fig. 14: Diagram of a stirred tank [59]

6.1.4 Screw/rotary kiln reactor

In a rotary kiln reactor shown in Fig. 15, the waste tires are fed into the front end of the reactor. Pyrolytic gases are released as the waste tires inside the reactor heat up and go down the cylinder. The reactor is tilted and gently rotated to guarantee that waste tires are mixed and heated evenly[69]. Numerous distinctive features of this reactor include its ability to handle heterogeneous feedstock, flexibility in adjusting residence duration, correct and uniform waste tire mixing, lack of requirement for pre-treatment of waste tires, and ease and simplicity of maintenance. However, Due to their slow heating rate, these reactors are typically used for slow pyrolysis applications. Due to the small particle size and little surface area between the feedstock and reactor wall surface, the feedstock only receives a small amount of heat from the outside reactor, which results in low heating rates. The maximum heating rate is 100 C/min, and a minimum residence period is 1 hour[80].

Fig. 11 (green legend) plots the product yields obtained by Galvagno et al.[70] at the ENEA Research Center when operating at different temperatures. The rotating reactor featured an externally heated capacity of 4.8 kg/hr electrical furnaces, a diameter of 0.4 m, and a rotational speed of 3 rpm. A condensation system was used to condense the heavy and light pyrolysis oil fractions, and the non-condensable gases were cleansed to eliminate any acid gases before being burned in a flare. In a water-cooled tank, the pyrolysis char (residue) was continually discharged. When they burned off waste tires at 500 degrees Celsius, they produced 45.1 percent oil, 44.3 percent char, and 13.6 percent gas.

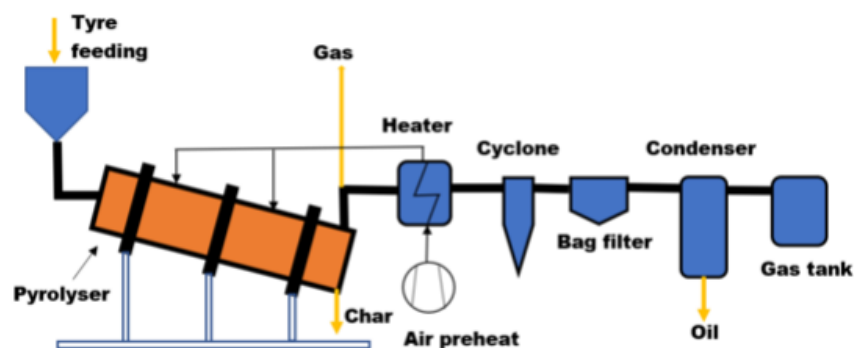


Fig. 15. diagram of a rotary kiln reactor [57]

The constantly operating, tubular screw bed reactors include a revolving screw similar to that in Fig. 16. While the heat needed for the pyrolysis process is transferred across the tubular reactor wall by the screw's rotation, feedstock supply into the reactor is aided. Thus, the screw has two purposes: mixing the feedstock and controlling the feedstock's residence duration in the reactor. Tire scraps are fed into the screw bed using a large hopper. Usually, N_2 is an inert gas. To make the feedstock oxygen-free and the pyrolysis system completely devoid of oxygen, the hopper is delivered to the hopper. The inert gas also helps transport pyrolysis vapour by generating a little amount of positive pressure at the screw bed[57]. Feedstock particles, which act as a solid heat carrier for Pyrolysis, are commonly packed into steel and ceramic pellets. As the feedstock particles pass through the screw bed, this enables closer particle interaction. By forcing the pyrolysis-generated vapours into a condenser, the oil is created. A key benefit of a screw bed reactor is that, depending on the circumstances, it may be relatively portable and small, allowing it to be utilized anywhere there is a large feedstock supply. Feedstock transportation costs to the biorefinery are decreased by on-site feedstock processing, which lowers operating costs[81]. However, if the reactor is not designed correctly, Poor heat transmission and temperature management in an improperly built reactor will lead to the deposition of polymeric materials inside the reactor[82].

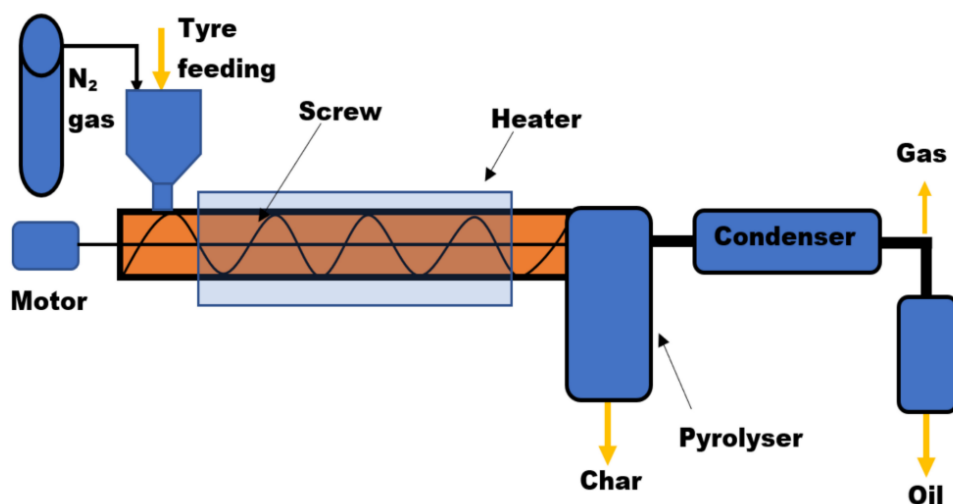


Fig. 16. diagram of a rotary screw bed reactor [57]

For the Pyrolysis of used tires, continuous-functioning reactors have been created. For example, Aylón et al.[83],[84]studied the effects of several parameters, including tire mass flow rate and pyrolysis temperature, which ranged from 600 °C to 800 °C, on product yield and composition using a moving bed reactor was an electric furnace-heated continuous screw kiln reactor. With throughputs ranging from 3.5 to 8.0 kg/h, shredded tires were fed into the reactor through a screw feeder. In a shell-and-tube condenser, pyrolysis oils were condensed while non-condensable gases were burned. At the screw kiln reactor outlet's end, the solid char was collected. At a tire mass flow rate of 600 ml/s and a pyrolysis temperature of 600 °C, the greatest oil output of 48.4 wt% was observed.

6.1.5 Conical spouted bed reactor (CSBR)

CSBR (shown in Fig. 17) allows for obtaining higher yields of products with greater quality

- (i) without needing a gas distributor or simple construction[85],[86].
- (ii) Low-pressure drop

- (iii) can be employed with particles of various shapes and densities due to its adaptability.
- (iv) Vigorous gas-solid contact to avoid clogging the reactor
- (v) with the uniform and low residence time of the volatiles in the reactor.

The product distribution data shown in Fig. 11 illustrates the simplicity of employing a CSBR reactor when the primary goal is to optimize the liquid product yield while concomitantly restricting gas yields[59].



Fig. 17. Diagram of a SCBR reactor [59]

Fig. 17 (red legend) demonstrates the product distribution attained by López et al. [43] operating in a continuous regime at 425–600 °C. In contrast to previous technologies, a CSBR produced greater liquid yields (44.5-55.0 wt%). In addition, they noticed that operating at higher temperatures improved the char quality and oil fraction's aromaticity. These outcomes are a result of the fascinating CSBR features.

6.2 Temperature

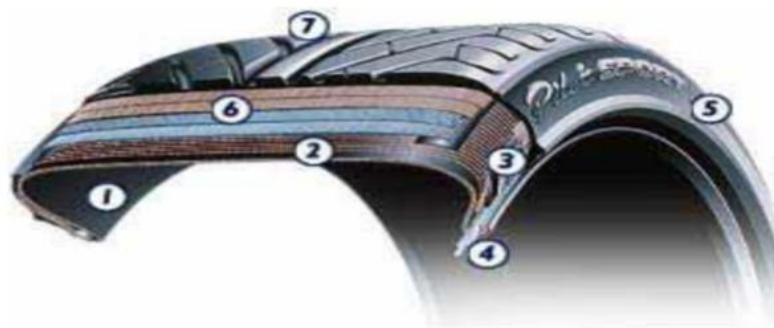
Pyrolysis temperature significantly influences the pyrolysis product of tire decomposition, ensuring a constant heat supply is required to effectively degrade the tires into various products[32]. The product yield of the process (tire pyrolysis oil, gas, and char) changes as temperature varies. It has been recorded that the low to medium-temperature pyrolysis process favours the production of tire pyrolysis oil, while the high-temperature process favours the production of gases. Pyrolysis can be carried out through the fast or slow pyrolysis process. Fast Pyrolysis is known for its high heating rate (1000 °C/s), short residence time of about 3 seconds, and the gaseous products' fast quenching. The characteristics of this process cause a minimal secondary reaction, leading to a high pyro-oil yield. In contrast, slow Pyrolysis, characterized by its low heating rate and long residence time, promotes the secondary reaction, thus increasing the yield of gas and char products [58].

M. Rofiqul et al. [87] found that the rubber tire decomposes at 375°C, the solid decreases, and gas and liquid increase until 475°C. Then, above 475°C, both liquid and gas yields decrease and increase due to the decomposing of some oil vapour into permanent gases.

6.3 Particle size

it is postulated that small particles present an isothermal behaviour. If so, there are no internal mass transfer limitations, while the opposite is for large particles[11]. Uniformity of temperature throughout the particle is the case for small particles, whereas the interior of the larger particles heats up slowly. However, smaller particles are often accompanied by conversion to the liquid and gas phases. In contrast, the interior remains in the solid

phase for the larger particles due to the lower temperature. Smaller particles are adequate if maximizing the oil yield is an important objective[30]. As the tire consists of different heterogeneous layers, as shown in Fig. 18, the pyrolyzed sample should represent the whole tire, so it is mixed well and gets fine and small portions[45].



- | |
|------------------------|
| 1. A rubber sheet |
| 2. Water frame |
| 3. Lower area jam |
| 4. Rods |
| 5. Sides |
| 6. Tablecloths-summits |
| 7. Tread |

Fig. 18. tire composition[45]

M. Rofiqul et al. [87] studied the effect of changing particle size on the yield of pyrolytic oil under fixed applied conditions, temperature at 475°C, and residence time of 5 seconds. They found that with an increase in the particle size from 2 cm³ to 12 cm³, the pyrolytic oil yield increases until the particle size is 4 cm³ with 51%. After that, the yield decreases. They came to the conclusion that since smaller particle sizes offer more reaction surfaces, the rubber heats too quickly and decomposes too quickly. On the other hand, compared to the nearly complete thermal breakdown of the smaller particles, the heating rate in big particle sizes is low because of its reduced thermal conductivity, and heat can only travel to a given depth in the available pyrolysis period. As a result, the bigger pieces' cores carbonize and cannot breakdown, increasing the amount of char and lowering the production of liquid and gas.

6.4 Tire residence time

residence time optimization is a key factor in scaling up an industrial system. Lower residence times involve lower reactor volumes to process a certain tire load and, therefore, lower the cost of the system. The variation of the solid residence time consists of the variation of the gas residence time. This variation is due to the increment of the free volume inside the reactor[45].

6.5 Heating rate

Higher heating rates lead to higher temperatures, which can lead to more secondary reactions and produce more gas-phase products[88]. Increasing the heating rate increases the degradation rate and affects the temperature at which maximum volatilization starts and stops[11]. Also, the Heating rate impacts the time to complete Pyrolysis and energy required: lower heating rates necessitate longer residence times but require less energy[89]. The nature of the secondary reactions can impact the gas and liquid composition. Heating rate, temperature, and particle size can produce different impacts depending on values of other parameters[30].

6.6 Carrier gas Flow Rate/Volatiles Residence Time

An increase in carrier gas flow rate carries the gaseous products away more quickly by decreasing the volatile product's residence time [90]. A longer volatile residence time means that secondary reactions are more likely to occur, which can reduce oil yield if liquid-phase compounds convert to the gas phase. Thus, increasing carrier gas flow rate has been found to increase oil yield [83],[73],[30].

6.7 Atmospheric pressure

Increasing atmospheric pressure has been found to increase oil viscosity [91]. On the other hand, reduced pressure (often associated with vacuum pyrolysis) has been found to reduce secondary reactions in the gas phase by reducing volatile residence time; this would tend to increase oil yield [11],[30],[69]. Also, reducing secondary reactions can reduce gas deposition onto the solid char surface, making the char more valuable as an activated carbon adsorbent, with higher surface area and increased reactivity. Decreasing process pressure may also decrease process temperature ($PV=nRT$). Decreasing process temperature decreases energy demand[30].

6.8 Catalytic

Yield and the quality of pyrolysis oil not only depend on the temperature but also the use of catalytic [92]. Zhang et al.[54] reported that catalysts and necessary additives lowered the reaction temperature. The percentages of pyrolysis oil, char, and gasses produced by non-catalytic Pyrolysis are 40%, 40%, and 20%, respectively. With the exception of catalytic pyrolysis procedures utilizing Ca(OH)_2 and Al_2O_3 catalysts, respectively, the use of catalysts generally enhanced yields of char and fumes while decreasing liquid oil yields[92]. Ates, et al.[93] reported that a 10% catalyst-tire ratio produced maximum liquid oil. Moreover, Saeng-arayakul and Jitkarnka[94] $\text{NiMoS/Al}_2\text{O}_3$ catalyst was used for the catalytic Pyrolysis of tire waste. These studies concluded that the catalyst's qualities expedited the breakdown of tires into lighter materials, resulting in lower yields of liquid oil when catalysts were used (gasses). Additionally, the most char (55.6%) and least amount of liquid oil (26%) and odours were produced after the catalytic Pyrolysis of tire waste utilizing a Ca(OH)_2 catalyst (18.4 %).

7 PROPERTIES OF WASTE TIRE PYROLYSIS PRODUCTS

the three primary fractions for ST pyrolysis that were produced (gas, liquid, and char)[95] have many different uses, as shown in Fig. 20[59].

7.1 gasses

In general, gases comprise mostly paraffinic and olefinic compounds, with trace quantities of other $\text{C}_1\text{-C}_4$ addition hydrocarbons. There may be some CO and CO_2 about. These gases are produced by the oxygenated tire polymers[45], compared with natural gas, which has 35 MJ/m^3 . Therefore, pyrolytic gas is successfully employed as fuel, especially for producing electricity, or, at least, it can supply the needed energy for the pyrolysis process as it can be energetically self-sufficient[59],[22].

Williams [78] evaluated the gases generated by the Pyrolysis of discarded tires according to several research Hydrogen (H_2), butene (C_4H_8), methane (CH_4), ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), butadiene (C_4H_6), carbon dioxide (CO_2), carbon monoxide (CO), ethene (C_2H_4), propene (C_3H_6), and hydrogen sulfide are among the principal gas components (H_2S). The particular rubbers used in tire manufacturing and the pyrolysis temperature affect the gas composition precisely. With higher pyrolysis temperatures, gas output rises as more oil becomes vapour. Raising pyrolysis temperature can also increase hydrogen production, which is desirable if that is a goal of the process [11],[30].

7.2 Liquid

Typically, the liquid component is referred to as "scrap tire pyrolysis oil" (STPO). It contains valuable compounds, such as aromatics, d-limonene, and BTX (benzene, toluene, xylenes) portion, which have a greater market value than raw oils[87],[8]. Additionally, this STPO has favourable qualities for usage as automobile fuel and shares the same fuel characteristics as commercial-grade light gasoline, as indicated in Table 7, following an upgrade for pollutant and heavy component removal[59]. It has also been shown that pyrolytic oil contains monoterpenes like limonene, a high-value light hydrocarbon with a variety of industrial uses, including the formulation of solvents, resins, and adhesives, the dispersing of pigments, the fragrance of cleaning products, and the use of limonene as an environmentally friendly solvent. Limonene is very common in cosmetic products and is a flaming, combustible liquid. The presence of aromatic compounds in the pyrolytic oil is due to, on the one hand, the fragrant nature of the source polymeric materials and, on the other hand, to recombination reactions that take place among aliphatic and aromatic fragments and also to the cyclization of aliphatic chains followed by dehydration reactions, which take place during the pyrolysis processes[87].

Furthermore, Over 100 compounds have been identified in tire pyrolysis oil; most of these are C₅–C₂₀ hydrocarbons which include polyaromatic hydrocarbons (PAHs), polyaromatic nitrogen hydrocarbon (PANH), and polyaromatic sulfur hydrocarbons (PASHs) Predominant aromatics include benzene, toluene, xylenes, styrene, limonene, and indene. The most abundant aliphatic are straight-chain alkanes (C₆–C₃₇), with fewer alkenes [30]. NMR, GC, GC-MS, and FT-IR analytical techniques showed that its composition consists of various chemicals with various molecular weights (a mixture of paraffin, olefins, and aromatic compounds). Its high gross calorific value (GCV) of around 41-44 MJ/Kg encourages its use as a replacement for conventional liquid fuels [45].

Table 7. comparison between pyrolysis oil and fossil fuel [45]

Element	Pyrolysis oil %	Diesel %	Physical properties	Pyrolytic oil	Diesel
C	86.52	84-87	density(kg/m ³)	943	820-860
H	9.35	12.8-15.7	Viscosity(cSt)	4.62	2-4.5
N	0.53	<3000 ppm	Flash point (°C)	≤30	>55
S	1.30	<7000 ppm	Pour point (°C)	-4	(-40) – (-39)
Ash	0.2	0.0	Water (wt%)	N/A	≈ 80ppm
O	2.10	0.0	pH value	4.30	-
H/C	1.30	1.76-2.24	GCV MJ/kg	41.60	44 - 46

The density of pyrolytic oil is higher than that of commercial diesel fuel but lower than that of heavy fuel oil. The viscosity of pyrolytic oil is slightly higher than that of diesel but much lower than that of heavy fuel oil. Refining the pyrolytic oil could change these properties. Pyrolytic oil requires preliminary treatments such as decanting, centrifugation, filtration, desulphurization, and hydro-treating before being used as fuels directly (industrial furnaces, power plants, Hot mix plants, Forging units, Steel Industries, Rolling Mill Industries, Chemical Industries, Die casting units, Boilers Furnaces[22].) or by blending with fossil diesel. The manufacturing pathway for tire pyrolysis liquids is shown in Fig. 19, along with several possible uses for heat, chemicals, fuels, and power.[87],[30].

Aydın and Ilkilic [44] studied the impact of pyrolysis temperature on the resulting oil sulfur content. They found the lowest sulfur content in pyrolysis oil at an intermediate pyrolysis temperature of 550 °C, with higher sulfur content as temperatures were reduced to 400 °C or increased to 650 °C. Cunliffe and Williams [73]found higher sulfur content (1.4 wt. %) of oils produced at lower pyrolysis temperatures (450 °C and 475 °C) compared to higher temperatures.

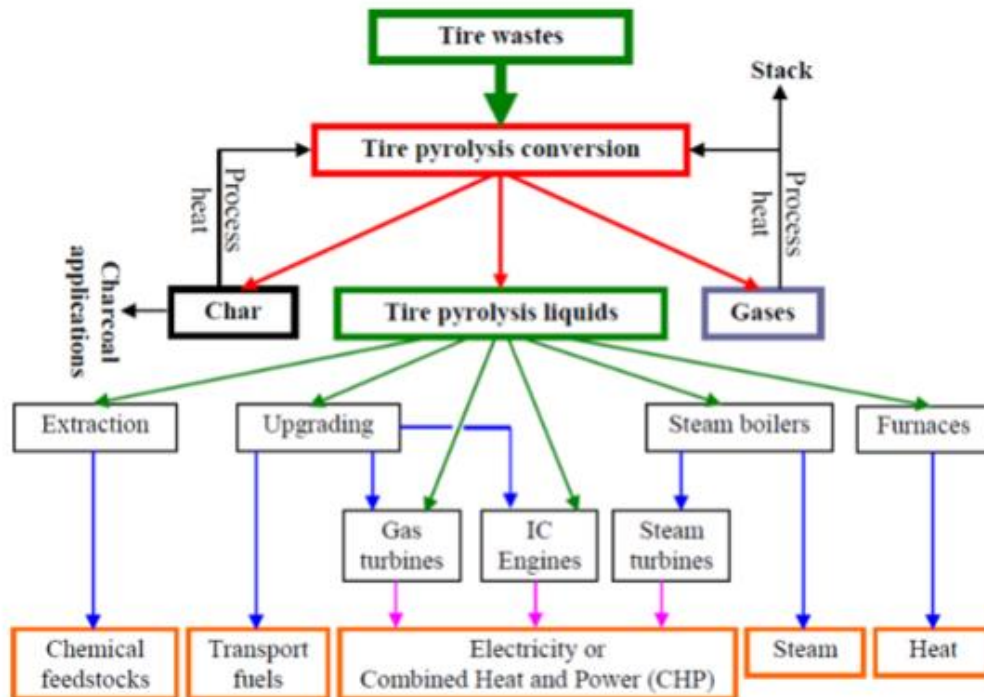


Fig. 19. tire pyrolysis conversion and application of products [87]

7.3 Solid

yield and application depend upon the composition of raw materials and the conditions of the pyrolysis process. By normal Pyrolysis using shredded scrap tires, the yield is 35-40 wt.% calorific value $\approx 30\text{MJ.Kg}^{-1}$ [45]char obtained from ST pyrolysis can be activated via different physicochemical procedures to obtain activated carbon [59]. Several studies have attempted to increase char commercial value by creating higher quality carbon black or using steam or CO₂ to create activated carbons with high surface areas (1000 m²/g)[11].it is used as a reasonable source of solid fuel or has properties suitable for its use as a low-grade activated carbon or carbon black. Carbon black may be used as an additive for road bitumen [45]. It can be sold to the brick factory for internal combustion or to the factory that needs raw materials, such as shoes, tires, cables, and sealant companies. can be compressed into briquettes for industrial heating[29],[22].As a drawback, It cannot be reused as raw material because of impurities in its content. Sulfur, ash, and dirt make it less appealing to be recycled back into tire manufacturing[95].

The pyrolytic char obtained by Jasmin et al. [96] was treated with acid to remove the mineral and then activated at 900°C. The resulting active carbon was comparable with commercially available surface area and adsorption capacity. Activated carbon is used for water purification, air purification, batteries, and fuel cells.

7.4 Steel

Tire contains steel wires, ranging from 13% to 15% of the total Tire wastage. All the steel in the tire can be detached when the process is completed. Then, It can be sold directly to the iron and steel company [22].

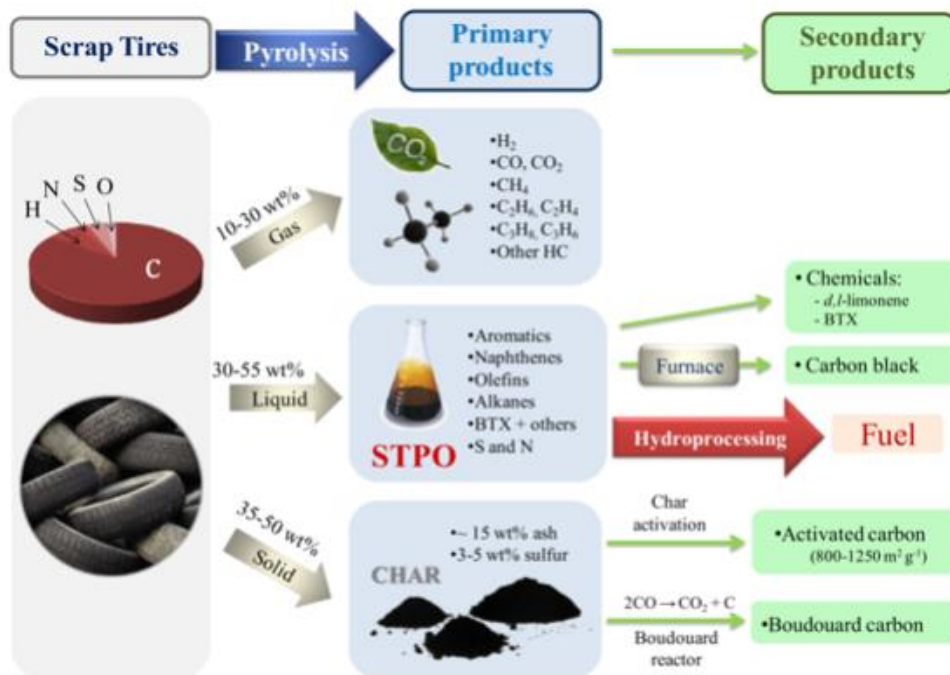


Fig. 20. Primary and auxiliary compounds from ST pyrolysis that are useful[59]

8 MARKET OPPORTUNITY

There have been rising environmental concerns and rapid depletion of fossil fuel supplies, due to which the energy sector is progressively shifting toward a more sustainable and efficient path. Pyrolysis oil has the potential to be a viable alternative to diesel in compression ignition engines. This could further boost demand for the pyrolysis oil market. The market players are focused on alternative fuel resources to lessen reliance on a single energy source and use various renewable energy sources. These factors will further fuel the consumption and adoption of pyrolysis oil globally, thus aiding the market growth even during the forecast period. Global Pyrolysis Oil Market was valued at USD 315.69 million in 2021 and is expected to reach USD 448.95 million by 2029, registering a CAGR of 4.50% during the forecast period of 2022-2029. In addition to the market insights (market value, growth rate, market segments, geographical coverage, market players, and market scenario), the market report curated by the Data Bridge Market Research team also includes in-depth expert analysis, import/export analysis, pricing analysis, production consumption analysis, and climate chain scenario[97].but what mostly effecting the economic prosses are the tipping fees charged for tires disposal and the selling prices of products[98].

The Basel Convention also considers recycling scrap tires a better option than using them as tire-derived fuel. The Alternative and Renewable Energy (ARE) Policy is a particular policy. It shows that the transport sector employs about 17% of the country's total energy. The alternative component should be introduced by a comprehensive ARE policy. Pyrolysis oil is required for the transportation of long-distance vehicles, trucks, automobiles, maritime vessels, and aircraft. For the purpose of starting up tire pyrolysis oil manufacturing from used tires, the government should offer financing[17]. As a solution to the issue of expensive imported fuel, the government ought to boost the usage of tire pyrolysis oil in the nation[99]. TPO's documentation and quality control methods must be expanded to conquer extension[100].

9 CONCLUSION

Pyrolysis is the process in which decomposition occurs. It is produced by-products (gas, oil, char)by reducing environmental and health concerns while making alternative energy sources that are extremely worthwhile to meet the increasing energy demand. The products' quality and composition depend on many factors such as heating rate, particle size, feedstock composition, pyrolysis time/tire residence time, carrier gas flow rate/volatiles residence time, presence of steam in the carrier gas, plus the presence of a catalyst. Mainly, the products depend on temperature, plus the reactor types (fixed-bed (batch), screw kiln, rotary kiln, vacuum, and fluidized-bed...) also play a considerable role in Pyrolysis. The typical heating value is around 40MJ/Kg. Pyrolysis oils can also yield useful chemicals for the petrochemical industry, including light olefins and aromatics. Solid-phase pyrolysis char can create carbon black or activated carbon for pollutant removal. Gases produced, including hydrogen and various hydrocarbons, can be used as fuel for the pyrolysis process.

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