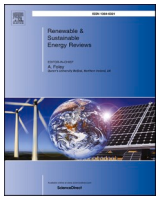
Renewable and Sustainable Energy Reviews 209 (2025) 115062

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Integrating medical plastic waste pyrolysis and circular economy for environmental sustainability

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ARTICLE INFO

Keywords:
Artificial intelligence
Circular economy
Medical waste pyrolysis
Simulation
Valorization

ABSTRACT

A critical assessment of pyrolysis technologies and reactor designs was discussed, highlighting various reactor configurations. This study explored the influence of catalysts, temperature, heating rate, and residence time on the pyrolysis process, and addressed their effects on product distribution and composition. Safety considerations and strategies for mitigating the potential environmental impacts of pyrolysis were presented. Comparative analyses of the environmental impacts of traditional waste disposal methods versus pyrolysis-based approaches provided insights into the potential reduction of greenhouse gas emissions and other pollutants. The circular economy approach was explored in the context of medical plastic waste pyrolysis. The potential for closing the loop by transforming plastic waste into valuable resources was addressed. The integration of pyrolysis-derived products into existing supply chains was discussed in detail. The role of simulation technology, with an emphasis on Aspen Plus, in optimizing the plastic pyrolysis process was explained. The integration of simulation technology allowed for the prediction and optimization of product yields, energy consumption, and overall process efficiency. The application of AI-enabled predictive maintenance, early detection of process anomalies, and adaptive control strategies contributing to safer and more efficient pyrolysis operations. The integration of pyrolysis-derived products into existing supply chains was studied, illustrating how they can serve as raw materials for manufacturing new products, thereby reducing the demand for virgin resources. Incorporating simulation technology, artificial intelligence, and circular economy principles into the discussion enriched the review by providing insights into the technical and strategic aspects of advancing medical plastic waste pyrolysis as a sustainable waste management solution.

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https://doi.org/10.1016/j.rser.2024.115062
Received 9 May 2024; Received in revised form 19 October 2024; Accepted 25 October 2024
Available online 24 November 2024

List of Abbreviations

AA	Acid activation	**HHV**	Higher heating value	**PV**	Photovoltaic
AAEM	Alkali and alkali earth metal	**LB**	Lignocellulosic biomass	**PVC**	Polyvinyl chloride
AI	Artificial intelligence	**LCA**	Life cycle assessment	**RMSE**	Root-mean-square-error
ANN	Artificial neural network	**LDPE**	Low density polyethylene	**SEM**	Scanning electron microscope
BET	Brunuaer-Emmett-Teller	**LOC**	Limiting oxygen concentration	**ST19**	SY blend with TDS in ratio 1:9
BFB	Bubbling fluidized bed	**MB**	Medical bottles	**SY**	Syringes
BMEP	Break mean effective pressure	**MDPE**	Medium density polyethylene	**TA**	Thermal activation
CBA	Cost-benefit analysis	**MPC**	Medical protective clothing	**TDS**	Textile dyeing sludge
CCP	Catalytic co-pyrolysis	**MPW**	Medical plastic waste	**TG**	Thermogravimetry
CFB	Circulating fluidized bed	**MS**	Moisture content	**TGA**	Thermogravimetric analysis
CFR	Catalyst-to-feedstock ration	**MT19**	MB blend with TDS in ratio 1:9	**VOC**	Volatile organic compound
CNT	Carbon nanotube	**NCG**	Non-condensable gas	**WPP**	Poplar wood and polypropylene
CP	Co-Pyrolysis	**NIST**	National institute of standards and technology	**XRD**	X-ray diffraction
CSBR	Conical spouted bed reactor	**NPV**	Net present value	**XRF**	W-ray fluorescence
CSTR	Continuous stirred tank reactor	**NZ**	Natural zeolite		
CVD	Chemical vapor deposition	**PAH**	Polycyclic aromatic hydrocarbon		
DAEM	Distributed activation energy model	**PBP**	Payback period		
DTG	Differential thermogravimetry	**PC**	Polycarbonates		
EDS	Energy dispersive spectrophotometer	**PCB**	Polychlorinated biphenyls		
EFB	Empty fruit bunch	**PCM**	Phase change material		
FBR	Fluidized bed reactor	**PDO**	Plastic derived oil		
FCC	Fluid catalytic cracking	**PE**	Polyethylene		
FID	Flame ionization detector	**PET**	Polyethylene terephthalate		
FT-IR	Fourier transform infrared	**PF**	Palm frond		
GC	Gas chromatography	**PKS**	Palm kernel shell		
MS	Mass spectroscopy	**PP**	Polypropylene		
GHG	Greenhouse gas	**PPE**	Personal protective equipment		
GWP	Global warming potential	**PR**	Pineapple rind		
HDPE	High density polyethylene	**PS**	Polystyrene		
IRR	Internal rate of return	**R^2**	Coefficient of determination		

1. Introduction

Plastic waste is a worldwide dilemma. In recent years the impact of human activities on the environment has been extraordinary. Worldwide concerns caused several initiatives like conferences of parties (COP) and others to make its main aim to limit and control the environmental effects, like climate change; developing a more ecofriendly waste disposing habit. Focusing on medical waste, a huge surge in demand due to the COVID-19 epidemic led to generating a large amount of unplanned plastic waste. Due to the urgency, mismanagement of this waste has caused even more harm than merits. According to a recent estimate as of the year 2021 the amount of excess total mismanaged plastic waste generated at the peak time of the pandemic is 15.1 million tons [1]. Healthcare has a substantial carbon footprint that counts to almost 2 gig tons of CO_2 equivalent, comparable to the greenhouse gas emissions of 514 coal-fired plants [2]. Even before the pandemic the numerous negative impacts on the environment including but not limited to wildlife harm, water and land pollution were already significant enough to raise awareness and provide alternative solutions to such issues. An added challenge in medical waste is that most of the time it can be a source of infection that can be toxic to all life forms. When discarding medical waste, some disinfection technologies must take place as the first step of disposal; whether chemical, physical, or incarnation, all must be done properly inside the facility where the medical waste is generated before any discharging or transportation. Pyrolysis has proven to be more effective than incineration due to the added benefit of trapping the mostly toxic vaporized gases till complete eradication of the toxins available [3]. Plastic recycling is an essential process that helps reduce pollution caused by plastic waste. To make the recycling process efficient and environmentally friendly, there is a need to improve the process efficiency and conserve energy. There are four distinct approaches to recycling plastics: primary, secondary, tertiary, and quaternary recycling. Primary recycling involves transforming plastic waste into a final product with similar properties to the original item. In contrast, secondary recycling focuses on converting waste plastics into finished goods with properties different from the initial product. Tertiary recycling is centred around producing essential chemicals and fuels from plastic waste, which can originate from either municipal waste streams or segregated refuse. Finally, quaternary recycling value-added around extracting the energy content of waste plastics through methods such as burning or incineration. Effective management of plastic waste is crucial for mitigating environmental pollution. Employing a variety of recycling techniques to repurpose plastic waste into useful products is essential for advancing towards a sustainable future. It is, therefore, important to choose the right method of recycling based on the characteristics of the waste material to be recycled [4]. All the previous facts led to the main disposal method was always landfilling or incineration to avoid any human contact. Although landfilling is an easy low-cost solution, it presents undesirable effects of requiring huge amount of land and toxic gases. Finding a greener ecofriendly solution is a necessity rather than an option. Pyrolysis offers a solution for every proposed problem. Due to its high safety and the option of producing value added products, pyrolysis can be the number one substitute to landfilling. Material may vary according to the feedstock and the operational parameters; the high variety offers several routes that all lead to the goal of finding a viable option to discard unwanted polymeric waste. Products of pyrolysis can be found in all forms, solid products like char and carbon black can be used in various applications like rubbers and as a primary source of activated carbon; it also can be found in liquid state in the form of oil; used in a chemical feedstock that can be further more refined and valorized to produce gasoline, and diesel. Lastly pyrolysis release a mixture of gases that are considered of high value like methane, hydrogen and syngas [4,5]. Plastics can be found generally in the medical waste in an ideal feedstock form for pyrolysis; that consists of polyvinylchloride (PVC), polystyrene, polyurethanes, polyethylene, polyethylene terephthalate (PET) [6]. The operating conditions are the ones that determine how long the carbon chain of the product and puts it in the range of light olefins, aromatics, gasoline and diesel range [7]. The variety of feedstock offers a wide variation of operability. To the extent of using already established pre-existing fluid catalytic cracking units and add plastics to a vacuum gas oil stream to enhance the overall gasoline yield [4]. Another advantage to pyrolysis is its high scalability according to the production rate; starting as small scale units to evaluate the economic and technical

feasibility then transforming in a relative fashion into a pilot and plant scale [8]. This flexibility is not only in the scaling, but also in the type of pyrolysis system in use. Operation can be in a continuous matter in a fixed bed, fluidized bed or a continuous stirred tank reactor (CSTR) or it can be in a semi batch from operation under mixed or static conditions in an autoclave, round-bottom flask and a chemical vapor deposition reactors [9].

For furthermore enhancement of the yield, some of the pyrolysis process can be combined with the use of catalyst to have a higher production rate with a high product value. The effects of catalyst have been studied to show if used in the right & optimized concentration the products are most likely to have a higher yield of fuels compared to hydrocarbon char and carbon black. The oil that was produced from a catalyzed process also has lower density and lower viscosity with higher heating value; making the physicochemical properties of the oil more comparable to ones produced from fossil fuel-based sources [10].

Although pyrolysis is considered to be flexible to a high extent, it comes with some limitations. The main issue with pyrolysis is the yield consistency; due to having several interconnected operational parameters with numerous amounts of feedstock combinations with high sensitivity, the consistency of having a constant yield of product is relatively low. One way to overcome the limitation of the various parameters is to have a simulation testing all the combinations to assure the effect and the sensitivity of each parameter. Simulations could be done to try to find the optimum process of using the right blend of plastic types; whether the use of biomass can provide a synergistic effect or not; the type of catalyst in use and how much effect does it have with the yield. All the previous parameters can be rightly adjusted to get the most out the pyrolysis process. Furthermore, it can put an estimate of the economic viability of the product by assessing several factors from equipment design, energy consumption and overall cost. Lastly it can help in knowing the environmental repercussions that allow in developing more sustainable and green pyrolysis technologies.

To guarantee the previous simulated trials are recreated in real time with the highest accuracy, proper characterization of all the feedstock and product must take place. Raw material characterization is crucial before proceeding to determine the type of polymer in use and make notice of any contaminants present that can affect the proposed final product. Some of the characterization tools in use are spectroscopy to identify the elemental absorption of light and chromatography to separate and study each polymer inside a blend [11]. Product composition is essential to be characterized to make sure of the results and upgrade the system if needed. This counts for all the products fractions obtained from the process whether in the liquid, solid or gaseous form. Fourier Transform Infrared Spectroscopy (FT-IR) and Gas chromatography mass spectroscopy (GC-MS) are to among many other confirmation tests that quantifies the pyrolysis products.

The challenges related to medical waste persist even after the disinfection stage. The large volume of plastic generated in healthcare settings often leads to improper disposal, contributing to long-term environmental pollution as these plastics take centuries to decompose [12]. Approximately 25 % of biomedical waste consists of recyclable plastics, highlighting the critical need to focus on recycling efforts within this sector [13]. Medical plastic waste and general plastic waste differ considerably in terms of composition, risks, and regulatory requirements. Medical plastic waste often includes hazardous materials, such as sharp medical instruments and biohazardous substances, which can pose significant health risks to waste handlers and the environment if not managed correctly. General plastic waste mainly consists of consumer products that, while environmentally harmful, typically do not present the same immediate health dangers [14]. The regulatory frameworks for medical plastic waste are more stringent, necessitating specific disposal methods like incineration and autoclaving to address the risks associated with infectious and toxic materials, whereas general plastic waste is usually recycled or disposed of in landfills. However, hazardous materials in some medical plastics can release toxic emissions during incineration such as furans, dioxins, and hydrogen chloride, creating further environmental risks [13].

2. Types of reactors

The type of reactor to be selected is a significant factor as it controls other parameters such as temperature, heating rates, vapor residence time that influence the secondary reactions, and the particle size to be charged to the reactor. Hence, continuous development is required in this field for further improvement of the process. The main design consideration for the pyrolysis reactors was to deliver high oil yield. As a result of this, developed fast pyrolysis reactors were designed to provide short vapor residence time and receive small biomass particle size of less than 2 mm. Recent studies have proved that the operating conditions significantly affect the oil composition [15]. Consequently, pyrolysis reactor design became a process that consider various objectives, compromising between the advantages and the limitations as listed in Table 1 [16]. Pyrolysis reactors can be generally classified based on the supplied heating system into three main categories. The first category is the conventional heating system that relies on the principle of heat transfer by means of conduction and convection, in which heat is transmitted from the outside of the reactor. The second category is the microwave heating system, in which the heat in this case is generated inside the reactor due to the interaction of charged ions in the supplied feed and magnetic poles with varying field forces. In case of the third category which is the plasma heating system, high temperatures and heating rates are supplied through the generation of plasma with the absence of reaction undesired emissions [17]. Different types of reactors are shown in Fig. 1. It is worth mentioning that energy can be supplied to pyrolysis reactors using the solar energy either as solar thermal by preheating the feed, or as solar electricity in which photovoltaic (PV) panels can provide the system with required electricity [18]. A study was conducted on a hybrid system of solar and wind energy, used to power a conventional pyrolysis reactor charged with plastics. The study revealed that the hybrid off-grid system supplied all energy requirements and produced high-quality oil [19].

2.1. Fixed bed reactor

Fixed bed pyrolysis reactors are the simplest form of pyrolysis reactors that consist of the following units: fuel feeding unit, furnace, ash removal unit, condenser, and product collector unit. Fixed bed reactors are mostly used in small-scale applications due to its limitations [20]. In this reactor, the system is set at an anaerobic atmosphere mode through purging by an inert gas which is mostly nitrogen or argon. After satisfying this condition, the feed is charged into the stainless-steel reactor to be heated at a low rate using an electric furnace or a fuel cylinder. The generated products of the condensable and non-condensable gases are withdrawn from the reactor to be purified and condensed to obtain both the oil and pyrolysis gas. Char is then extracted after the process completion [3]. It is concluded from the research that the higher the temperature inside the reactor, the higher the volume of the formed liquid, and the higher the calorific value of the oil for the two processes of pyrolysis and co-pyrolysis [42,43]. Though the process is favored for its simplicity, the reactor is operated at a slow pyrolysis mode that consumes a long residence time with poor distribution of heat and mass transfer [44].

2.2. Rotary kiln reactor

The rotary kiln reactor is a modified reactor version to be implemented in the industry. The main forming units of the system are reactor equipped with a burner, installed lifters, motor, and condenser. The reactor can be operated under a semi-batch or a continuous flow mode which is the reason behind its extensive application. In this process, the solid waste feed with different sizes is charged into the rotating kiln. By

Table 1
Types of reactors.

Type	Pyrolysis type	Operating conditions	Advantages	Disadvantages	Scale/scaling-up	Feed mode	Heat source	Ref.
Fixed bed	Slow	– 300 °C–500 °C.	- Simple in design. - It can be easily operated. - Economically cheap.	- Long process residence time. - Poor heat and mass distribution. - Feeding issues with large particle size. - Uneconomical for mass production. - Difficult to be operated on continuous mode. - Limited liquid oil product.	Lab scale Easy scale-up	Batch, Semi-batch	Conventional	[3, 16, 20, 21, 22]
Rotary kiln	Slow	– 300 °C–500 °C. - Residence time of almost 0.3 h–1 h and heating rate of 100 °C/min - Blending by: control of the kiln rotational speed - lifters geometry.	- Improved heat transfer compared to fixed bed reactor. - Easier operation compared to fluidized bed reactor. - It can be implemented in the industry at different scales. - Uniformity of products due to good feed mixing. - Flexibility in residence time control. - Satisfying char and oil yield balance which is reported to be 19 wt% - 38 wt% and 37 wt% - 62 wt% respectively.	- Waste sorting and shredding is required before introducing the feed into the kiln.	Industrial scale. Easy scale-up	Semi-batch, Continuous	Conventional	[3, 15, 16, 21]
Vacuum pyrolysis	Slow	– 400 °C–500 °C. – 5 kPa–20 kPa. - Particle size range: 2 cm–5 cm.	- Processing large particle sizes. - Lower decomposition temperature of about 100 °C than in fluidized bed reactor and short vapor residence time due to vacuum. - Oil yield is nearly free of char.	- Proper sealing is essential in feeders and discharging devices to maintain the vacuum. - High capital and maintenance cost. - Complex in design.	Lab and pilot scale	Semi-batch, Continuous.	Conventional	[3, 23, 24, 25]
Auger pyrolysis	Slow, medium, fast	- >400 °C - Blending by: screw rotation - Particle size range: granules	- Easy to operate. - The products can be tuned based on the selected pyrolysis type. - The process can be installed at different locations due to the fact that it can be applied on a small scale and receive different feedstock. - Anti-clogging	- The scale-up from the lab scale to be implemented in the industry is still considered challenging due to the existence of moving parts inside the reactor. - Easy to wear.	Lab and pilot scale. Scale-up is under investigation.	Continuous	Conventional	[16, 26, 21, 22, 27]
Fluidized bed	Fast	– 300 °C–850 °C. - Particle size range: 0.01 mm–3 mm. - Residence time: 2 s–3 s for BFB, and 0.5 sec–1 s for CFB. - Blending by: fluidizing agent	- Improved heat and mass transfer compared to fixed bed reactor or tube reactors. - High liquid oil yield was produced with a range of 50 wt% −75 wt% in case of BFB, and 75 wt% −80 wt% in case CFB. Pyrolysis gas contains high amount of methane. - CFB can process large quantity of feedstock.	- Construction and operation are difficult compared to the fixed bed reactor. - Feedstock must be obtained at small particle size to be capable of floating. - Difficulty of separation of char from the inorganic bed material in the BFB. - High tar content in the oil yield. - A high sand/feed ratio at high gas flowrates is required to avoid bed de-fluidization through using a large reactor size, which unfortunately will consume more energy. - High gas velocities are required which adds to the capital and operational cost. - Heat losses by carrier gases.	Lab, pilot, and industrial scale. Easy scale-up	Batch, Semi-batch, Continuous	Conventional	[3, 16, 20, 28, 29, 30, 21, 22, 31, 32]

(*continued on next page*)

Table 1 (*continued*)

Type	Pyrolysis type	Operating conditions	Advantages	Disadvantages	Scale/scaling-up	Feed mode	Heat source	Ref.
				- Erosion issues.				
Conical spouted bed	Slow, Fast, flash	– 500 °C–850 °C. - Blending by: continuously pumped fluidizing agent	- Higher rate of heat and mass transfer compared to fluidized bed reactor. - Less agglomeration compared to FBR as it can handle sticky plastic materials. - Compared to FBR, scaling-up is easier as CSBR can handle the same feed capacity with smaller reactor volumes. The distributor plate is also not required. - High liquid oil yield is produced with a range of 75 %–80 %. - Beneficial for wax extraction at low temperature.	- Feedstock must be obtained at small particle size to be capable of floating. - The reactor design complexity level is higher compared to fixed and fluidized bed reactor with large number of required pumps to be installed. - Catalyst feeding difficulty.	Lab Difficult scale-up	Continuous	Conventional	[3, 16, 30, 21, 33, 34]
Microwave assisted reactor	Fast		- High energy efficiency. - High chemical conversion of biomass, even at considerably large particle size. - Microwave heating requires shorter time than conventional heating. - Products produced from microwave reactors are cleaner than that produced from the conventional reactors due to the absence of harmful heavy polycyclic aromatic compounds. - Easy process control.	- Lack of heating uniformity that can result in hot spots. - Addition of microwave absorbers that add to the operating cost. - Difficult to obtain an accurate temperature measurement inside the reactor. - High capital cost.	Lab scale	Batch	Microwave	[3, 35, 36, 37]
Solar reactor	Fast	−300 °C–900 °C.	- Useful in locations with energy access difficulty.	- Weather dependent. - Additional heat source might be required. - Lack of experimental studies.	Lab scale, modelling	Batch	Conventional (solar energy)	[3, 38]
Plasma		−625 °C–860 °C.	- Complete destroy of pathogens with limited production of toxic gases. - Tar is no longer formed. - High energy density.	- High operating cost. - Commercialization is still a challenge due to complex chemistry and corrosion problems. - Lack of experimental studies on medical plastic waste.	Lab scale		Plasma	[3, 39, 40, 41]

controlling key design aspects such as the reactor diameter, tilt angle, and rotational speed, heat and mass can be more evenly distributed inside the reactor as feed is introduced, ensuring an effective reactor performance [45,46]. Another significant factor that contributes to the particles motion inside the reactor is the lifters design. Besides serving as fins, lifters geometry can improve the transmission of the waste from the bottom of the kiln to be distributed over the upper wall surface in a way that guarantee high heat and mass transfer [45,47]. With respect to the operating conditions, rotary kilns are usually operated in the slow pyrolysis phase at a temperature range of 300–500 °C, and a residence time of less than an hour. The advantage of rotary kiln reactor over the fixed bed reactor is the flexibility of controlling the product uniformity that is adjusted by the kiln rotational speed [44].

2.3. Vacuum pyrolysis reactor

Vacuum pyrolysis reactors are a type of slow pyrolysis system, in which the process is operated under vacuum instead of retained inert gases. In this process, a pump is installed to provide the required vacuum, while molten salt (such as sodium nitrate or potassium nitrate) along with heaters is used as a heat carrier for waste feed [48]. For continuous flow operations, a vacuum feeder is used to prevent airflow while introducing biomass or plastic feed into the system. Furthermore, conveyors are installed within the vacuum chamber to ensure a consistent supply of materials and to facilitate the removal of processed products. The system is also flexible in receiving numerous feed types with varying particle sizes. The vacuum pyrolysis system is characterized by the short residence time of the volatiles due to their continuous suction. This is beneficial in reducing the secondary reactions that negatively affect the yield and result in high char and low oil products.

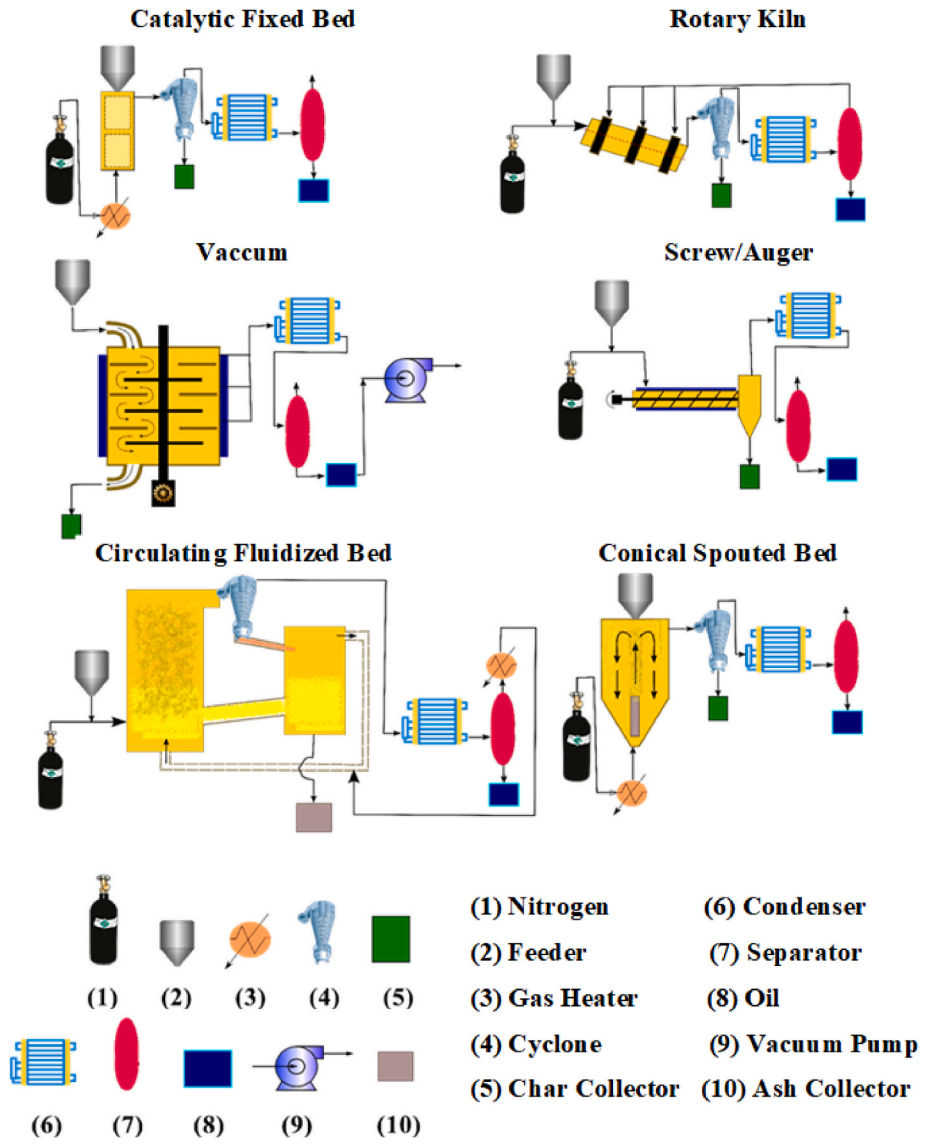

Fig. 1. Pyrolysis processes configurations.

Since char is not carried over under vacuum conditions, the resulting oil is nearly free of char. Regarding the operating conditions, the process is operated under an induced vacuum between 5 kPa and 20 kPa which is opposed to the slow pyrolysis that takes place under atmospheric pressure. The operating temperature lies in the typical conventional pyrolysis range at 400 °C–500 °C [44,49]. On comparing the vacuum pyrolysis reactor to the fluidized bed reactor, Young Min Ju et al. reported that the obtained oil from the vacuum pyrolysis is characterized by a high heating value which is 6 MJ/kg higher than that obtained by the fluidized bed reactor. The reason behind this returns back to the low oxygen and water content of the vacuum pyrolysis oil yield [23].

2.4. Auger/screw reactor

Auger reactor or screw reactor is a type of pyrolysis reactor that is still under research and not widely commercialized. The process is composed of four main sections which are: the feeding section, reaction zone, char extraction part, and condensers. Firstly, the process begins with the purging step in which the inert gas is pumped into the system. Secondly, the auger conveyors are heated until the required pyrolysis temperature is exceeded to ensure that sufficient pyrolysis energy will be transmitted through the reactor wall. Thirdly, the waste feed is charged into the system in which the feed is conveyed along the reactor using the endless rotating screw installed inside the reactor shell. In this stage, the auger motor plays an important role in controlling the feed residence time inside the reactor by adjusting the auger rotation speed [50]. The inert gas can also be a supplementary factor for controlling the residence time by providing a positive pressure for moving the formed vapors forward. Moreover, the screw act as a mixer to the feedstock in which the particles can witness a better heat transfer rate through continuous contact with the reactor wall. The output products of this stage consist of solid char and vapors. While the char is being formed and collected, the vapors produced are getting transferred to the fourth stage. In this stage, condensers are used to separate the condensable vapors which are then stored in a tank while the non-condensable gases are mainly directed to provide heat to the system. At the final stage when the process completely cooled down, the char is removed from the char extraction section to be stored for further application [51,52]. The controlling parameters are the screw rotational speed and the inert gas flow rate as they are both important in adjusting the solids and vapors residence time. The operating pyrolysis mode can be adjusted as slow, medium, or fast. For slow pyrolysis, the reactor tubular shell can be only heated with slow heating rates to produce char, viscous wax-like fractions, and heat [51,53]. In the case of medium and fast pyrolysis, extra heating can be

delivered to the system to increase the heating rate through heating the screws in addition to the reactor shell as well as mixing the feed with heat carriers such as pre-heated metal balls or sand. As a result of this, more volumes of liquid oil can be obtained compared to char [51,26].

2.5. Fluidized bed reactor

The fluidized bed reactor consists of four major sections which are: the feeding system, reaction zone, pre-heating system, and condensation zone. First, the waste feedstock is transported from the silo to the reactor inlet through cold and hot screw feeders to bring the feed to the required reaction temperature. In parallel to this process, the fluidizing agent is preheated by the plant's residual heat before being introduced into the reactor. As the pressurized fluidizing agent enters the reactor cylindrical vessel, the hot incombustible bed material of the reactor which is sand gets distributed homogeneously while mixing with the side charged reactants, thus allowing for better heat and mass transfer which are important pillars in the pyrolysis step [44,54,28]. The fluidized bed reactor can be operated on the fast pyrolysis mode due to the high heating rates that can be achieved from both the embedded reactor heating system and the preheated bed material. Similar to the previous processes, the char passing by the cyclone is separated from the vapors which are then sent to the condensers for further separation. There are two common types of fluidized bed reactors: the bubbling fluidized bed (BFB) and the circulating fluidized bed (CFB). Both reactors have a similar configuration, except for the reaction zone partition. Bubbling fluidized bed (BFB) is a simpler form of the fluidized bed reactor, as it contains only one combustion zone which is the reactor. In contrast, CFB is designed to have a combustion zone with two separate units. The first unit is the reactor, where both waste and bed material are fed. The second unit is the char combustor, where the sand and char are exposed to high temperatures to generate heat from the char. Sand is then recirculated to the reactor along with the generated heat, which supplies most of the required energy for the pyrolytic reaction [20,55]. Sometimes, the selected inorganic bed material is chosen with some sort of catalytic properties that act on adhering the char to its surface. Once the char is attached to the heat carrier surface, it gets consumed by combusting it, allowing the bed material to be reused in the reactor [56]. It is worth mentioning that the oil produced from the CFB contains a higher amount of tar compared to that produced from BFB [57]. Finally, the major controlling parameters in a fluidized bed reactor are the velocity of the fluidizing agent which controls the solids and vapor residence time, the type of fluidizing agent (which can be nitrogen, air, or steam), and the operating temperature [28,29].

2.6. Conical spouted bed reactor

In fact, some reactors such as the fluidized bed reactor (FBR) and the conical spouted bed reactor (CSBR) deliver promising solutions for the issue of plastic waste pyrolysis. This is due to the challenging fact that plastics possess low thermal conductivity which makes it hard to reach high heat transfer rates. Fortunately, both FBR and CSBR supply adequate amount of energy for the fast/flash pyrolytic reaction due to their outstanding design that enables the reactants and the bed material to come in contact ensuring a high rate of heat and mass transfer [44,58]. Basically, the CSBR is a more advanced version of the fluidized bed reactor that tackle some of the fluidized bed reactor operational issues. The most highlighted issue of the FBR is bed de-fluidization that occurs when the plastic melts on the sand resulting in increasing its thickness and leading to agglomeration. To overcome this, the design of the CSBR relies on vigorous collision of particles through the operation with a very high gas flow rate that makes it hard for the sand particles size to grow and agglomerate [59,30]. In other words, sand particles due to the high fluidizing agent velocity and cyclic movement are coated uniformly without major increase in their thickness. In fact, the CSBR has undergone successful operation tests with various types of plastics such as: polyethylene, polypropylene, polyethylene terephthalate, and polystyrene [44]. The process of both the FBR and the CSBR are common as both include the waste and fluidizing agent feeding system, the reaction zone, cyclone, and condenser system. The difference lies in the reactor operation mechanism such that the feed is mixed in a fountain cyclic movement using a fountain confiner, and a draft tube might be used for better performance. The role of draft tube is to save energy by providing a steady spouting at low gas velocities, guaranteeing a notable improvement of the reactor hydrodynamics [30].

2.7. Microwave assisted reactor

This type of reactor is still under research and development due to the multiple advantages it offers over the reactors operated by the conventional heating method. Energy is first supplied to the reactants in the form of electromagnetic waves, which are usually generated by the microwave generator installed in the reactor and typically have a frequency of 2.45 GHz. The dielectric materials in the reaction mixture absorb the microwave energy, resulting in rapid volumetric heating of the mixture. Organic compounds, including biomass waste, can be effectively paralyzed inside a microwave reactor due to their high moisture content and ability to absorb microwaves. However, plastics are poor microwave absorbers and require the addition of susceptors for processing in a microwave-assisted reactor [44,35]. Heating modes in a microwave-assisted reactor can be categorized as either direct or indirect. Direct heating, which is more of an energy conversion, involves the transfer of energy directly to the reactants, which is suitable for biomass pyrolysis. Indirect heating, as used in the case of plastic pyrolysis, involves the transfer of microwave energy to susceptors, which are strongly heated and then emit heat to the waste material through conventional heating methods such as conduction and convection. In general, susceptors can be found as carbon-based compounds like graphite and activated carbon, zeolites, clays, or metals. A lot of attention has been directed towards identifying efficient and cost-effective susceptors which is currently a popular research topic. This is to find an economical alternative to zeolites, as susceptors play a crucial role in improving product characteristics (e.g., production of char with better pore structure, increasing of the oil higher heating value) and reducing process power requirements [60,36].

2.8. Solar reactor

The intense and concentrated energy of solar radiation can reach up to 1000 °C if a sufficient capacity is installed, which makes the solar reactor a good choice for co-pyrolysis. The advantage of such a system is the integration between two low energy-density sources (solar and biomass/plastic energy) to produce a high energy-density fuel [38,61]. The selection of optical devices can be determined based on the desired temperature. Options include the parabolic trough and solar dish collector for the low-temperature range of 100–500 °C, and the linear Fresnel and solar tower for temperatures above 1000 °C. Solar reactors may require supplementary heating due to weather instability [38].

2.9. Plasma reactor

A plasma reactor usually uses an electric field to ionize a gas, causing its molecules to become charged particles. These particles then interact with each other and the reactor walls, producing a range of reactive species and heat. The oxygen is removed by the introduction of an inert gas into the system which can also serve as a working gas for plasma production [44]. Plasma pyrolysis destroys most of the medical waste, with hydrogen and carbon monoxide being generated as byproducts. The heat produced by the combustion of these gases can be reused, and the amount of other harmful gases produced is within safe limits. Furthermore, plasma pyrolysis effectively eliminates pathogenic bacteria due to the high temperature and radiation environment [62,63].

There are two types of generated plasma which are: thermal and non-thermal (cold plasma). In thermal plasma, only char and pyrolysis gas are obtained, with a wide yield pyrolysis gas percentage of 50 wt% - 98 wt% [44]. The results of a study on a hybrid cold plasma gasification reactor showed that the pyrolysis gas yield from plastic waste feedstock ranged from 10 wt% to 23 wt%, while the oil yield was between 76 wt% and 88 wt%, and the char yield was 4–15 wt%. In addition to that the reported calorific value from the oil is 39 MJ/kg - 41 MJ/kg providing a promising substitute for conventional fuel [63]. Another study conducted on low-density polyethylene (LDPE) at a temperature range of 625 °C-860 °C resulted in pyrolysis gas, oil, and char yield of 37 wt%, 57 wt%, and 6 wt% respectively [39].

3. Operating conditions

Pyrolysis is classified based on various operating conditions into three primary categories: conventional (slow) pyrolysis, fast pyrolysis, and flash pyrolysis. These categories differ in process temperature, heating rate, solid residence time, biomass particle size, and other factors. Slow pyrolysis involves the conversion of biomass into char. This method employs temperatures ranging from 300 500 °C–500 °C, low heating rates (0.1 °C/min – 1 °C/min), long residence times (up to 2 h), and relatively large particle sizes (5 mm–50 mm). Slow pyrolysis yields char with a solid production of around 45 wt%. Fast pyrolysis is a process utilized to convert biomass into oil. It operates at higher temperatures (450 °C - 700 °C), faster heating rates (1 °C/s - 200 °C/s), and uses smaller particle sizes (less than 1 mm), resulting in an oil yield that accounts for approximately 75 wt% of the total products obtained. Flash pyrolysis employs temperatures above 800 °C, extremely short retention times (1 s), very high heating rates (over 1000 °C/s), and small particle sizes (less than 0.2 mm). It generates non-condensable pyrolysis gas consisting of hydrogen, carbon dioxide, carbon monoxide, methane, ethylene, and ethane [64].

The yield of liquid oil fuel is influenced by the complex interactive effects of various operating conditions. Relying solely on one-by-one relationship interactions may not provide convincing results when determining the optimal operating conditions. Consequently, it becomes necessary to establish a multipara meter mathematical expression to accurately evaluate the liquid oil fuel yield in different pyrolysis systems [65]. During a study that involved varying temperatures in the range of 450 °C–550 °C, a heating rate range of 20 °C/min - 50 °C/min, and a residence time of 40 min–120 min, it was discovered found that the liquid oil yield was primarily influenced by temperature. Following temperature, residence time had a greater influence at lower temperatures while the heating rate was the least significant factor. The impact of temperature on the calorific value of the liquid oil fuel was minimal,

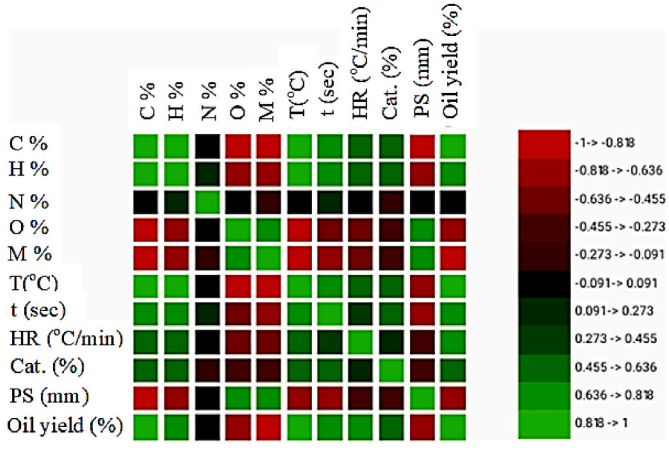

Fig. 2. Pearson matrix between process parameters and oil yield for co-pyrolysis [67].

as the results showed little variation [66]. In a study conducted by Vaishnavi et al. the statistical influence of a total of 11 parameters for co-pyrolysis processes was analyzed and ranked in terms of their impact on the desired liquid oil yield as shown in Fig. 2. According to the Pearson correlation coefficient, the parameters were ranked from the most significant to the least significant as follows: temperature, feedstock type (carbon content (C)), moisture content (MS), hydrogen content (H), oxygen content (O), nitrogen content (N)), particle size, catalyst loading percentage, heating rate, plastic content percentage, and residence time. Most process parameters showed positive correlations, while parameters such as moisture content, particle size, and oxygen content showed negative correlations. The nitrogen content (N %), however, exhibited moderate correlations as it approached a coefficient of determination value close to zero (0.1 in both cases), rendering any potential correlations with oil yield invalid [67].

3.1. Temperature

Based on evidence from prior research, it was recommended that the ideal reaction temperature for achieving the highest amount of oil product from individual plastic waste pyrolysis was within the range of 300 °C-500 °C [68]. High liquid wax yield above 80 wt% can also be obtained near the end of that temperature range [33]. If the reaction temperature exceeded 500–600 °C, a greater proportion of gaseous products was produced leading to a decrease in the yield of pyrolysis oil [68–70]. When dealing with mixed plastic waste that contains more than two types of plastics, the temperature range that maximizes the yield may not be identical to that of individual plastics [68]. For the cellulose feedstock, the liquid oil yield was obtained at a pyrolysis temperature range between 400 °C and 700 °C with char and oil yield of 29 % and 55 % respectively. One reasonable hypothesis is that, at high temperatures, the liquid products decompose and transform into gaseous products [62]. For char, the results suggested that its yield increased with prolonged residence time and elevated temperatures. Conversely, a longer residence time at lower temperatures decreased the char yield. These findings indicated that temperature has a significant role that can exceed other parameters such as residence time [71].

3.2. Hydrogen to carbon ratio

On comparing medical waste to other types of feedstocks such as polypropylene, tires, kitchen waste, coal, sewage sludge, bamboo, and chlorella vulgaris, it was found that the third-highest calorific value and the second-highest volatile matter content was that of the medical waste. Medical waste is highly heterogeneous because it is composed of various materials that depend on different factors. Medical wastes primarily consist of plastics, paper, and textiles. Plastic materials such as waste syringes, infusion sets, medical bottles, and packages contain high carbon and hydrogen content which results in high calorific value [72]. However, lignocellulosic biomasses such as gauze, bamboo sticks, cotton, and tissues do not perform well in terms of higher heating value (HHV) due to their high oxygen content [68,72]. Additionally, the oil produced from biomass pyrolysis is unsuitable for industrial applications due to its poor thermal stability and high corrosivity [73]. Biomass with a low H/C ratio can be improved by adding hydrogen-rich plastics as input. When biomass and plastic are co-fed, the oxygen content of the resulting oil is reduced and the preference for aromatic compounds is increased. This implies that combining the pyrolysis of lignocellulosic biomass and plastics is advantageous for enhancing the quality of oil [74]. Compared to individual pyrolysis, co-pyrolysis resulted in lower microwave energy requirements (2267 J/g - 2385 J/g), heat energy requirements (1410 J/g – 1421 J/g), and conductive heat losses (85 J/g - 89 J/g) [75]. It is worth noting that the type of plastic feedstock has a significant impact on the composition of the produced oil. Samples of medical waste taken from five hospitals in Cartagena-Colombia revealed the presence of PP, PS, and PE in average proportions of 85.37 wt%,

12.05 wt%, and 2.78 wt%, respectively. When the waste residues underwent pyrolysis, the average yield obtained was 31.42 wt% propylene, 8.81 wt% ethane, 30.2 wt% aromatic hydrocarbons, and 0.04 wt% permanent gases. Among the aromatic compounds, the highest concentrations were found in toluene, ethyl benzene, styrene, 1,3-dimethylbenzene, indene, and naphthalene [76]. The pyrolysis process can also be affected by the feedstock type and composition. It was recorded that the operating temperature for the complete degradation of PE and PP plastic waste is higher than that of PS waste [77].

3.3. Particle size

The size of particles is a critical factor that is closely connected to other process variables such as reaction temperature, heating rate, and residence time. Therefore, it indirectly impacts the distribution and yield of the final product. As particle size increases, the temperature gradient also rises, potentially preventing the process from completing within the designated time. In contrast, the use of smaller particles resulted in a larger surface area, facilitating faster heating and ultimately leading to a higher yield of liquid products [68,78]. However, at high reaction temperatures, the impact of particle size on product distribution was minimal because the radiative heat transfer at higher temperatures mitigated the temperature gradient within the particle to some degree [68].

3.4. Catalyst

The effectiveness of plastic pyrolysis reactions relies on the actions of solid acid mechanisms occurring on the catalyst's surface. These mechanisms involve cracking, isomerization, oligomerization, cyclization, and aromatization reactions. The mechanism in each case is a factor in several catalyst characteristics including catalyst acidity and pore size [79]. For instance, when the pore size is larger, it becomes easier to transform plastic into polyalkylaromatics. A smaller pore size only allows the conversion into aromatic compounds with smaller dynamic diameters [21]. Consequently, polycyclic aromatics may be generated through secondary reactions occurring on the crystal surface or through the reaction of smaller aromatic compounds [80]. Simultaneously, cracking reactions of the large molecules on the external surface of the small pore-sized catalyst will lead to the deactivation of the catalyst due to coke formation [81]. Zeolites can be selected based on their pore size that is classified into large pore (SSZ-55, Y zeolite, Beta zeolite), medium pore (ferrierite, MCM-22, TNU-9, ZSM-5, ZSM-11, ZSM-20, ZSM-23, SSZ-20), and small pore (SAPO-34, ZK-5). A study conducted to investigate the effect of pore size in various zeolite catalysts during glucose pyrolysis confirmed this finding. It was found that using a catalyst with a small pore size did not lead to the production of aromatics. Instead, it led to the production of coke, CO_2, and CO. Medium pore zeolites with pore sizes ranging from 5.2 Å to 5.9 Å exhibited the highest yields of aromatics. Lastly, large pore zeolites resulted in lower aromatic yields, higher coke yields, and reduced yields of oxygenates [80]. Additionally, other factors are essential to improve both the quantity and quality of the products including the catalyst-to-feedstock ratio and the mode of catalyst addition [79]. In the ex-situ co-pyrolysis of polystyrene and corn stalk using HZSM-5, increasing the catalyst-to-feedstock ratio (CFR) from 1:10 to 1:1 led to specific observations. The liquid oil yield decreased from 64.5 wt% to 53 wt%, while the pyrolysis gas yield increased from 23 wt% to 32.5 wt %. Additionally, there was a simultaneous increase in coke formation from 2 wt% to 3.5 wt%. These outcomes can be attributed to the increased amount of catalyst which enhanced the rate of catalytic cracking by increasing the acidic sites on the catalyst and extending the residence time of pyrolysis vapors within the catalyst bed. Consequently, this led to secondary reactions that favored the formation of gas and coke. Increasing the CFR in both catalytic modes also resulted in a decrease in styrene formation and an increase in benzene production [82]. The impact of the catalyst addition mode is still under research to evaluate its effect on the production of valuable hydrocarbon yield. A comparison was made between in-situ and ex-situ catalytic pyrolysis of lignin using HZSM-5. The findings revealed that the ex-situ approach resulted in a lower yield of oil but exhibited the highest aromatic selectivity [83]. This was also similar to the results of Muneer et al. obtained from the co-pyrolysis process [84].

3.5. Residence time and heating rate

The residence time of the feedstock is a significant factor that ultimately determines the composition of the resulting pyrolytic product [71,85]. The term 'residence time' is defined relative to the type of process operation. Fast and continuous pyrolysis processes typically refer to the time the plastic feedstock spends in contact with the hot surface inside the reactor. In contrast, for slow pyrolysis and batch processes, 'residence time' typically refers to the period from the initial heating of the feedstock plastic to the final removal of the resulting products. It is possible to regulate the residence time of slow pyrolysis by adjusting the feed flow rate [86]. Research has proved that the short residence time of volatiles from plastic waste pyrolysis favors the formation of monomer products [69]. Conversely, longer residence times were associated with the formation of thermodynamically stable products including hydrogen, methane, aromatic compounds, and carbon [30,69]. In a study examining the simultaneous effects of temperature (ranging from 410 °C to 550 °C) and residence time (0.42 h–1 h) on the yield from plastic waste mixture pyrolysis in a semi-batch reactor, it was found that the maximum oil yield of 69 wt% was achieved at the lowest temperature of 410 °C and the longest residence time of 1 h. Altering either parameter within the specified range led to an increase in pyrolysis gas formation [87]. In fast pyrolysis systems, with a vapor residence time between 0 and 4.5 s and temperatures of 600 °C-700 °C for HDPE feedstock, it was found that longer volatile residence times combined with a low heating rate increased hydrocarbon cracking. This resulted in a decrease in wax yield and an increase in the amount of light compounds (C15 and below) reaching up to 96 wt% [34,88]. This was approved by another study conducted on a mixture of plastic waste at both non-isothermal (slow pyrolysis) and isothermal (fast/flash pyrolysis) conditions. In this study, the oil was also reported to be the dominant product in the former condition, while pyrolysis gas was dominant in case of the latter. In the non-isothermal conditions, the pyrolysis reactor was operated at heating rates of 10 °C/min and 20 °C/min which resulted in an oil yield of nearly 76 wt % and 82 wt % respectively. Under isothermal conditions with a heating rate of 10 °C/ms, the oil yield obtained was 7 %, while the pyrolysis gas yield accounted for 91 wt% [89]. Another recent study contradicted the previous work in which the change in the heating rates between 10 and 40 °C/min in a temperature range of 50 °C-850 °C resulted in no significant effect on the co-pyrolysis process of oily sludge and walnut shell [90].

3.6. Plastic to biomass ratio

The complexity of plastic and biomass wastes, both in terms of their chemical and physical structures, is highlighted in the research by Okolie et al. (2019). Complications can arise from various mineral substances with diverse reactivity characteristics. As a result, the decomposition process of plastic, biomass, and their combinations involves a complex mechanism consisting of numerous parallel or competing reactions [91]. Reported studies indicated that co-pyrolyzing biomass with plastic waste yielded a positive synergistic effect as listed in Table 2. This explained the reason behind the existence of few oxygenated compounds in the derived oil. This reduction in oxygenated compounds is attributed to the deoxidation effect, leading to improved stability of the oil and a decrease in its potential to cause corrosion [68]. An in-situ catalytic co-pyrolysis experiment was conducted at a

Table 2
Plastic/composite waste.

Plastic type	Temperature range	Summary	Yield	Reference
HDPE	400 °C–450 °C	100 kg of HDPE were pyrolyzed at 400 °C, 425 °C, and 450 °C.	22.5 L, 27 L, and 40.5 L of oil were obtained	[88]
PP	560 °C	Pyrolysis was conducted in the presence of zeolite ZSM-5 under vacuum conditions of −3 mm H_2O.at 560 °C	68.43 wt% of oil	[94]
PP, LDPE (85.2 %), and HDPE (11.3 %) mixture	410 °C–550 °C	Maximum oil yield was achieved at lowest temperature of 410 °C.	69 % of oil that accounts for 0.85 L/Kg waste	[87]
LDPE	200 °C–400 °C	Shredded LDPE of 0.25 cm^3 are pyrolyzed at 200, 250, 300, 350, and 400 °C at a heating rate of 10 °C/min.	90 % of oil was obtained at 350 °C in the standard range of oil fuel properties.	[95]
HDPE (25 %), pine sawdust (25 %), and HZSM-5 (50 %)	400 °C–700 °C	Catalytic co-pyrolysis of HDPE and (pine sawdust mixed with 8 % $MgCl_2$ catalyst) takes place inside a tubular quartz reactor at a temperature range of 400–700 °C, a heating rate of 40 °C/s, and isotherm period of 5 min.	The oil yield at 400 °C, 500 °C, and 700 °C is 18.1 %, 43.7 %, and 36.5 %, respectively.	[96]
Extruded PS	450 °C	Process is operated at 450 °C, 30 min solid residence time, and a feed particle size of less than 6 mm inside a screw reactor,	75 % oil	[97]
PS (PE/PS)	500 °C 500 °C	Process is operated inside a continuous reactor at both temperature and heating rate of 500 °C and 120 min. Feed particles size for PS and (PE/PS) mixture is 2 cm and 2.75 cm, respectively.	91.4 % oil 46.7 % oil	[98]

temperature of 510 °C with three different feed ratios of lignocellulosic biomass (LB) to plastic (1:2, 1:1, and 2:1). A semi-batch reactor was utilized to host the mixture consisting of LB and two types of plastic, namely polypropylene (PP) and polystyrene (PS), along with spent fluid catalytic cracking (FCC) catalyst. The findings revealed that the highest selectivity to aromatics was achieved when both polymers observed at a feed ratio of 0.5. In addition, more valuable chemicals like toluene and xylene were obtained at equal mixing ratios of LB and PP [92]. A recent study has suggested the adoption of a new method called the distributed activation energy model (DAEM) to gain valuable insights. This model enabled the precise estimation of the volatile quantity released from different types and ratios of plastic and biomass wastes, considering factors such as activation energy and time during catalytic co-pyrolysis (CCP). By utilizing the DAEM, it becomes feasible to characterize the varying reactivity of varied species based on their respective activation energies [93].

3.7. Reactor configuration

The reactor configuration plays a crucial role in determining both the overall yield and composition of pyrolysis products, and it can be customized to meet specific process requirements. Among the key factors impacting yield, the heat transfer rate between the reactor and feedstock particles is especially significant [71]. Further research indicated that the height of a fixed-bed reactor also influenced char yield. Increased bed height allowed vapors to have extended residence time promoting polymerization processes that enhanced char yield [22,65]. In commercial char production through pyrolysis, continuous methods such as rotary kilns, drum pyrolyzers, and screw pyrolyzers are widely used [99].

To enhance the production yield of hydrogen, it is possible to connect two reactors in series, combining catalytic pyrolysis and reforming steps. Various configurations, such as in-line fixed-bed-fixed-bed, fluidized-bed-fixed-bed, spouted-bed-fixed-bed, spouted-bed-fluidized-bed, and screw-kiln-fixed-bed two-stage reactor combinations can be employed for the continuous process of plastic pyrolysis and catalytic reforming [100]. For instance, a fixed bed-fluidized bed reactor can allow for an integrated system. The fixed-bed reactor can be utilized to enhance the heating value by effectively reducing moisture content and increasing the carbon-to-oxygen ratio. This configuration enabled the subsequent pyrolysis reaction inside the fluidized bed reactor to yield higher-quality fuels [22]. Akubo et al. reported on a two-stage fixed-bed reactor for catalytic pyrolysis, utilizing zeolite catalysts impregnated with transition metals for the pyrolysis of high-density polyethylene (HDPE). The first reactor, made of stainless steel, contained the waste plastics and was heated to 600 °C at a rate of 10 °C/min. The volatiles produced in the first reactor then passed into the second reactor, which held the catalyst. Non-catalytic pyrolysis of HDPE using this two-stage fixed-bed reactor resulted in a high oil yield of approximately 70 C%, consisting entirely of aliphatic hydrocarbons. However, when a Y-zeolite catalyst was introduced, the oil yield decreased, but over 80 wt% of the oil comprised mono or bicyclic aromatic compounds [101].

3.8. Pressure

The operating pressures have an impact on both the pyrolysis processes and the resulting products [69]. Plastic waste can undergo both thermal and catalytic pyrolysis at varying pressure levels including vacuum (<1 bar), atmospheric, and excess pressure above atmospheric (2 bar–9 bar). However, due to the considerable cost savings in operating expenses, plastic waste pyrolysis is usually performed at atmospheric pressure instead of vacuum or high-pressure operations [102]. When conducted under low pressure, such as vacuum or in the presence of an inert diluent, pyrolysis tends to produce primary products like monomers. Conversely, complex liquid fractions are more commonly associated with high pressures. At high pressures, the boiling point of pyrolytic products increases leading to a pressurized environment in which heavy hydrocarbons are more likely to undergo further pyrolysis instead of vaporization at a given operating temperature resulting in an increased residence time [69,103]. This was confirmed by a study in which LDPE was pyrolyzed in an increased pressure from 6 bar to 51 bar at a temperature range of 330 °C–380 °C. The results showed that aromatics were exclusively detected at high pressure which was also

associated with a higher concentration of cycloalkanes [104]. Both the oil product quality and the pyrolysis gas yield were also enhanced with the increase in pressure [105,106]. In another study, the PP-derived light and heavy oils were evaluated based on their HHV and aromatic compositions under vacuum and atmospheric conditions. It was found that HHV was negatively influenced by the increase of temperature during the atmospheric conditions, while no significant change was observed under the vacuum conditions. The aromatic composition of the vacuum pyrolysis process at a temperature range of 450 °C–600 °C was noticeably low with almost no existing aromatic content in the heavy oil compared to the pyrolysis process operated under atmospheric pressure [107].

3.9. Carrier gas flow rate

In the pyrolysis process, the vapors generated are purged by the flow of carrier gas. This purging is essential because if these vapors are not removed, they can undergo secondary reactions that might have undesired effects on the physicochemical properties and overall yield of the pyrolysis products [71]. Argon, nitrogen, carbon dioxide, and steam are among the most commonly used carrier gases [108]. Other carrier gases that were discussed in several studies are hydrogen, helium, ethylene, and propylene [100]. Among these options, nitrogen gas has been extensively employed in commercial pyrolysis operations due to its availability, attractive cost, and inert nature [109]. Even though helium is effective in generating high yields of oil, it is less abundant and more costly compared to nitrogen. The molecular weight of carrier gases determines their impact, with lighter gases being capable of generating a substantial quantity of condensed oil product [100]. It was also observed that increasing the nitrogen gas flow rate led to a slightly higher yield of oil and a lower yield of char. This was affirmed by a study in which the co-pyrolysis process of corn cobs and PP took place in a stirred tank reactor with a heating rate of 5 °C/min. The nitrogen gas flow rate was adjusted to three different levels: 400, 500, and 600 mL/min at three distinct ratios of biomass-plastic feed compositions. The maximum oil yield was achieved at a nitrogen gas flow rate of 600 mL/min. The following plastic-to-biomass ratios (0:1, 1:1, 1:0) [110]. The relationship between oil fuel production and operating conditions for the thermal pyrolysis of waste polyethylene (PE) was investigated using the adaptive neural fuzzy model. It was found that an increase in the carrier gas flow rate at 425 °C accompanied by a shorter residence time, resulted in a higher production of oil fuel. Specifically, when the carrier gas flow rate varied from 20 mL/min to 100 mL/min with a residence time of 20 min, the oil fuel production increased from 65.32 wt% to 73.54 wt%. This emphasizes the significant role of the carrier gas flow rate in improving the yield of oil fuel during the pyrolysis process [65].

3.10. Toxic compounds control

To comprehend and reduce potential concerns, a thorough evaluation of the effects that the pyrolysis of medical plastic waste will have on the environment and human health is necessary. If pyrolysis is not adequately controlled, it may unintentionally release hazardous byproducts. The possible emission of hazardous substances like dioxins and furans is a major worry. These extremely hazardous and enduring chlorinated chemicals can arise from the pyrolysis of specific polymers. Reproductive disorders, immune system suppression, cancer, and other major health problems can result from the accumulation of dioxins and furans in the food chain. The investigation showed that the concentration of dioxins and furans in the emission gases was reduced by more than 80 wt% with the optimized catalyst, demonstrating the efficiency of catalytic enhancement in reducing harmful byproducts [111].

To further mitigate the environmental and health risks posed by pyrolysis, advanced emission control systems are essential. Several cutting-edge control technologies were combined in the same Japanese plant to make sure that any leftover pollutants were efficiently controlled. Fine particulate matter was collected using high-efficiency particulate air (HEPA) filters, and other trace pollutants and volatile organic compounds were absorbed by activated carbon scrubbers. Additionally, catalytic converters were built to aid in the oxidation of any leftover organic gases into less toxic forms. Toxic byproduct generation can also be decreased by optimizing pyrolysis parameters such as temperature and residence time. The likelihood of dioxin and furan production can be reduced by promoting a more thorough breakdown of hazardous components by higher temperatures and longer residence durations. Effective waste feedstock management practices are also necessary to prevent impurities from entering the process, as these may facilitate the formation of hazardous substances [112].

A part from these technological approaches, continuous investigation and advancement are essential for enhancing pyrolysis technologies and discovering novel approaches to mitigate their effects on the environment and human health. The potential environmental and health issues connected with the pyrolysis of medical plastic waste can be handled opening the door for safer and more sustainable waste management procedures by addressing these concerns through effective mitigation strategies and ongoing development. Chlorine is typically sourced from organic forms such as PVC or inorganic forms like physiological saline found in medical wastes. During the pyrolysis of medical wastes, chlorine participates in chemical reactions and generates HCl which is a hazardous gaseous pollutant known for its corrosiveness and harmful effects including the potential to contribute to acid rain. Consequently, the removal or fixation of HCl or Cl is a critical research area. One prominent approach to mitigate HCl is the addition of alkaline additives such as Ca(OH)2, ZnO, CaO, and Fe_2O_3 during pyrolysis [113,114]. A study conducted on the pyrolysis of mixed plastics in a fluidized reactor observed the release of chlorine. With the inclusion of $Ca(OH)_2$, the majority of chlorine was found to exist as calcium chloride in the resulting oil [113]. Researchers have made efforts to explore the connection between experimental conditions and the release of HCl. In a study conducted by Dudkina et al. (2019) on the pyrolysis of medical wastes containing chlorine at a varying temperature range of (40–920 °C), it was found that the majority of HCl emissions (88.5 wt%) occurred at temperatures up to 350 °C, while the rest of the emissions were released when the temperature exceeded 350 °C up to 920 °C [115]. In the pyrolysis of PVC or chlorinated waste, studies utilized various catalysts or catalytic adsorbents including solid catalysts such as zeolites, FCC, mesoporous silica, $Al(OH)_3$, MoO_3, Al-Zn composites, and catalysts based on Ni, Ca, and iron oxides. These catalysts were shown to effectively reduce the chlorine content in the liquid products generated during pyrolysis [116]. The previous findings indicated that the catalysts hindered the production of HCl. Notably, silicalite significantly reduced the HCl content to 1.4 wt% [113]. Additionally, molecular sieve zeolite 13X demonstrated a chloride reduction of up to 3 wt% in an aromatic hydrocarbon mixture [117]. Despite efforts to add additives or modify operational conditions effectively inhibiting the formation of toxic gases such as PAHs, HCl, NOx, and SO_2 in compliance with regulations remained challenging. Therefore, it became essential to incorporate a gas cleaning system at the end of the pyrolysis equipment. This system would effectively eliminate these hazardous gaseous pollutants, ensuring environmental protection and safeguarding human health [113].

4. Mechanism

Organic polymers such as PET, nylons, polyesters, polycarbonates (PC), and polyamides that are formed by condensation reaction can be easily broken down into their monomers through reversible reactions like hydrolysis, alcoholysis, and glycolysis. Polymers like PP, LDPE, HDPE, PS, and PVC which grow in chains require thermal hydrocracking and catalytic cracking to break them into smaller fragments through formation of free radical fragments, as they cannot be directly reverted to their monomers. The different categories of the plastic pyrolysis

mechanism includes random-chain scission, end-chain scission, chain stripping, and cross-linking [100].

4.1. Non-catalytic mechanism

Synergistic effects between biomass and plastics were reported during co-pyrolysis (CP) resulting in increased hydrocarbon yield and reduced char formation. This synergy is a consequence of the interaction between the two feedstocks during pyrolysis. Oxygenates from biomass facilitate hydrogen abstraction from the polymer, leading to the cleavage of C-C bonds. Simultaneously, hydrogen transfer from the polyolefin to biomass-derived oxygenates minimizes char formation. Biomass degradation precedes polymer degradation, initiating depolymerization through forming radicals [17,118]. The pyrolysis of biomass is well-known to follow a radical mechanism involving initiation, propagation, and termination. However, when biomass and plastic are co-pyrolyzed, the process becomes more complex due to the generation of multiple chemical species. The reaction steps during co-pyrolysis include various stages. First, there is initiation, where an active radical is introduced. Then, secondary radicals evolve through a series of transformations including depolymerization, hydrogen transfer reactions (both desirable and undesirable), the creation of monomers, intermolecular hydrogen transfer leading to the formation of dienes and paraffin, and isomerization through vinyl groups. Finally, the process is terminated through either recombination of radicals or disproportionation. These steps contribute to the complexity and diversity of chemical species formed during the co-pyrolysis of biomass and plastic distinguishing it from the pyrolysis of biomass alone. For instance, the co-pyrolysis of wood biomass and polyolefin (PE or PP) involved a sequential reaction mechanism. It started with the thermal degradation of biomass which occurred at temperatures below 400 °C, preceding the degradation of polyolefins. At 400 °C, the solid char residues from biomass degradation acted as radical donors initiating the polymer chain scission of polyolefins. Simultaneously, polyolefins served as hydrogen donors to biomass particles. Consequently, the co-pyrolysis yielded two distinct sets of products: char, water, and pyrolysis gas derived from biomass, and oil and pyrolysis gas produced from polyolefins [119].

4.2. Catalytic mechanism

Catalytic co-pyrolysis (CCP) has received significant attention due to its ability to enhance the production of aromatic compounds and improve selectivity distinguishing it from non-catalytic pyrolysis as shown in Fig. 3 [93]. It offered advantages due to two main factors (i) the interaction between biomass and polymers during thermal degradation and (ii) the interaction of produced volatiles at the catalyst's active sites. The specific mechanisms employed differ based on the introduced feedstock type and catalyst applied [80]. In the catalytic pyrolysis process, both thermal cracking and catalytic cracking take place simultaneously following multiple reaction pathways [93]. According to reported study, it was demonstrated that furan and furfural, which were released from the degradation of both cellulose and hemicellulose in biomass could undergo Diels-Alder reactions with unsaturated hydrocarbons from PP and PE. This chemical reaction led to the formation of aromatic compounds with the aid of dehydration reactions occurring simultaneously [80,120,121]. While the Diels-Alder reaction can be a viable mechanism for cellulose and hemicellulose which is not well-suited for lignin. This is because the main products of lignin's thermal decomposition are phenolic monomers and oligomers which do not readily participate in Diels-Alder reactions [118]. In the case of polystyrene, the major active intermediate from its degradation is styrene, instead of the olefins found in PP and PE. Through successive alkylation with allene derived from furans, the styrene intermediate forms indene. The reaction between allene and indene further generated naphthalene resulting in an increased yield of aromatic compounds [80]. In addition to the aromatic yield enhancement, catalytic co-pyrolysis was effective in limiting the coke production as well. The degradation of polyolefins released alkanes, alkenes, and alkynes that provided hydrogen for the oxygenates generated from cellulose to form water [80,84]. As a result, the production of coke was reduced providing a longer service life for the catalyst [93]. Metallic zeolites such as Ni/ZSM-5, Cu/ZSM-5, and Pt/ZSM-5 in the presence of hydrogen gas atmosphere have been reported to be effective during biomass pyrolysis in activating the hydrogen gas. Once the hydrogen gas was activated, the carbonaceous compounds were hydrogenated leading to a reduction in the coke formation [122]. Several techniques have been developed to enhance the quality of oil. These methods aim to reduce the molecular weight of heavy fractions, remove oxygen from oxygenated compounds,

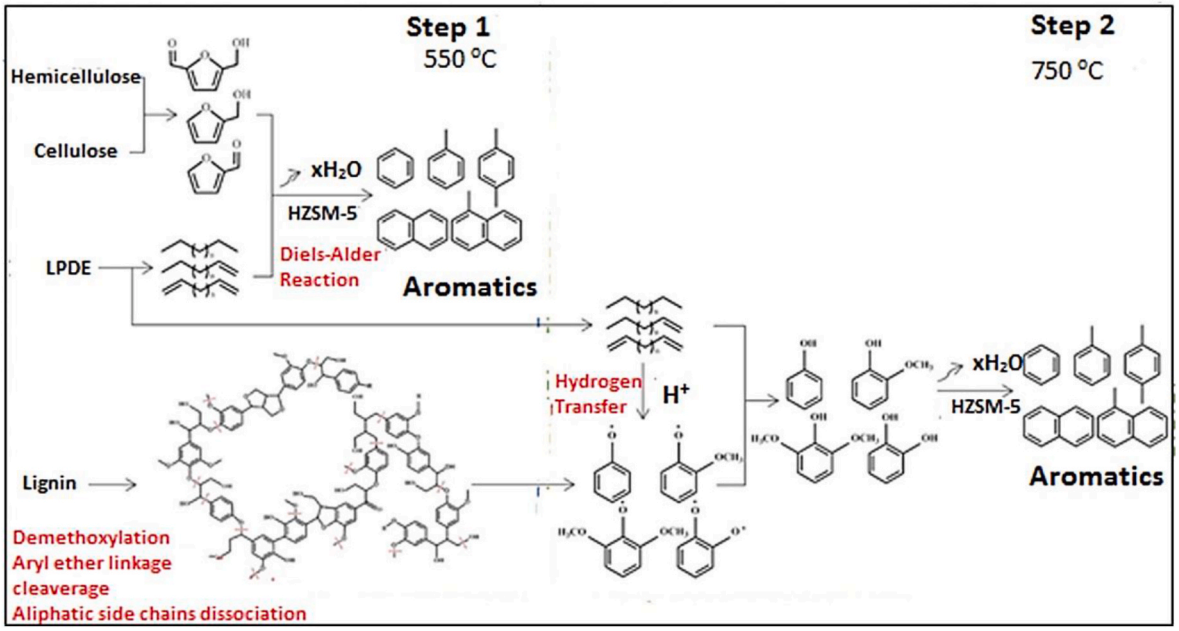

Fig. 3. Mechanism of plastic/biomass mixture pyrolysis for the production of oil fuel enriched with aromatic compounds [93].

and alter the chemical structure of undesirable products [123]. Removing the oxygen content is considered the most practical approach to enhance the quality of oil. Currently, two widely reported thermochemical methods for oxygen removal from oil are hydrodeoxygenation and catalytic cracking. Hydrodeoxygenation employs hydrogen to convert oxygenated compounds into water while catalytic cracking utilizes shape-selective catalysts to eliminate oxygen in the form of carbon oxides and water. Notably, catalytic cracking offers more advantages and appeal as it eliminates the need for hydrogen and can be integrated with pyrolysis at atmospheric pressure making it cost-effective and logistically favorable [84]. It is important to note that noble metal-supported catalysts were shown to effectively enhance hydrogenation and deoxygenation reactions in the oil upgrading process [124].

[122].

5. Feedstock composition

Feedstock composition is one of the most critical parameters which may determine the constituents of pyrolysis products. Therefore, it is important to study its composition based on elemental analysis [125], component analysis [126], and synergetic blending [127]. The effect of each element on the resulting products and characteristics such as heating value was discussed along with how the degree of blending plastics with biomass affected the synergism of pyrolysis products.

5.1. Elemental composition

Elemental analysis measures the effect of elemental constituents on the pyrolysis process which includes carbon, hydrogen, nitrogen, sulfur, and oxygen. Elemental analysis can be carried out commonly using CHNS analysis [127]. Every element plays a role in shaping the composition of pyrolysis products. Thus, each element will undergo analysis both individually and in combination with others based on the resulting pyrolysis composition. The key elements under discussion include carbon, hydrogen, nitrogen, sulfur, and oxygen. The pyrolysis product or fuel compositions are mainly affected by three elements; carbon, hydrogen, and oxygen [128]. If the hydrogen-to-carbon ratio (H/C) is determined, it has a direct effect on the energy efficiency and higher heating value (HHV) of the plastic composition [129]. When the H/C ratio increases, both energy efficiency and HHV increase accordingly, and vice versa [124]. The carbon content also influences the heating value of raw materials and pyrolysis products, implying that the carbon content can impact the HHV of the plastic raw material [124] and the HHV of its corresponding char product [125]. Moreover, a higher H/C ratio results in lower CO and CO2 emissions [130]. As for oxygen, an increase in the oxygen content may cause a decrease in the HHV of plastic feedstock [128,131]. Concerning the oxygen-to-carbon ratio, as the O/C ratio increases, there is an observed increase in the production of non-condensable gases (NCG) accompanied by a decrease in char yield [127,132]. Low oxygen content is also desired to reduce instability in oil product. Pyrolysis is known for being carried out in the absence of oxygen [133] Thus the presence of gaseous oxygen is purged out using inert nitrogen gas [134]. Recent studies indicated that the nitrogen content in the input raw material may lead to the release of a broader range of gases which decreased the overall thermal stability of the material [131]. Alongside the sulfur content, it would be preferable if the nitrogen and sulfur contents were relatively low to minimize the emissions of greenhouse gases (GHGs), especially NO_x and SO_x [132]. Such emissions have a negative impact on the environment contributing to climate change as well as posing several health risks and causing water pollution [133]. Table 3 provides insight into the relationship between elemental composition and pyrolysis products. Across all feedstocks listed in Table 3, the oxygen content has been maintained at a low level which does not directly illustrate the impact of the O/C ratio on plastics or medical plastics and their HHV [120,122,134]. However, this relationship was clearly demonstrated in other studies focusing on solid biomass with a significant oxygen content such as oak. In such cases, a higher O/C ratio resulted in a feedstock with lower HHV [122] confirming the correlation between the O/C ratio and HHV [124,125]. Across all feedstocks the nitrogen and sulfur have been kept low which favors the minimum release of NOx and SOx [135]. When comparing the three plastics—PE, PS, and PP—it becomes evident that PE and PP exhibit similar HHV which is relatively higher than that of PS [122]. This outcome can be attributed to the fact that both PP and PE possess higher H/C ratios compared to PS [122], thereby confirming the correlation between the H/C ratio and their HHV [124]. From Tables 3, it can also be determined that PS produced the highest oil content of 91.9 (wt.%) at 450 °C in fixed bed reactor [127]. Numerous plastic feedstocks stem from medical plastic waste (MPW), primarily comprising HDPE, PP, PC [136], and LDPE [121]. Research into the pyrolysis of medical plastic waste has seen a notable surge since the onset of COVID-19 [121,136] primarily due to the substantial increase in medical plastic waste emissions including mask filters, discarded masks, gloves, and other personal protective equipment (PPE) [121,134,136]. It can be noticed from Table 3 that the pyrolysis of medical plastic waste resulted in a lower oil yield and a higher pyrolysis gas yield. Several factors could contribute to this variation including the pyrolysis mode, temperature, and the composition of the medical plastic waste itself. Medical plastic waste is not solely composed of pure plastic; it also contains other materials such as rubber (e.g., gloves), biomass (e.g., cotton swab sticks, absorbent cotton, and toilet paper), proteins, synthetic fibers (e.g., dress core), in addition to conventional plastic components like LDPE gloves, PP syringes, PVC infusion tubes, and others [135]. These diverse materials within medical plastic waste can influence the pyrolysis process and its outcomes.

5.2. Synergistic blend

While pyrolysis of neat plastics and medical waste may offer a

Table 3
Elemental composition and HHV of different plastics, medical plastic waste feedstocks, and composition of pyrolysis product.

Feedstock	HHV (kcal/kg)	Operating Conditions	C (wt.%)	H (wt.%)	O (wt.%)	N (wt.%)	S (wt.%)	Oil (wt.%)	Pyrolysis Gas (wt.%)	Char (wt.%)	Reference
Mixed plastic	N/A	Fixed bed reactor 500 °C 17 °C/min 60 min	73.31 ± 1.60	10.07 ± 0.49	16.07 ± 1.8	0.55 ± 0.14	0.0	65.9	13.7	13.2	[125]
PE	44.2	Fixed bed reactor	85.6	14.3	0.1	0.0	0.0	85	12	3	[127]
PS	40.5	450 °C	91.9	8.0	0.1	0.0	0.0	92	7	1	
PP	43.8		85.4	14.5	0.1	0.0	0.0	81	17	2	
Mask filter	N/A	650 °C 20 °C/ms 30 s	84.35	14.49	0.73	0.26	0.17	47.2	48.32	4.5	[136]
Medical waste	26.6	Fixed bed reactor 500 °C	59.8	8.17	26.7	2.14	5.44	50	38	12	[137]

Table 4
Product yield compositions of selected synergistic feedstock blends between several plastics and biomass ratios.

Feed	Ratio	Parameters	Oil %	Char %	Pyrolysis Gas %	Ref.
Pine + HDPE	0:100	500 °C, Fixed bed reactor, 25 °C/min	30.5	0.50	69.0	[138]
	100:0		26.3	22.8	50.9	
	50:50		22.8	12.6	64.6	
	25:75		23.0	7.3	69.7	
	75:25		26.2	17.7	56.1	
LDPE	–	540 °C	82.6	2.0	15.4	[139]
PP	–	540 °C	75.3	3.1	21.6	
Empty Fruit Bunch	–	390 °C	44.0	27.2	28.8	
Oil Palm Frond	–	390 °C	40.0	28.1	31.9	
Empty Fruit Bunch + LDPE	1:1	520 °C, Fixed bed reactor, 10 °C/min, 45 min	67.1	14.5	18.4	
Oil Palm Frond + LDPE	1:1	510 °C, Fixed bed reactor, 10 °C/min, 45 min	65.0	15.1	19.1	
Empty Fruit Bunch + PP	1:1	540 °C, Fixed bed reactor, 10 °C/min, 45 min	59.8	14.3	25.9	
Oil Palm Frond + PP	1:1		54.7	14.1	31.2	
Potato Peel + PP	0:1	430 °C–450 °C	89	–	–	[140]
	40:60		58	15	27	
Rice Straw + Polythene	0:1	450 °C–500 °C, Fixed bed reactor, 60 min	80	–	21.5	[141]
	75:25		40.2	26.78	35.71	
	50:50		60.7	18.64	21	
Wheat Straw	–	600 °C, Microwave oven, 61.2 °C/min	40.3	16.5	43.2	[142]
Rice Straw	–	600 °C, Microwave oven, 66.8 °C/min	365	21.5	42	
PP	–	600 °C, Microwave oven, 58.3 °C/min	60.4	1.5	38.1	
PS	1:1	600 °C, Microwave oven, 61.9 °C/min	84.1	0.1	15.8	
Wheat Straw + PP	1:1	600 °C, Microwave oven, 59.9 °C/min	47.5	8.8	43.7	
Wheat Straw + PS	1:1	600 °C, Microwave oven, 61.1 °C/min	58.4	7.5	34.1	
Rice Straw + PP	1:1	600 °C, Microwave oven, 63.8 °C/min	46.1	11.3	42.6	
Rice Straw + PS	1:1	600 °C, Microwave oven, 64.9 °C/min	56.3	12.3	31.4	
Pine Cone	–	500 °C, Semi-batch glass reactor, 10 °C/min	47.5	36.6	15.9	[143]
PE	–		68.2	16.8	15	
PP	–		72.6	14.7	12.7	
PS	–		85.2	13.8	1.0	
Pine Cone + PE	1:1		63.9	19.6	16.5	
Pine Cone + PP	1:1		64.1	19.1	16.8	
Pine Cone + PS	1:1		69.7	21.5	8.8	
Pine Cone + PE + PP + PS	3:4:2:1		76	12.7	11.3	
Cellulose + Pine Cone + PE + PP + PS	3:4:2:1		68.9	9.6	21.5	
Waste Motor Oil + Surgical Masks + Woody Biomass Ashes	4:1:1	400 °C, Batch reactor, 2 °C/min	89.535	1.481	8.984	[144]
Waste Motor Oil + Surgical Masks	4:1		89.574	1.378	8.395	
Waste Motor Oil + Surgical Masks + Woody Biomass	4:1:1		77.603	6.315	11.018	
Waste Motor Oil + Woody Biomass	4:1		71.950	9.284	12.965	
Palm Kernel Shell	–	550 °C	36	32	32	[145]
Palm Kernel Shell + Medical Protective Clothing	1:1		48	28	24	
Empty Fruit Bunch	1:1		39	19	42	
Empty Fruit Bunch + Medical Protective Clothing	1:1		31	34	35	
Palm Frond	–		33	28	39	
Palm Frond + Medical Protective Clothing	1:1		35	26	39	
Medical Protective Clothing	–		19	21	60	
Hospital Plastic Waste	–	Microwave, 700 W, 20 min–30 min	73.4	–	–	[146]
Hospital Plastic Waste + Palm Kernel Shell	1:1		78.2	–	–	
Hospital Plastic Waste + Waste Vegetable Oil	1:1		80.5	–	–	

substantial oil yield, it is essential to recognize scenarios or applications that necessitate significant char and pyrolysis gas production. In such cases, biomass or lignocellulose may serve as a superior feedstock as its substantial fixed carbon content can yield a higher char output [137]. Alternatively, there are situations where it is preferable to produce a blend of oil, pyrolysis gas, and char in a significant ratio. This can be achieved by harnessing the synergistic effects of blending biomass and plastic creating a feedstock blend for co-pyrolysis. The results and effects are listed in Table 4.

Neat plastic pyrolysis can yield a substantial amount of oil which often exceeds 80 wt% as listed in Table 4. It was found that low-density polyethylene (LDPE) pyrolysis produced 82.6 wt% oil, PS yielded 85.2 wt% oil, and PP achieved the highest yield at 89 wt% [139,140].

Table 5
Comparison between pyrolysis product yields from each type of feedstock.

	Plastic	Biomass	Blend
Oil yield	High	Moderate	Low
Pyrolysis gas yield	Low	Moderate	High
Char yield	Low	Moderate	High

However, adding biomass to plastic feedstock reduces the overall oil yield and increases the production of pyrolysis gas and char. This occurs because biomass generally contains a higher fixed carbon content than plastics, which contributes to increased char formation [147]. This effect is clear in Table 4 where adding pinecone to PS reduced the oil yield from 85.2 wt% to 69.7 wt% while increasing the char yield from 13.8 wt % to 21.5 wt% and pyrolysis gas yield from 1.0 wt% to 8.8 wt% [143]. Similarly, blending rice straw with PP resulted in a decrease in oil content from 60.4 wt% to 46.1 wt%, along with an increase in char yield from 0.1 wt% to 11.3 wt% and pyrolysis gas yield from 15.8 wt% to 42.6 wt% [142]. Blending biomass with plastic generated an overall synergistic effect with product yields varying based on the blend ratio. Increasing the biomass content in the feedstock typically enhanced char and pyrolysis gas yields while slightly reducing the oil yield achievable from neat plastic pyrolysis [147]. Table 5 provides a detailed overview of the benefits associated with each type of feedstock.

6. Catalyst

Catalysts can be divided into two categories: (i) homogeneous and

(ii)heterogeneous. Homogeneous catalysts such as NaOH, KOH, and AlCl3 exist in the same phase as the reactants and products typically in liquid solutions. Heterogeneous catalysts are primarily in solid form and added to mixtures of solid, liquid, or gaseous compounds. Heterogeneous catalysts such as acid solids and nanocrystalline zeolites are widely preferred because they can be easily separated from liquid pyrolysis products, allowing for reuse and regeneration. Another advantage is that they are non-corrosive and capable of enduring high temperatures up to 1300 °C unlike homogeneous catalysts [21,147]. Thus, catalysts play a vital role in the pyrolysis and co-pyrolysis of medical waste offering several benefits such as reducing char content, improving the quality of oil by increasing product selectivity, and enhancing process conditions. This includes lowering the required temperature or time through a reduction in the reaction activation energy resulting in overall efficiency improvement [68,90,147]. The selectivity of the liquid products can be manipulated through the specific surface area, redox properties, crystallinity, and acidity of the prepared catalyst. However, other properties such as chemical and thermal stability should be considered to guarantee an efficient operation [68]. It was reported that catalyst types used in the pyrolysis process were classified into zeolites, clays, and bimetallic catalysts [67]. Plastic pyrolysis processes showed a diverse array of catalysts with ZSM-5, zeolite, Y-zeolite, FCC, and MCM-41 being the most widely utilized [148]. Studies have recently shown interest in a wide range of catalysts derived from organic sources and industrial wastes including fly ash, steel slag, bentonite, silicate, silica-alumina, alumina, ceramic, activated char, and MVM-41 [21,93].

6.1. Types of catalyst

6.1.1. Zeolites

The catalytic reactions reported on solid acid catalysts during plastic waste pyrolysis include cracking, decarboxylation, oligomerization, cyclization, aromatization, isomerization, and Diels-Alder reactions [148]. The SiO_2/Al_2O_3 ratio significantly influenced the reactivity and effectiveness of zeolite catalysts which in turn affected the type and quality of the final pyrolysis yield. Pal S. et al. conducted experiments using HZSM-5 zeolite as the catalyst and varied the SiO2/Al2O3 ratios (30, 80, and 280) to investigate their influence. It was found that a SiO2/Al2O3 ratio of 30 yielded the highest acid strength, the largest BET surface area, and the average pore diameter. This higher acidity associated with the SiO2/Al2O3 ratio of 30 was effective in cracking the wax leading to a significant increase in the yield of light olefins (35.5 wt% – 58.0 wt%) and a considerable reduction in the heavy fraction (C12–C20) from 28.0 wt% to 5.3 wt% [21]. Typically, microporous zeolites of the β and Y types are commonly utilized to break the carbon-carbon bonds found in long-chain hydrocarbons. During the pyrolysis of municipal solid waste (MSW) using Y-zeolite, a notable decrease in the heavy oil fraction and a corresponding increase in the gasoline fraction were observed [149]. Research has demonstrated that hydrogen-exchanged Zeolite Second Mobil-5 (HZSM-5) exhibited promising catalyst properties, including shape selectivity, high Brønsted acidity, and a large surface area [84]. By applying the HZSM-5 catalyst to the pyrolysis process of individual plastic components (PE, PP, PS, & PET) and postconsumer mixed plastics, the impact of catalytic pyrolysis was examined in relation to thermal pyrolysis. The findings emphasized the crucial role of the catalyst in reducing the content of oil and wax, resulting in a significant decrease from 81 wt% - 97 wt% to 44 wt% −51 wt%. Moreover, this reduction in oil/wax content was accompanied by an increase in pyrolysis gas yield, highlighting the catalyst's significance in enhancing the overall pyrolysis process [21,147]. In addition, the utilization of highly acidic zeolites in the cracking process enhanced the production of light olefins and reduced the formation of heavy fractions [147]. This catalytic cracking yielded high-quality products within the range of motor engine fuels, minimizing the requirement for further upgrading [21]. Based on that manner, HZSM-5 with its unique microporous structure demonstrated remarkable efficiency in the production of monocyclic aromatics such as toluene and xylene through cyclization and hydrogen transfer reactions; however, it was also accompanied by coke formation that could accumulate in the small sized pores leading to decline in the catalyst life [74,90]. Consequently, the inclusion of mesopores within microporous zeolites was employed to enhance the rate of mass transfer and reduce the formation of coke [74]. Sivagami also found out that the oil yield generated from the pyrolysis of LDPE increased with the utilization of ZSM-5 catalyst at 500 °C, in which the oil yield reached 70 wt% [150]. Zeolite catalysts were also studied under the effect of loading transition metals. The results revealed that transition metals facilitated the aromatization reaction by acting as a metal Lewis acid that was responsible of the dehydrogenation process. This resulted in the formation of molecular hydrogen as a byproduct which was preferred as it didn't interfere with the catalyst activity resulting in a longer service life of the catalyst [74,90]. Another study also reported that metals such as $Fe^{2+/3+}$, Cu^{2+}, Ce^{2+}, Mg^{2+}, Ni^{2+}, Sn^{2+}, and Zn^{2+} could contribute to controlling the pore size when present in the range of 8 wt%–10 wt%, [79]. Large-scale experiments were conducted to investigate the catalytic co-pyrolysis of real municipal solid waste consisting of paper and plastic mixtures, using an electrically heated furnace in batch and continuous modes. The use of zeolite-based catalysts with alkali properties led to notable findings revealing a decrease in the content of oxygenated hydrocarbons [151]. The further effects of the catalysts are provided in Table 6.

6.1.2. Fluid catalytic cracking

Fluid catalytic cracking (FCC) catalysts are commonly referred to as silica-alumina catalysts where the binder consists of a non-zeolite matrix combined with zeolite crystals. The utilization of recycled catalysts from FCC units has proven to be a highly promising approach in the catalytic pyrolysis of plastic waste. This method offers greater profitability compared to alternative catalysts making it an attractive choice for a sustainable process. It must also be considered that the composition of the catalysts significantly affects the obtained fraction relying on the porous nature of the catalyst's surface and its acidity. Excessive acidity could lead to uncontrolled fractionation causing a decrease in the liquid fraction and an increase in gas production [158]. Fluid catalytic cracking spent catalyst was utilized in the co-pyrolysis process of lignocellulosic biomass and (PP – PS) plastic with a feedstock to catalyst ratio equal to 10:1 at 510 °C. The study focused on the importance of the FCC pyrolysis process in improving the oil quality by increasing the aromatic content in comparison to the thermal pyrolysis process [159]. A comparative study was conducted between commercial and spent FCC catalysts to assess their influence on the oil yield generated from PP pyrolysis. The study yielded promising results revealing an oil yield percentage of 77.6 wt% when using the spent catalyst at 450 °C. This result was relatively close to the yield percentage of the commercial FCC catalyst at 83.3 wt% [160]. Another study used a regenerated FCC catalyst with a surface area of 112.56 m^2/g (determined by BET analysis) to pyrolyze PP. The study findings supported the importance of FCC in lowering the degradation temperature which dropped from 467 °C to 443.5 °C as well as increasing the gaseous product by 20 wt% while promoting the formation of unsaturated aliphatic compounds [161].

6.1.3. Clay

The presence of micropores within the clay can function as a heat absorber enabling a longer period for reactants to absorb heat and engage in reactions that lead to polymer degradation. This is beneficial in limiting the wax content and at the same time, it would increase the oil content due to the clay surface acidity [79]. The subsequent clay catalysts exhibited optimal efficiency for distinct plastic varieties: bentonite/spent fluid cracking catalyst for HDPE; acid-restructured montmorillonite for medium-density polyethylene (MDPE); pure kaolin powder for LDPE; Ni/acid-washed bentonite clay for PP; pure kaolin for PS; and Fe-restructured natural clay for a blend of PE, PP, PS, PVC, and

Table 6
Effect of zeolite catalyst on pyrolysis product yields.

Type	Catalyst Properties	Feedstock	Conditions	Output	Ref.
USY zeolite	• $SiO2/Al_2O_3$ = 15:1 • BET surface area = 550 m^2/g	PE & PP	• 500 °C • plastic/catalyst ratio = 10:1 • Continuous pilot plant	• Dominant liquid hydrocarbon fractions: C5-C7 • Dominant gaseous hydrocarbon fractions: C3-C4 • Oil yield from PE and PP are 75 wt% and 80 wt%, while pyrolysis gas yield is 24 wt% and 19 wt%.	[152]
ZAP USY zeolite	• $SiO2/Al_2O_3$ = 13:1 • BET surface area = 540 m^2/g	HDPE, LDPE, PP, and PS	• 400 °C ± 30 °C • Plastic/catalyst ratio = 10:1 • Laboratory scale batch fixed bed reactor	• The catalytic pyrolysis was effective in increasing the amount of gaseous product for all plastic types except PS which was characterized by a dominant oil yield percentage of 81.5 %. • The catalyst was beneficial in lowering the activation energy through reducing the process reaction time. • Catalytic pyrolysis yields pyrolysis oil with a greater proportion of shorter chain molecules compared to that obtained from thermal pyrolysis	[153]
HZSM-5	• SiO_2/Al_2O_3 = 38:1 • BET surface area = 268 m^2/g	PS	• 500 °C • Heating rate of 30 °C/min. • Fixed bed reactor accompanied by a catalytic reactor.	• Oil yield accounted for 70 wt%, while pyrolysis gas yield accounted for almost 30 wt% with negligible char yield due to the absence of fixed carbon and ash content.	[84]
ZSM-5	• SiO_2/Al_2O_3 = 38:1 • BET surface area = 282 m^2/g	LDPE, HDPE, PP, PET, PS, and waste wood	• 500 °C • Heating rate of 10 °C/min. • Plastic/biomass/catalyst ratio = 1:1:4 • Fixed bed reactor accompanied by a catalytic reactor.	• For the co-pyrolysis of waste wood with LDPE, HDPE, PP, PET, and PS, the oil yields were 56.0 wt%, 53.1 wt%, 51.6 wt%, 37.9 wt%, and 66.3 wt%, respectively, while the pyrolysis gas yields were 36.6 wt%, 31.4 wt %, 35.9 wt%, 22.2 wt%, and 18.9 wt%."	[120]
Fe-ZSM-5	• BET surface area = 392 m^2/g	LDPE	• 450 °C • ZSM-5 catalyst with 1 wt % Fe loading. • Two stage reactors consisting of pyrolizer and condenser	• Comparing thermal to catalytic pyrolysis, the introduction of the catalyst resulted in converting up to 70 wt% of the aliphatic hydrocarbon into aromatic.	[154]
HZSM-5	• Si/Al = 36:1	HDPE, seaweeds	• Plastic/biomass/catalyst ratio = 1:1:2 • 550 °C • HDPE powder size below 500 μm • Fixed bed reactor	• Oxygenates, acids and nitrogen containing compounds were reduced in the oil content. • Reduction in reaction activation energy was achieved.	[155]
CaO/ HZSM-5	• SiO_2/Al_2O_3 = 50:1 • BET surface area = 425 m^2_{BET}/g	LDPE, xylan	• 600 °C • Plastic/biomass/catalyst ratio = 1:1:2 • CaO/HZSM-5 ratio = 1:2	• Hydrocarbon yield equals to 82.47 wt% with aromatic yield of 40 wt%.	[156]
$MgCl_2$/ HZSM-5	• Si/Al = 25:1	HDPE, pine sawdust	• 500 °C • Plastic/biomass • /HZSM-5 ratio = 1:1:2 • $MgCl_2$/biomass ratio = 1.08:1	• The hydrocarbon compounds exhibited a dominant aromatic yield, reaching a maximum of 88.4 wt% with a decrease in the phenol content. • Increase in the yield of gaseous products by more than 11 wt%. on account of a slight decrease in oil product through the introduction of $MgCl_2$.	[157]

PET [162]. Bentonite clay was utilized as a catalyst in the pelletized form to investigate its effect on the process efficiency and yield produced from the catalytic pyrolysis process of LDPE, HDPE, PP, and PS. It was found that pelletized bentonite clay was characterized by its high acidity that almost restricted the wax from being formed. In addition, the reactants' residence time and generated pressure drops throughout the process were reduced [147].

6.1.4. Carbon-rich materials

A previous study introduced catalysts based on blank activated carbon and activated carbon with charcoal granules separately into a batch reactor, operated at 240 °C under vacuum, to examine their impact on the pyrolysis process of a PE, PP, and PS mixture. The results highlighted the significance of the catalyst in increasing the oil yield which reached 82.43 wt% and 95.54 wt% using the activated carbon and activated carbon/charcoal, respectively. Meanwhile, the oil yield from the thermal pyrolysis process was only 66.86 wt% [100]. Activated carbon is also widely applied in the microwave pyrolysis reactor. In a study by Prathiba et al. an oil yield of 93 wt% was obtained when activated carbon was mixed with polystyrene waste at a ratio of 1:10 and fed to a 450 W microwave reactor. This yield was reported to be the maximum at a temperature of 330 °C with a residence time of 5.5 min [163].

6.1.5. Metallic catalyst

Due to the desirable properties of metallic catalysts such as superior catalytic activity, reasonable chemical stability, increased production of aromatic hydrocarbons, selectivity, and high turnover frequency, metal-supported catalysts are widely employed in the process of oil upgrading [124]. Lin et al. explored the catalytic pyrolysis of a composite material consisting of poplar wood and polypropylene (WPP) at 873 K, employing ZnO, CaO, Fe_2O_3, and MgO catalysts. The study highlighted the significant impact of metal oxides on the distribution of pyrolytic products. All catalysts resulted in a decrease in the yield of carboxylic acids while increasing the production of alkenes owing to their inherent basic nature. Zinc oxide (ZnO) contributed to elevated yield of ketones and phenols along with reduced carboxylic acids while exhibiting the highest levels of alkenes. Calcium oxide (CaO) effectively facilitated oxygen removal leading to a decrease in carboxylic acids and phenols while slightly enhancing the presence of cyclopentanones and alkenes. Ferric oxide (Fe_2O_3) prompted an increase in hydrocarbon products and a decrease in oxygenated compounds. Magnesium oxide (MgO) exhibited comparatively less oxygen removal but displayed stronger chain

scission activity significantly boosting alkene yields [164]. Examining the catalytic effect of calcium oxide (CaO) on converting Moringa oleifera biomass and COVID-19 waste specifically used face masks into valuable products through co-pyrolysis. It was found that the inclusion of CaO catalyst during the pyrolysis process at a temperature of 450 °C and a residence time of 15 min led to a reduction in oxygen, sulfur, and carboxylic acids in the oil. Furthermore, the catalytic activity of CaO enhanced the alcoholic content and oil yield resulting in a higher overall yield of 52 wt% compared to non-catalytic pyrolysis [165]. Bimetallic catalysts have gained widespread use in the conversion of plastic waste to fuel through pyrolysis. The integration of several types of materials in bimetallic catalysts offered several advantages including a larger surface area resulting from their smaller size, improved stability, and synergistic effects derived from the combination of two metals [79].

6.1.6. Molten salts

Molten salts provided a distinct advantage by offering a liquid medium that enhanced heat transfer thereby contributing to superior catalytic performance. Alkali earth metals were identified as the optimal choice for the cations in the molten salt composition [166,167]. Carbonates among anions have been shown to significantly enhance pyrolysis gas production. Research indicated that molten salts containing Li_2CO_3 and K_2CO_3 yielded a pyrolysis gas volume of 70.52 vol%, while a combination of Li_2CO_3, Na_2CO_3, and K_2CO_3 produced a pyrolysis gas volume of 75.43 vol%. The process was carried out at 850 °C [166]. Another study reported notable improvements when molten salt was utilized including a reduction in tar and carbon dioxide formation which was attributed to the high heating rate of 141 °C/s provided by the molten salt. In addition to the reduction in tar and carbon dioxide concentrations, an increase in pyrolysis gas concentration was also observed. Despite these promising results, the application of molten salt remains challenging due to its corrosive properties [167].

6.1.7. Hybrid catalyst

A reported study on the catalytic co-pyrolysis of agricultural residue and waste PP involved the preparation of six different hybrid catalysts using the impregnation method to assess their impact on the yield and composition of pyrolysis products (oil, pyrolysis gas, and biochar). The six different catalysts that were synthesized to be tested inside a two-stage fixed bed reactor were: NiFe/ZSM-5, NiCo/ZSM-5, NiCu/ZSM-5, NiFe/char, NiCo/char and NiCu/char. The results indicated that bimetallic char catalysts exhibited a significantly higher specific surface area (SBET) ranging from 831 m^2/g to 926 m^2/g compared to bimetallic zeolite catalysts which have a narrower range of 338–358 m^2/g. This disparity accounted for the superior catalytic activity observed in the char catalysts. Notably, NiCu/char demonstrated exceptional performance yielding the highest hydrocarbon content (80.47 wt%), including the highest proportion of aromatic hydrocarbons (58.88 wt%). Additionally, NiCu/char showcased its effectiveness in enhancing Fischer-Tropsch synthesis, thereby increasing the yield of oil. Such presence of a rich carbon source facilitated the formation of carbon nanotubes (CNTs) and hydrogen gas [73]. The molten salts also utilized in a hybrid system in which a study found that the combined use of carbonate molten salt and a Nickel-supported alumina catalyst (Ni/Al_2O_3) during cellulose pyrolysis at 700 °C resulted in a significant reduction of tar to just 1 wt% in the final product. This represented a fivefold decrease in tar compared to using molten salt alone. Moreover, the hybridization of molten salt and Ni/Al_2O_3 increased pyrolysis gas yield by 15 wt%. Despite these promising results, challenges remain particularly with the dispersion of the catalyst in the molten salt, and the high temperature and corrosiveness of the molten salt which can potentially damage the catalyst [167].

6.2. Active site

6.2.1. Acid catalysts

A small-scale pilot study was conducted to explore the catalytic pyrolysis of several types of plastic waste (PS, PE, PP, and PET), either individually or in different combinations using modified natural zeolite (NZ) catalysts. The NZ catalysts underwent modifications through thermal activation (TA-NZ) at 550 °C and acid activation (AA-NZ) using nitric acid to enhance their catalytic properties. The results showed that the catalytic pyrolysis of PS yielded a higher proportion of oil (70 wt% and 60 wt%) compared to PP (40 wt% and 54 wt%) and PE (40 wt% and 42 wt%) when utilizing TA-NZ and AA-NZ catalysts, respectively [148].

6.2.2. Base catalyst

Alkali and alkaline earth metals (AAEMs) including Ca, K, Mg, and Na are commonly present in the residual ash of biomass. These metals tend to be readily deposited on the acid sites of a catalyst leading to the swift deactivation of the acid catalyst. In contrast, catalysts that have base sites instead of acid sites exhibit greater resistance to deactivation caused by the deposition of AAEMs. Earlier studies have utilized base catalysts due to their reported capacity to facilitate the generation of CO_2, rather than CO and H_2O leading to reduced oxygen content and increased oil carbon efficiency [118]. According to previous studies, combining base catalysts with acid catalysts enhanced the yield of hydrocarbons. In particular, the mixture of CaO with HZSM-5 demonstrated effectiveness in reducing acids and promoting the production of monoaromatic hydrocarbons during the catalytic pyrolysis of hemicellulose and LDPE. The mechanism behind this involved the addition of CaO that facilitated the ketonization process in which the acids were converted into ketones while HZSM-5 subsequently converted these ketones into aromatic hydrocarbons via aromatization [168].

6.3. Nano catalyst

The drawbacks associated with conventional catalysts used in oil upgrading including rapid catalyst deactivation, catalyst clogging/sintering, and coke formation. These issues can be effectively mitigated through the application of nanotechnologies. They provide a promising avenue to develop highly efficient catalysts with enhanced durability, selectivity, and activity. By utilizing nano-catalysts, significant improvements in oil upgrading can be achieved even at lower loadings compared to conventional bulk catalysts [124]. This is due to the increased external surface area of the active sites that is beneficial in converting feedstock including the polymer's macromolecules into useful products [169]. It is demonstrated by David et al. that Zn/13X zeolite and Cr/13X zeolite nano-catalysts exhibited a remarkable conversion rate of over 97 wt % for oxygen-containing compounds to aliphatic and aromatic hydrocarbons in a combined process utilizing both in-situ and ex-situ biomass pyrolysis variants. During the in-situ pyrolysis process, the Cr/13X zeolite catalyst exhibited a preference for generating aliphatic hydrocarbons. In the ex-situ pyrolysis process, the Zn/13X zeolite catalyst demonstrated a preference for the production of aromatic hydrocarbons. Overall, the utilization of Zn/13X zeolite and Cr/13X zeolite nano-catalysts in a combined pyrolysis process proved to enhance the quality of oil [170]. A recent study investigated the catalytic pyrolysis of LDPE using a Si-rich Ni/ZSM-5 nanocatalyst in a dual-bed semi-batch reactor at atmospheric. The use of a high Ni contents (25 wt %) yielded the highest quantity of gasoline range hydrocarbons (61 wt %) demonstrating their suitability for industrial applications. Optimal operational conditions include a temperature of 525 °C, a catalyst to plastic ratio of 1:20, and a nitrogen flow rate of 2.5 ml/min. These conditions yielded the highest production of aromatic, olefin, and paraffin compounds within the C6 -C12 range of gasoline hydrocarbons [171].

7. Characterization techniques

Characterization techniques are mainly used to perform detailed analysis on a qualitative and quantitative aspect providing information such as chemical composition, and microstructure. They are also used to obtain other properties such as calorific value, viscosity, and heating value. Such techniques can be used to analyze the feedstock as well as the pyrolysis products in the form of solid char, liquid oil, and pyrolysis gas. These techniques can also be used to assess the pyrolysis process and predict reaction pathways which were discussed in further detail in this section.

7.1. Feedstock analysis

Medical plastic waste is commonly found in the solid phase. Therefore, the methods used to characterize such feedstock can vary based on the characteristics being identified. The functional groups of the feedstock can be characterized by using FT-IR [172–174] where FT-IR helps in polymer identification [173]. It can also be used in detecting the functional groups found in catalysts [174]. The feedstock's microstructure and morphology can be studied by using the scanning electron microscope (SEM) [172]. In another aspect, the elemental composition can be determined with the aid of an elemental analyzer or CHNS analyzer which gives a detailed breakdown of the elemental content of carbon, hydrogen, nitrogen sulfur, and oxygen present in the feedstock [175,176]. Commonly, the oxygen content is mathematically calculated by obtaining the difference. The elemental analyzer can also detect the ash content in the feedstock if present [173,175].

7.2. Solid analysis

The analysis of the resulting solid char products from pyrolysis can be carried out using the same techniques that were used in feedstock analysis. For instance, FT-IR can be used to detect char's surface functional groups [177,178]. A scanning electron microscope can be coupled with an energy-dispersive spectrophotometer (EDS) where SEM provides the morphology of the char while EDS shows the elemental distribution within the solid sample [175]. Other methods, such as X-ray diffraction (XRD), can also be used to investigate crystallographic structure [179]. The elemental composition can be analyzed through X-ray fluorescence (XRF) [178,179]. In some cases, the resulting char produced was not even analyzed due to the fact that it was barely present [173]. Fig. 4 shows an example of a microscopic technique used to characterize the morphological microstructure of feedstock and

Fig. 4. SEM images of a-c. Red oak feedstock, d-f. Pretreated red oak feedstock, g-I. Solid char result from co-pyrolysis of red oak and polyvinyl chloride (PVC) ratio 1:1, j-l. solid char result from co-pyrolysis of red oak and PVC ratio 2:3 [172].

produced char [172]. Surface morphology analysis using SEM showed that co-conversion of red oak and PVC (1:1) at 280 °C altered the red oak's structure producing condensed, uniform microstructures compared to untreated red oak. The PVC-derived HCl catalyzed carbohydrate dissolution causing structural changes.

Solid char analysis can also be performed using X-ray photoelectron spectroscopy (XPS) and Raman. It was emphasized that pyrolysis is one promising technique for the disposal and use of waste tires (WT). However, after pyrolysis, a substantial amount of low-value waste tire chars (WTCs) remains and there are potentially many uses for these WTCs. The structural properties of WTCs at different pyrolysis temperatures would be better directed for their applications with a deeper understanding of the structural properties of WTCs at various pyrolysis temperatures. Pyrolysis tests of the WTCs by heating them at 400 °C, 600 °C, 800 °C, and 1000 °C were reported. The structural properties of WTCs were studied. It showed that the breakdown of defects with ordered configurations of the carbon skeleton structure, alkyl-aryl C-C bonds, and both large and small aromatic ring systems were favored at high temperatures. Pyrolysis would greatly increase the production of pores. Micropores formed at higher temperatures. Macropores and mesopores were broken down below 600 °C and then reformed. An increase in temperature was applied to accelerate the breakdown of pyrrolic nitrogen and sulfur bridges and enhanced the formation of oxidized nitrogen and sulfur bridges. At higher temperatures, an increase in the production of quaternary nitrogen was observed up to 600 °C and pyridinic nitrogen up to 800 °C [178].

7.3. Liquid analysis

The most common technique used to analyze the chemical composition of the oil pyrolysis product is gas chromatography coupled with mass spectroscopy (GC-MS) [178,180]. GC-MS can be equipped with a flame ionization detector (FID), where MS identifies the monomer constituents in the liquid oil while FID quantifies them [172]. The GC-MS analyses the chemical composition by classifying the chromatogram developed through the area normalization method [180], thus the chemical composition is presented in the form of peak percentages, where each peak area presents a certain compound [146], making GC-MS a suitable instrument for the analysis of volatiles. Fig. 5 shows an example of the area percentages of volatiles found in pyrolysis products of pineapple rind (PR) and LDPE at different ratios [180]. The quantitative yields of the compounds present can be then identified as listed in Table 7 [180] using an MS library which is the most common

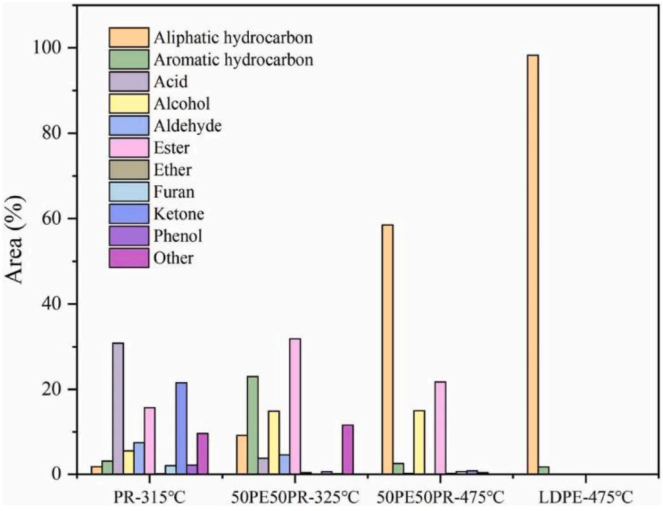

Fig. 5. The area% of each type of volatiles found in PR, LDPE, and their blends at different ratios [181].

Table 7
Yield of the chemical components of each feedstock.

Component (%)	100 PP-315	50PE50PR-325	50PE50PR-475	100PE475
Aliphatic hydrocarbon	1.81	9.2	58.56	98.3
Aromatic hydrocarbon	3.08	22.98	2.54	1.7
Acid	30.84	3.79	0.14	0
Alcohol	5.51	14.93	15.07	0
Aldehyde	7.47	4.57	0	0
Ester	15.75	31.85	21.76	0
Ether	0.12	0.33	0.15	0
Furan	2.05	0	0.61	0
Ketone	21.57	0.6	0.78	0
Phenol	2.17	0.1	0.38	0
Other	9.63	11.65	0.01	0

library used is the National Institute of Standards and Technology (NIST) library [174,178]. FT-IR can also be used to identify chemical compounds found in the oil product [175], where FTIR can also be coupled with GC-MS to get more accurate results [178,180]. Similar to solid elemental analysis, the elemental analysis of liquid oil can be achieved through the use of a CHNS elemental analyzer [175,176] where the ash content is also determined, and oxygen content is usually calculated by difference [175].

It was reported that some heavy liquid fractions may not be detected using such techniques, in which other techniques were used where Bio-oils were produced from pine wood chip and empty palm fruit bunch by using flash pyrolysis. They were examined using negative ion electrospray ionization. Fourier transform ion cyclotron resonance mass spectrometry (ESI(−)-FT-ICR MS) and comprehensive two dimensional gas chromatography with time of flight mass spectrometry (GC x GC-TOFMS) were used to give a complete and complementary characterization of the bio oils. ESI(−)-FT-ICR MS showed the presence of high oxygen content compounds. The *m/z* values of these compounds ranged from 150 to 700 giving that assignable peak percentages were more than 80 %. The constituting compounds were heteroatom classes from O_2 to O_{14}, C_6 to C_{27} and double bond equivalent [DBE] of 1–14. All assignable signals displayed extremely high mass accuracy and resolution (mean mass error less than 0.05 ppm). GC × GC-TOFMS was used to identify several low oxygen content classes (classes from O_0 through O_8 with carbon number range of C_3-C_{14}) not resolvable by ESI-FT-ICRMS, and to characterize the chemical composition of the bio-oils by the combined high dynamic range of *m/z* for ESI-FT-ICRMS and high chromatographic resolution for GC × GC-TOFMS (detecting volatile components) [181].

7.4. Gas analysis

When the oil and char yields are analytically determined, the pyrolysis gas yield can be determined indirectly by subtracting the combined oil and char yields from the total feedstock amount. This method assumed that any material not accounted for as oil or char was converted into pyrolysis gas [176]. Pyrolysis gas can be analyzed by using FT-IR [180], or by using GC-MS in which micro-GC was applied to determine the pyrolysis gas component distribution [177]. In recent studies, these two methods were coupled together to get more accurate results alongside thermogravimetric analysis (TGA) [178,180]. Consequently, TG- FT-IR with GC-Ms was used to detect the evolved gases [178]. It is an efficient method but cannot detect certain specific volatiles [180]. Therefore, TG- FT-IR with GC-MS was used to detect released gases and study pyrolysis behaviors [178,180]. Fig. 6 shows an example of how FT-IR was used to identify gases, where it displayed FTIR spectra of the produced gases alongside other volatiles from the pyrolysis of syringes (SY), medical bottles (MB), textile dyeing sludge (TDS), SY blend with TDS in ratio 1:9 (ST19) and MB blend with TDS in ratio 1:9 (MT19) [178].

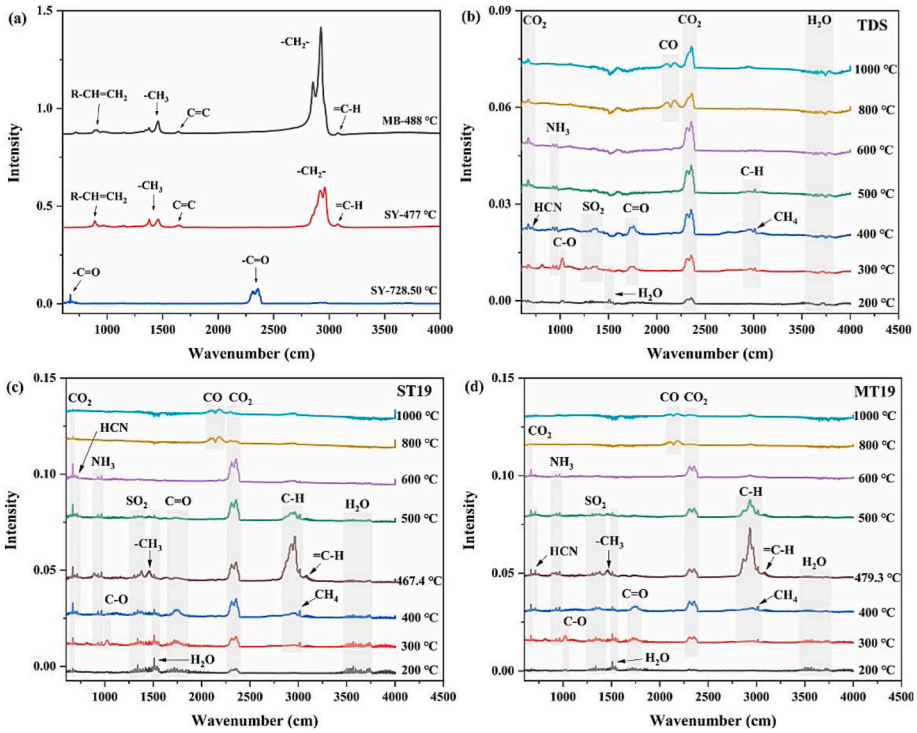

Fig. 6. FT-IR spectra of (a) SY and MB, (b) TDS, (c) ST19, and (d) MT19 at different temperatures [178].

In some cases, gases with traces such as N, S, and Cl can be difficult to detect using the mentioned techniques where characterization methods such as ion chromatography were reported. A polyvinyl chloride detection method was developed using ion chromatography in conjunction with a micro-sample pretreatment procedure. A glass capillary was sealed and 10 μL of deionized water was held on it while the sample of polyvinyl chloride was put inside it. To act as a micro pyrolysis reactor, the sealed glass capillary was placed in an oven at 300 °C for 2 min. Quick pyrolysis of polyvinyl chloride occurred at this temperature with the release of hydrogen chloride readily absorbed by deionized water. The liquid was then transferred to a volumetric flask and brought to 10 mL of absorption liquid. The number of chloride ions

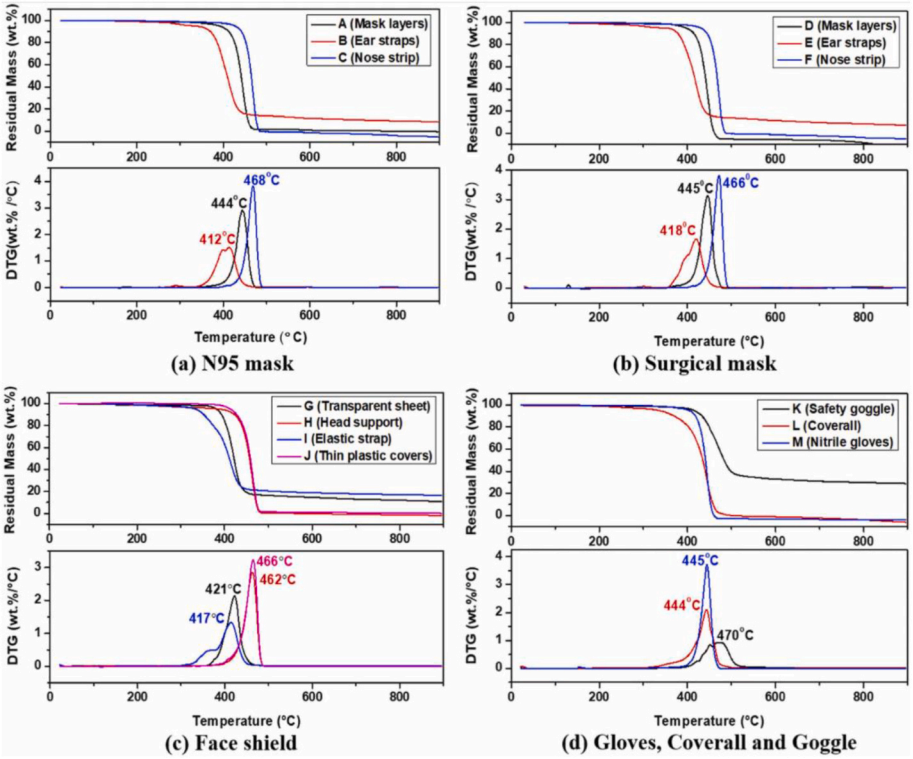

Figure 7. TG and DTG curves for mass loss during COVID-19 PPE kit [173].

in the diluted absorption liquid was measured by ion chromatography to quantify polyvinyl chloride in samples. A good linear correlation coefficient (r = 0.9999) was found for 0.02 mg–2.00 mg of polyvinyl chloride. This experiment achieved appropriate precision with a relative standard deviation of less than 16.4 % and acceptable recoveries between 86.0 % and 119.4 %. The limits of quantification and detection were 0.012 mg and 0.004 mg for polyvinyl chloride. Results from calculating the polyvinyl chloride content of actual samples using the micro-sample pretreatment methodology compared with the oxygen flask combustion method that was cited. The proposed method for the qualitative estimation of polyvinyl chloride in real samples was proved to be simple, fast, and correct [180]. FTIR can also be used to detect polluting gases where a reported study showed methods of Py–GC/MS and TG–FTIR were used to study kinetics, evolved gas analysis and pyrolysis features of chrome-tanned sludge. Kinetic parameters were calculated using Friedman, Flynn-Wall-Ozawa (FWO), and Kissinger-Akahira-Sunose (KAS) techniques in kinetic analysis. Residue sampling of the chrome browned sludge which contained 41 400 mg/kg S and 7600 mg/kg Cr as CrOOH. The activation energy was measured using the Friedman technique increased from 139.83 kJ/mol to 590.72 kJ/mol as the temperature increased from 50 °C to 500 °C, compared to lignocellulosic biomass and sewage sludge. The majority of the pyrolysis gases as determined by the TG–FTIR measurements were organics with alkane groups with an optimum component at about 500 °C. From the Py–GC/MS data, the diesel range organics (C10 – C28) made about 65 wt % of the evolved gases and comprised 20 wt% – 31 wt% of the evolved gases from C16 and C18, consisting mainly of palmitic, stearic and oleic acids. The evolved gases contained high concentrations of sulfur and nitrogen compounds, mainly elemental sulfur (S6, S8) and nitriles. Kinetics and evolved gas determination provided a deeper comprehension of brown sludge pyrolysis and references for pyrolysis reactor design and scale-up [182–184]. Fig. 7 shows the results of TGA representing the thermogravimetric (TG) and differential thermogravimetric (DTG) curves for the pyrolysis process of N95 masks, surgical masks, face shields, gloves, coveralls, and goggles, which represent all types of typical medical waste that were intensively disposed of during the COVID-19 pandemic [173].

The TGA provides graphical curves of two variants; The TG curves which represent the residual mass remaining over temperature, and the DTG curves which present the breakdown temperatures that achieved maximum weight loss in the form of peaks. The curves in Fig. 7 were derived from a recent research study [173]. The mask layers showed that maximum loss in weight percentage (wt. %) was achieved around 445 °C. The components B, E, G, and I have shown similar TGA profiles since they were all commonly made from polyester. The TG curves of these four components indicated residual mass ranging from 11 wt% to 18 wt% [173]. The components A, D, and L showed little to no residual mass (0.1 wt%) which reflected the presence of highly volatile matter with insignificant amounts of fixed carbon [173]. The component K, which represented goggles resulted in the highest yield of char (29 wt%) reflecting the high fixed carbon content [173]. The TGA showed that the decomposition of biomedical waste occurred in a distinct temperature region [173].

7.5. Higher heating value

The higher heating value (HHV) can be considered the main indicator for fuel quality [172]; thus it would be essential to analyze the pyrolysis product's higher heating value if it is to be utilized as fuel or compared with other forms of energy. The higher heating value can be either tested using certain equipment or calculated through equations and formulas. The higher heating value of solids and char are commonly estimated using Dulong's formula [172], or the use of empirical equations [173]. The higher heating value of oil products can be tested by various instruments such as the automatic calorimeter [175], or the oxygen bomb calorimeter [174,176]. It is possible to refer to a certain standard to determine the HHV such as the DIN 51900 standard [146].

8. Experimental analysis and simulation

Computer-assisted modeling and simulation approaches help develop appropriate designs and testing methodologies for increased efficiency. Modeling enables the determination of optimal operating parameters and the understanding of the routes involved in pyrolysis. Alongside the simulation models, data from experimental studies regarding the pyrolysis of medical wastes such as syringes and medical masks were presented in which the preprocessing methods, operating conditions, and product yields were analyzed.

8.1. Experimental analysis

The pyrolysis of sterilized medical masks, primarily composed of polypropylene (PP) was reported [183]. The masks, sourced from a hospital environment underwent a thorough sanitization process that included sterilization and drying under sunlight to ensure the removal of biological contaminants and residual moisture. After sterilization, non-PP components such as elastic bands and metal nose strips were removed to ensure feedstock purity. The sanitized masks were shredded to increase the surface area facilitating effective pyrolysis. The pyrolysis was performed in a batch-type reactor at 430 °C resulting in an oil yield of approximately 41.87 wt% ± 4.51 wt% [183]. Proximate analysis from another study exploring different medical masks revealed moisture contents of 0.1 wt% for surgical masks and 4.3 wt% for tissue masks, with volatile matter contents of 97.9 wt% and 87.8 wt% as listed in Table 8 [184,185]. This case study demonstrated the potential of converting medical PPE into valuable products and highlighted the greater efficiency of pyrolysis for synthetic materials like PP compared to natural fiber-based masks. Natural fiber masks with higher moisture and fixed carbon content yielded lower amounts of oil and more char and pyrolysis gas showing the advantages of synthetic materials for higher oil recovery and process efficiency [186].

Another study focused on the pyrolysis of syringes using a dual-stage pyrolysis-catalysis process [187]. The syringes were preprocessed by washing them with deionized water, drying at 105 °C, and pulverizing them to a 10–20 mesh size. Proximate analysis indicated a high volatile matter content of 98.3 wt% and minimal moisture of 0.11 wt% with an ash content of 1.86 wt% and no fixed carbon making the material well-suited for pyrolysis. The dual-stage process was conducted at 500 °C and employed metal-doped porous char catalysts to enhance the pyrolysis outcome. This process yielded significant amounts of liquid hydrocarbons and hydrogen-rich fuel gas. The Fe/C1 char catalyst achieved a 61.06 wt% yield of liquid hydrocarbons with over 78 wt% of these hydrocarbons falling within the jet fuel range. Additionally, the Zn-Fe/C1 catalyst produced over 37 vol% hydrogen while the Zn-Fe/C2 catalyst achieved the highest yield of liquid hydrocarbons at 62.76 wt% as listed in Table 8. These findings highlighted the effectiveness of catalytic pyrolysis in improving the yield and quality of recovered products from medical plastic waste [187].

8.2. Simulation process of plastics

Aspen Plus v10® [188] and Aspen HYSYS v10 [189] simulations were utilized for investigating the pyrolysis of plastics. High-density polyethylene (HDPE), Low-density polyethylene LDPE, PP, PS, PVC, and PET [190] were among the plastics employed in the simulation program's pyrolysis process. The process of plastic pyrolysis illustrated in Fig. 8 as a dryer was used to remove water and the feed was placed in a separator to remove moisture. The entire pyrolysis process was carried out in two reactors. The separator received a stream of ash and char as input. The stream of oil and pyrolysis gas was directed to a heat exchanger for cooling before being separated [186].

The simulation program using Aspen Plus, was reported that the

Table 8
Comparison of two pyrolysis case studies for Medical masks and syringes.

Material	Preprocessing	Pyrolysis Conditions	Oil Yield	Pyrolysis gas yield	Char Yield	Products	References
Medical Masks	Sterilization, drying, shredding	430 °C, Batch Reactor	41.87 wt% ± 4.51 wt%	–	–	High oil yield of gasoline range; efficient for PP	[185,186]
Syringes	Washing, drying, pulverizing	500 °C, Dual-Stage Pyrolysis-Catalysis	Liquid Hydrocarbons: 61.06 wt% (Fe/C1), 62.76 % wt. (Zn-Fe/C2)	H_2: 37 vol% (Zn-Fe/C1)	–	High yield of jet fuel range hydrocarbons, significant H_2 production	[187]

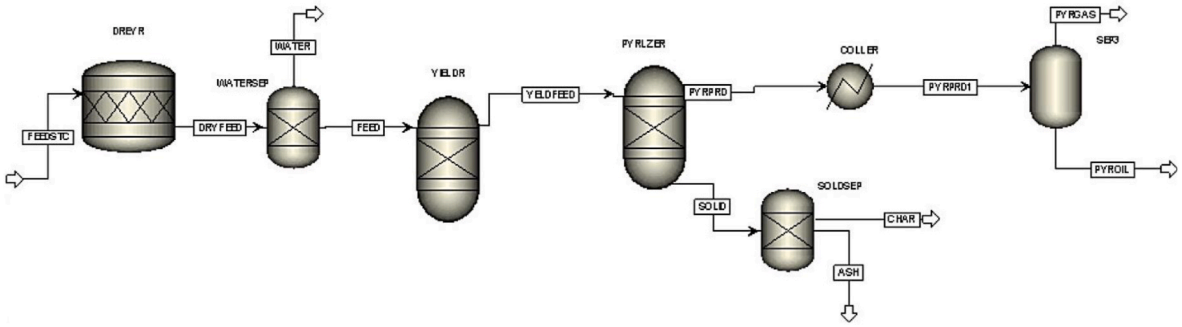

Figure 8. ProcesProcess flow sheet for pyrolysis process using (a) Aspen Plus® [186].

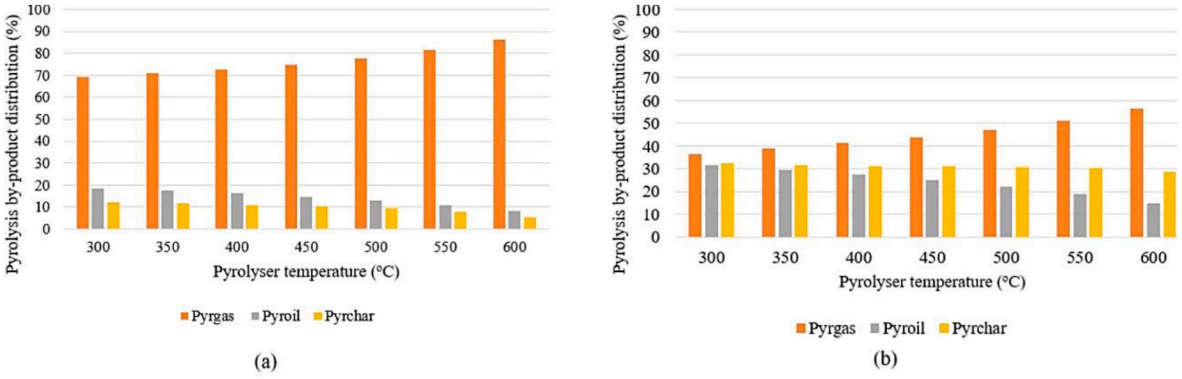

Fig. 9. Impact of temperature on pyrolysis products (a) LDPE and (b) HDPE [186].

following assumptions should be developed: (i) The Peng-Robinson physical property method was adopted; (ii) Carbon and Tar were considered a solid product [191]; (iii) All feedstock undergo conversion from non-conventional to conventional elements based on their proximate and ultimate analysis [183,184]; (iv) Model simulation utilized zero-dimensional blocks as the foundation for thermodynamic properties; (v) Process blocks were fully sealed from external influences, operating at atmospheric pressure with a reaction temperature matching the exit stream temperature; (vi) Ideal gas behavior was assumed for all gases [184]. In Aspen Hysys, assumptions included (i) utilization of the Peng-Robinson model for physical property calculations; (ii) Heavy fuel oil was designated as the heating fuel; (iii) Char resulting from pyrolysis comprises exclusively carbon; and (iv) The primary constituents of the fuel gas included ethylene, hydrogen, methane, ethane, propane,

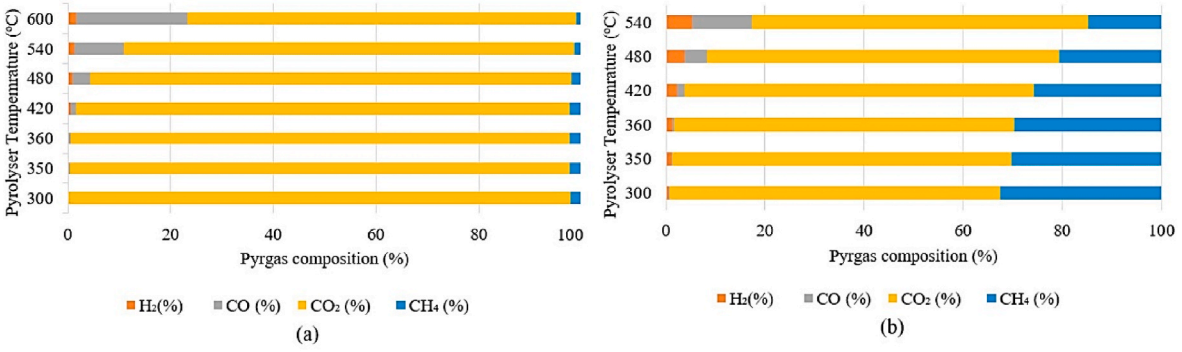

Fig. 10. Impact of temperature on pyrolysis gas composition (a) LDPE and (b) HDPE [186].

propene, and n-butane.; (v) Steady-state conditions were maintained with no accumulation in the process, char and oil levels dropped as the temperature rose. According to Fig. 9 (a) and (b), the generation of char increases from 44.49 wt% to 49.08 wt% for LDPE and from 47.81 wt% to 62.56 wt% for HDPE when the temperature increased from 300 to 600 °C. For LDPE feedstock, pyrolysis gas generation was higher at a lower temperature of 300 °C, about 43.12 wt%, and for HDPE, about 39.73 wt%. At a temperature of 300 °C, the maximal production of oil is 12.27 wt% for LDPE and 12.44 wt% for HDPE [186].

Hydrogen (H_2) was found in the pyrolysis gas product as indicated in Fig. 10 (a) and (b) at 480 °C in LDPE and at 350 °C in HDPE. The methane output was observed to decrease as the temperature increased.

8.3. Simulation process of plastics/biomass blend

Combining plastic with biomass provides a source of hydrocarbons, which significantly enhances H_2 and H^+ production during pyrolysis [185]. This integration of plastic into biomass feedstock enhanced the advantages of pyrolysis. The ultimate heating value of the resulting pyrolysis oil was influenced by the C:H ratio in the feedstock along with the quantity of oil produced and the efficiency of the pyrolysis process which collectively determined its quality and effectiveness. However, feedstocks rich in carbon and hydrogen typically yielded higher quantities of aromatic hydrocarbons while producing less char, though this outcome could be modified by employing specific catalysts [185]. An economical and practical waste management approach aimed at harnessing energy through the production of oil, pyrolysis gas, and char, with a specific focus on pyrolysis and co-pyrolysis of biomass and plastic. Various investigations were conducted on the thermal properties, heating values, and pyrolysis behavior of camel manure by Al-Rumaihi et al. [186]. Additionally, the production of pyrolysis gas, char, and oil from date palm (DP) waste was studied through pyrolysis. Fig. 11 (a, b, c, and d) shows that blends (S5) and (S6) with different feedstock ratios. In (S5), an equal blend of camel manure, date pits, LDPE, and HDPE yielded 62 wt% pyrchar and 43 wt% pyrgas at 600 °C, while pyroil decreased. In (S6), a 20 wt% LDPE, 30 wt% HDPE, and 50 wt% biomass mix showed increased pyrchar (44 wt% to 47.3 wt%) with temperature while pyroil decreased from 24.99 wt% to 13 wt%. While Kangash et al. [184] conducted pyrolysis of date pits to produce activated carbon. Aspen Plus software has been employed in numerous plastic and biomass pyrolysis studies. Moses [188] conducted HDPE pyrolysis in a semi-batch reactor to produce synthetic fuel comparing simulated results from Aspen HYSYS with experimental data. Gunukula and Tran [190] investigated the co-pyrolysis of wood chips and plastic to demonstrate the economic feasibility of small-scale plants for energy production and waste disposal. Chin et al. [191] co-pyrolyzed rubber seed oil and HDPE in a TGA, calculating activation energy and pre-exponential factor. The synergistic impact was identified as the primary factor driving co-pyrolysis of various feedstocks. Liew et al. [192] explored synergy between maize cob and HDPE with a catalyst, while Chai et al. [193] found that biomass-plastic co-pyrolysis generates more CO_2 at higher reforming temperatures. Another study examined seaweed and plastic waste co-pyrolysis using different LDPE blends. Economic feasibility studies suggested potential profits from pyrolysis factories over a 20-year period [194]. Distribution of pyrolysis products was analyzed under various feedstock mixing scenarios showing significant variations in product yields based on waste types, mixes, and temperatures. Notably, at 600 °C, a mixture comprising camel manure, date pits, LDPE, and HDPE yielded higher char and pyrolysis gas percentages, with CH_4 and CO_2 dominating pyrolysis gas composition at different temperatures. At 300 °C, the highest CH_4 generation was reported for specific feedstock mixtures.

Several scenarios with different mixing ratios were created and modeled to analyze the effect of temperature variation on the production of pyrolysis by-products and the composition of pyrolysis gas, as illustrated in Fig. 12. A mixture of LDPE: HDPE feedstock and camel manure: date pits at a ratio of 0.5:0.5 was examined, presenting results for each product over a temperature range of 300–600 °C. When LDPE and HDPE were mixed equally without biomass wastes (S7: 0.5:0.5:0:0), the yield of char was highest, followed by pyrolysis gas and oil. The

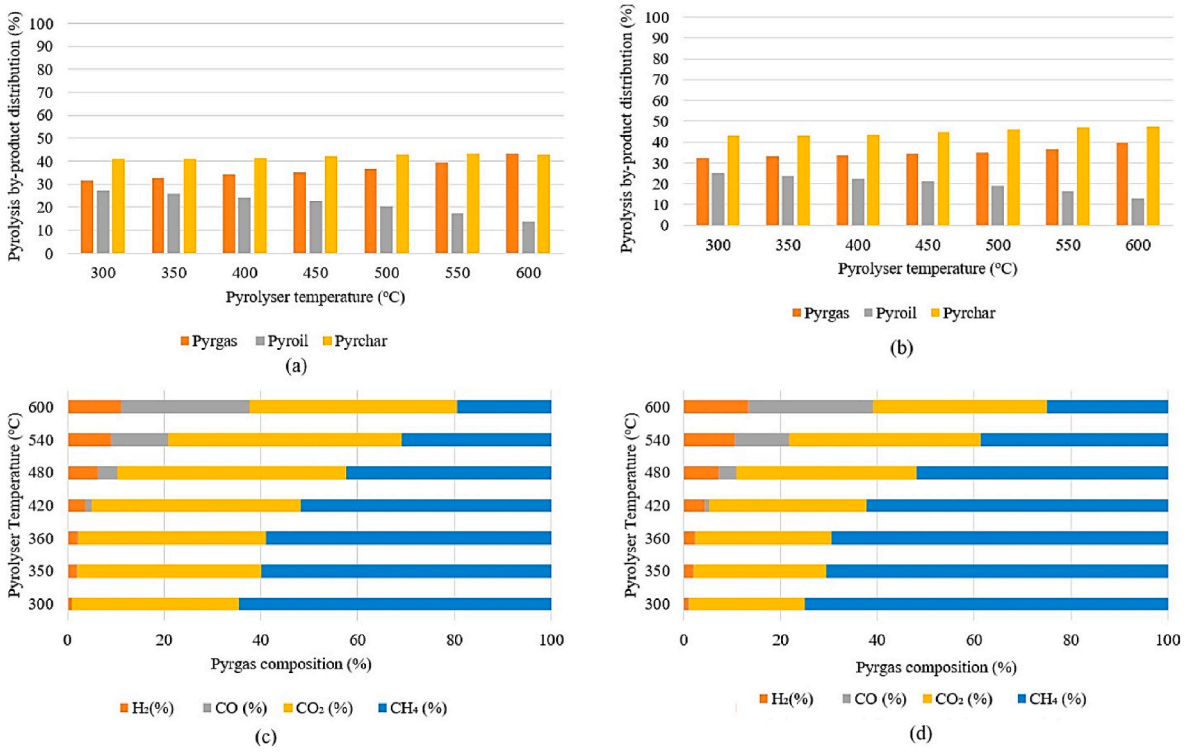

Fig. 11. Impact of temperature on blending scenario (a) on pyrolysis products S5 (b) on pyrolysis products S6 (c) on pyrolysis gas production S5 (d) on pyrolysis gas production S6 [186].

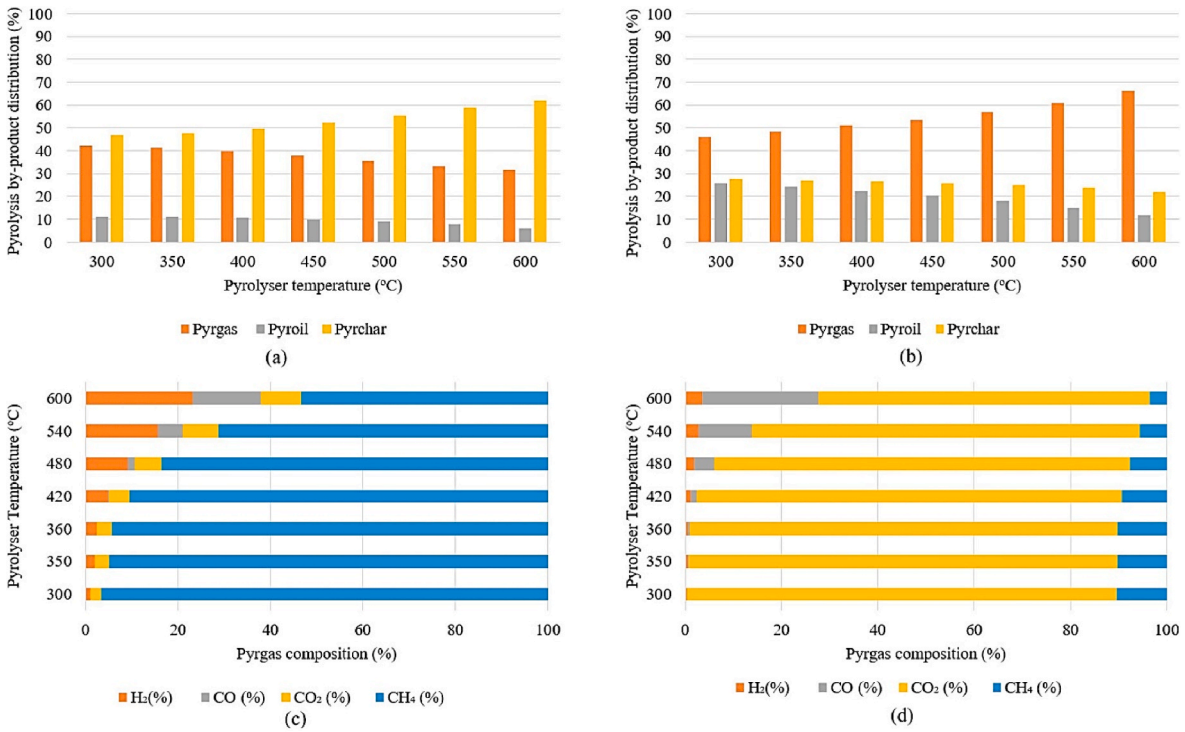

Fig. 12. Impact of temperature on pyrolysis by-products (a) S7 (b) S8 (c) S7 (d) S8 [186].

product profiling of mixed feedstock closely resembled that of individual evaluations, with char being the dominant product at a lower temperature of 300 °C (62.14 %) and pyrolysis gas predominating at the highest temperature of 600 °C (42.2 %). For a bio waste blend with a mixing ratio of 0.5:0.5:0:0 (S8), pyrolysis gas content surpasses char and oil, with pyrolysis gas reaching 66.43 % of total pyrolysis output at 600 °C, while oil production is notably lower due to reduced temperature. Among the mixing scenarios, the highest rates of char production are observed for 0.2CM: 0.2DP: 0.3LDPE: 0.3HDPE (S6) and 0CM: 0DP: 0.5LDPE: 0.5HDPE (S7) at 600 °C, with rates of 448.15 kg/h and 614.69 kg/h, respectively. Similarly, the maximum rates of pyrolysis gas production occur for mixing ratios of 0.25CM: 0.25DP: 0.25LDPE: 0.25HDPE (S5) and 0.5CM: 0.5DP: 0LDPE: 0HDPE (S8), with rates of 405.21 kg/h and 589.24 kg/h, respectively, at 600 °C.

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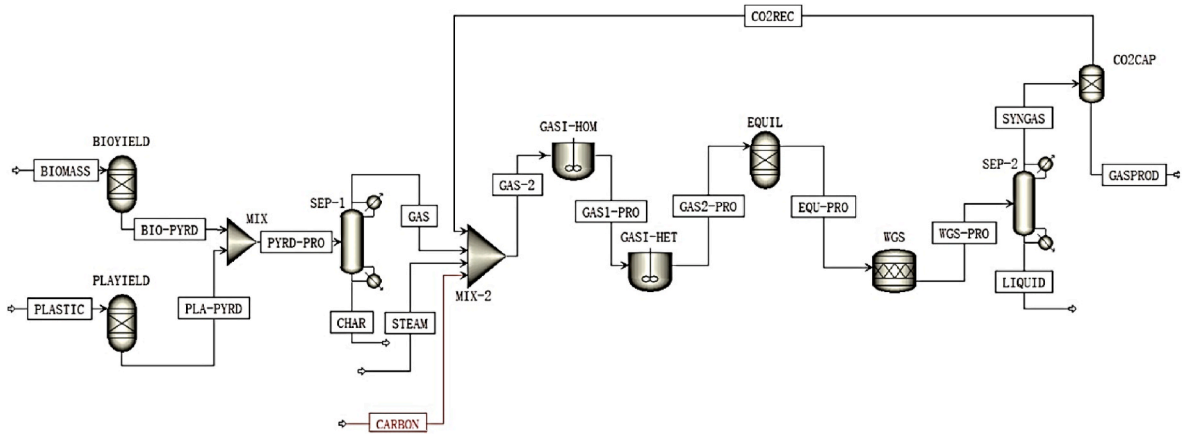

Fig. 13. Aspen Hysys flow diagram of the waste plastic power plant [188].

Table 9
Pyrolysis gas components from different plastics.

Plastic waste	Major gas components	Other Components	References
Polyethylene (PE)	Methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), and hydrogen (H_2)	Carbon monoxide (CO), carbon dioxide (CO_2), and higher hydrocarbons.	[186], [187]
Polypropylene (PP)	Methane (CH_4), propylene (C_3H_6), ethylene (C_2H_4), and hydrogen (H_2)	Carbon monoxide (CO), carbon dioxide (CO_2), and higher hydrocarbons.	
Polystyrene (PS)	Styrene, benzene, toluene, xylene.	Methane, hydrogen, carbon monoxide, and carbon dioxide.	
Polyvinyl Chloride (PVC)	Hydrogen chloride (HCl), ethylene, and acetylene.	Methane, hydrogen, carbon monoxide, and carbon dioxide.	
Polyethylene Terephthalate (PET)	Carbon monoxide (CO), carbon dioxide (CO_2), benzene, toluene, and xylene.	Methane, hydrogen, and other aromatic compounds.	
Polycarbonate (PC)	Phenol, benzene, toluene, and xylene.	Methane, hydrogen, carbon monoxide, and carbon dioxide.	

8.4. Integrated system

An integrated system designed for the co-pyrolysis of biomass and plastic is illustrated in Fig. 13 [188]. In this system, biomass and plastic streams were pretreated resulting in BIO-PYRD and PLA-PYRD which were then mixed and pyrolyzed to produce char and gas streams. The gas produced underwent further processing where condensable gases and trapped liquids were collected as the liquid stream. The remaining pyrolysis gas referred to as the pyrolysis gas stream, passed through a CO_2 capturing mechanism in the CO2CAP separator. The captured CO_2 was then recycled back into the mixer before entering the pyrolysis unit.

Table 10
Parameters affecting calorific value for different plastic waste in different reactor configurations.

Plastic waste	Reactor type	Calorific value (MJ/kg)	Key influencing parameters	References
Polyethylene (PE)	Fluidized bed	43.0	Temperature, Residence time, Particle size	[194]
Polystyrene (PS)	Batch	43.0	Heating rate, Final temperature, Particle size	[195]
Polypropylene (PP)	Rotary kiln	40.8	Rotation speed, Temperature, Residence time	[196]
Polyvinyl chloride (PVC)	Microwave	21.1	Microwave power, Irradiation time, Sample mass	[197,198]
Polyethylene terephthalate (PET)	Fixed bed	28.2	Temperature, Residence time, Catalyst presence	[195]
Mixed plastics (PE, PP and PS)	Fixed bed	42.57	Composition variability, Temperature, Particle size	[199]
High-density polyethylene (HDPE)	Fluidized bed	44.0–46.2	Like PE, but influenced by crystallinity	[200]
Low-density polyethylene (LDPE)	Rotary kiln	46.1–46.2	Like PE, but influenced by branching	[201]
Polycarbonate (PC)	Microwave	31.53	High energy content, potential for toxic byproducts	[198,202]
Polyurethane (PU)	Fixed bed	28.0	Complex composition, multiple degradation products	[203]

8.5. Product characteristics

The product's composition from the simulation has been analyzed thoroughly. While the Aspen HYSYS simulation results showed great prediction accuracy. The constituents of the gas product which included major components and other traces are provided in Table 9 where the gas components from PE, PP, PS, PVC, PET, and PC were reported from previous studies.

Another characteristic that refers to how effective pyrolysis products may act as an alternative fuel is the calorific value which indicates the amount of energy stored within the materials. In Table 10, the calorific value ranges for PE, PS, PP, PVC, PET, HDPE, LDPE, PC, and PU are listed in different reactor configurations, while the key influencing parameters were also analyzed to deduce the effect of parameters on the calorific value.

9. Valorization

In assessing the efficiency of plastic pyrolysis, it is essential to consider not just the volume of product generated, but also the characteristics defining its quality. Among these factors, carbon number plays a crucial role in indicating the number of carbon atoms within a molecule. Gaseous by-products of plastic pyrolysis typically exhibit low carbon numbers, spanning from C1 to C4 showcasing compounds like short-chain alkanes and alkenes. The term "plastic-derived oil" (PDO) encapsulates the liquid fraction obtained from pyrolysis including light oil (C5 to C11, akin to gasoline), heavy oil (C12 to C20, similar to diesel), and wax (>C20) as displayed in Fig. 14, which presents the fractionation process that produces various fractions from pyrolysis oil. However, it is important to note that carbon number alone may not fully elucidate unsaturation, as compounds with differing characteristics can share identical carbon numbers. Therefore, while carbon number data is insightful, a comprehensive understanding of oil products requires consideration of additional parameters such as aromatic/aliphatic content, physiochemical properties, and heating values.

By combining carbon number information with other details, critical insights into the oil products' characteristics can be obtained. For instance, aromatic/aliphatic content and physiochemical properties can provide additional information on the oil 's stability, reactivity, and chemical properties. Additionally, heating values can provide insights into the potential uses of the oil products as fuels or chemical feedstock. Carbon number is a vital aspect of product composition, but other characteristics should also be considered to gain a comprehensive understanding of the oil products' characteristics [204].

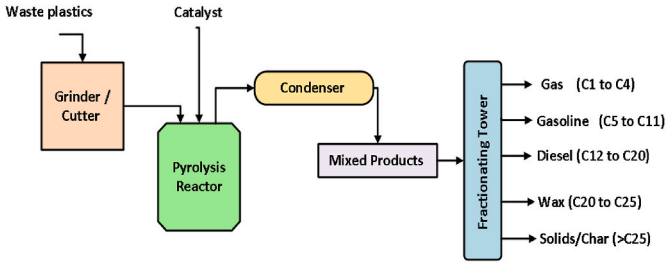

Fig. 14. Different product fractions according to the carbon number.

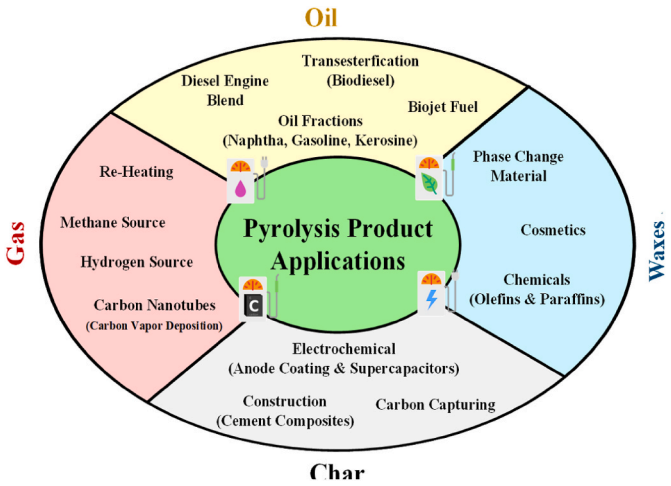

Fig. 15. Overview of the applications of pyrolysis products.

9.1. Gas

Pyrolysis gas often referred to as non-condensable oil is one of 3 main products that is derived from plastic-based feedstock as shown in Fig. 15. Operating parameters have the most adverse effect when it comes to product quality and type. Typically, pyrolysis gas is considered by many to be a by-product of the liquid form. However, it can be recovered for the purpose of reheating the pyrolysis reactor and utilizing the high calorific gaseous mixtures that can be anywhere from 13 to 15 MJ/m3 [205]. Studies have shown a correlation between the high heating rates during the pyrolysis process and the amount of pyrolysis gas yielded. Some of the gases produced are non-condensable due to being in the form of light gas fractions that mainly comprise short carbon chains. The longer the residence time at high temperatures, the higher the ratio of non-condensable gases to condensable ones is likely to become [206]. The short chain nature of the carbon chain makes the oil suitable for gas-fixed combustion equipment. A crucial factor that is related to all pyrolysis products but can be the most sensitive in gas production is energy quality. Energy quality refers to how easily the energy can be converted to useful work. In the case of pyrolysis gas, the sensitivity comes from the amount of carbon dioxide formed [207]. It is mostly relative to the carbon dioxide content in the mix of output pyrolysis gas; the higher the carbon dioxide content the less calorific value the pyrolysis gas has, but the methane number is increased which can later be utilized and extracted [208]. One of the gases produced via the pyrolysis reaction is hydrogen which gives the gaseous products some value. Studies have shown the hydrogen levels have been affected by introducing a catalyst. The catalyst in use was a ratio of NiO and Zeolite of 1:10. An additional benefit, besides the increase in hydrogen production, is that the presence of NiO aided in cyclizing and aromatizing the alkenes into various cyclo-alkenes and aromatics [209]. To mention a few of the various applications of pyrolysis gas; one application is related to co-pyrolysis where the water content available in the lignocellulosic feedstock is often a drawback that can lower the quality of oil produced. The maximum acceptable water content is 10 wt%; the gases produced can be re-used to dry the excess water from the new feedstock for more efficient next batch [210]. One other promising application is related to the nanotechnology sector. By utilizing the carbon in pyrolysis gas; the production of CNTs is possible by the process of chemical vapor deposition (CVD); the bottom-up synthesis doesn't only benefit from the carbon in the gas, but also the presence of hydrogen can catalyze the reaction. This occurs by maintaining the active and nucleation sites which helps in accelerating the rate of production of carbon nanoparticles that can be later synthesized into tubes [211,212].

9.2. Oil and waxes

The liquid form of the pyrolysis product is considered more sophisticated and in most feedstock cases have the highest yield [205]. That is due to the definition of a oil that includes a variety of different fractions. Carbon numbers from C5 to C19 are all considered in the liquid range. Those ranges are classified according to the distillation temperature; starting from the most volatile range of C5 to C7 (naphtha) that can be in liquid form in a temperature lower than 65 °C; the next most volatile range of C6 till C12 (gasoline) available at a temperature range of 65 °C-170 °C. One of the heavier liquids kerosene can be found in the carbon range of C10 to C14 at a distillation temperature range of 170 °C-250 °C; while the heaviest fractions; classified by some research to belong to the wax subcategory [213]. The pyrolysis diesel which lies in the range of C14 to C19 is distilled at temperatures higher than 250 °C. Liquid pyrolysis products have the highest demand due to their practicality; they often can be used interchangeably with conventional petroleum-based oils since their composition, chemical, and physical attributes are similar [205]. The similarity adds the option of using blends to convert high carbon-emitting applications into a semi-sustainable process [32]. Whether used in blends or independently, oils typically do not necessitate external modifications to existing technology, rendering them ideal candidates for fully replacing conventional fossil fuels [10]. While pure oil may induce knocking effects on diesel engines, the blending option remains viable until further research is conducted. Oils can be easily converted into different forms of higher-value products with very minimal effort. The chemical process of transesterification is often used to turn the plastic oil into diesel; providing several options for refining and upgrading the product [214]. One other form of fuel pyrolysis oil can be converted to jet fuel. The pyrolysis process helps in breaking down the long carbon chains into shorter radicals that can be then upgraded into liquid form to mimic the properties of conventional jet fuel [215]. As for waxes, their two main usages are as a raw material for various chemicals as well as cosmetic-based materials. Furthermore, waxes can be added for pavement construction with asphalt and various cement-based materials. Some studies showed great results in utilizing waxes that consist mainly of paraffin and olefin as a phase change material (PCM). The studies revealed high latent heat capture, which can be advantageous in thermal energy storage applications [216].

9.3. Char

Char is mainly the least desired product compared to the liquid and gas-based counterparts [217,218]. It is considered more relevant when the feedstock consists of organic based material due to it being richer in carbon content [219,220]. If the pyrolysis process aims to maximize the char or solid content, some adjustments to the parameters/operating conditions must take place. It is suggested to decrease the residence time accompanied by a low pyrolysis temperature to increase the char yield [221]. The most common application of char is for reheating purposes, aimed at reducing the energy costs required to attain the high temperatures necessary for the process. Char can be converted into briquettes and reused as a fuel source to reheat the reactor in use [222]. A more sophisticated approach to char valorization is to take advantage of the highly porous structure of its carbon base surface to be used as adsorbent material. This surface functionality also allows char to be used in applications electrochemical applications like as a coating material for anodes in an electrochemical cell and can also be utilized as supercapacitor material due to the high carbon content [223]. Furthermore, research proved the use of char hand in hand with cement-based composites showed an increase in mechanical properties while maintaining the same cost. Findings in Ref. [224] suggested that using char at the range of 0.5 wt% up to 40 wt% by weight in different cement-based composites allowed an increase in compressive strength up to 55 MPa [225], with a tensile strength increase up to 23 MPa. Carbon capturing

and sequestering also greatly benefit from char. The stable high carbon content with a large surface area-to-volume ratio provided by the micropores offers excellent carbon dioxide adsorption capacity (up to 5.0 mmol g^{-1}) at standard temperature and pressure [226].

10. Risk assessment

Pyrolysis Pyrolysis process requires heating the organic matter to high temperatures typically ranging from 400 °C to 800 °C. Throughout pyrolysis, there is the generation of gases that are both toxic and flammable. Inherent hazards associated with pyrolysis include the risks of fire, explosions, and accidental release of harmful gases and pollutants [227]. The most substantial dangers of fire, explosions, and toxic emissions occur during system startup, shutdown, or intermittent operation [228]. Comprehensive knowledge of the regulatory frameworks governing medical plastic waste management is essential for effectively implementing pyrolysis technologies. Key regulations from environmental and health agencies such as the Environmental Protection Agency (EPA) and the Centers for Disease Control and Prevention (CDC) significantly influence waste management practices by ensuring that pyrolysis processes do not pose risks to human health or the environment [229]. Hazardous waste including medical waste deemed harmful is disposed of by the Resource Conservation and Recovery Act (RCRA). Waste management procedures are required by RCRA to guarantee that it is handled, stored, and disposed of in a way that reduces risks to the environment and public health. This entails ensuring that emissions and byproducts are managed and that the procedure complies with strict environmental regulations in the case of pyrolysis technology. It is essential to follow specific requirements for waste feedstock quality, pyrolysis residual treatment, and emissions monitoring. Guidelines from the Centers for Disease Control and Prevention (CDC) for managing biohazardous medical waste are provided by the CDC with an emphasis on lowering the risk of infection and guaranteeing the security of waste management staff. The correct packaging, labeling, and waste segregation are stressed in these rules. In order to stop the spread of infectious diseases and guarantee the safe handling of potentially dangerous materials, the implementation of pyrolysis technologies must be in line with these guidelines [229]. The impact of these policies on pyrolysis technologies can be transcribed through operational parameters. Guidelines need to establish acceptable waste feedstock to prevent contamination, implement real-time emissions monitoring to control gases and particles, and specify high temperatures for the breakdown of hazardous compounds. Comprehensive operating procedures and safety measures, such as handling biohazardous items and using personal protective equipment (PPE) appropriately, should be covered in training and safety programs. Clear standards are required for the separation of infectious trash from other medical plastics prior to pyrolysis in waste segregation methods and laws. It is also advisable to promote investment in cutting-edge pyrolysis technology in order to maximize efficiency and minimize environmental effects [230]. The development of thorough guidelines by regulatory agencies for pyrolysis technologies is necessary. These guidelines should concentrate on defining operational standards, imposing stringent emission limits that are regularly tested, and creating thorough waste processing procedures. Expanding training and certification programs to cover advanced technical abilities for biohazard management and pyrolysis equipment operation and maintenance is necessary. It is essential to invest in grants and promote cooperation between industry, academic institutions, and regulators in order to support research and development. Campaigns for public awareness should inform stakeholders and communities about the advantages and security of pyrolysis. Furthermore, to guarantee adherence to new norms and standards, strengthening compliance and enforcement through frequent facility inspections and sanctions for non-compliance is crucial [113]. Medical waste involved in the pyrolysis process can also contain harmful bacteria and viruses leading to the spread of infectious diseases. During the rainy season, this waste can mix with solid waste and infiltrate groundwater resulting in water pollution. Microplastics from biomedical waste (BMW) can also contaminate soil and water posing threats to ecosystems and public health. Improper handling and disposal of medical waste carry significant risks that are difficult to manage once they occur. Various technologies, such as autoclaving, microwaving, and chemical treatments, are employed to disinfect viruses and bacteria in BMW [231]. When addressing risk assessment, several aspects, such as sterilization, safety protocols, management of pyrolysis emissions, and fire and explosion hazards, must be considered. Before undergoing pyrolysis, it is crucial to sterilize medical plastic waste to eliminate pathogens. Autoclaving, which involves using high-pressure steam at temperatures above 121 °C and pressures of 15 psi for over 45 min, is effective in destroying microorganisms and ensuring the waste is safe for further processing. Chemical sterilization with agents like chlorine dioxide or hydrogen peroxide is also effective when applied at specific concentrations and contact times. Microwave disinfection combines moisture and low heat, operating at 2450 MHz, to generate heat through molecular vibration and friction. This method has several advantages, including being energy efficient, minimizing heat loss, operating at low temperatures, being a considerably faster process, and leaving no toxic residues. All methods should be conducted according to established protocols to prevent residual hazards [231]. Sterilization alone is not sufficient to address the risks associated with handling biomedical waste (BMW); robust safety protocols for workers are also essential. Ensuring the safety of personnel handling medical plastic waste is crucial for the process to be effective and to prevent the spread of contaminants. Some countries, such as Ethiopia, Nigeria, Botswana, and Algeria, lack national guidelines for the proper disposal of hazardous medical waste. Personal protective equipment (PPE) such as gloves, protective clothing, and masks are not luxuries but necessities to minimize workers' exposure risks. Comprehensive training programs are also vital to educate workers about the risks associated with biohazardous waste and the correct handling procedures. This training, which should be regularly updated to reflect best practices, must also cover the operation of pyrolysis equipment and emergency response protocols for incidents like spills or accidental exposure to maintain a high level of preparedness [232]. One of the case studies has been adopted in this work to address the explosion hazard possible causes. Poor leadership and a lack of proper safety conditions led to accidents in previous pyrolysis plants [8]. In 2020 and 2021, two explosions occurred in a rural Danish pyrolysis prototype plant due to the autoignition of flammable pyrolysis vapors inside the reactor. The pyrolysis reactor always contains a source of ignition since its temperature exceeds the autoignition temperature of the pyrolysis gases. The company involved attributed the explosions solely to human error. However, the incidents highlighted two main issues. Firstly, the premature termination of the nitrogen purge indicated unqualified operators and a lack of understanding of process safety. To ensure a safe working environment, it is essential for every team member to acquire a thorough understanding of the entire process and the associated hazards. Secondly, the company's start-up procedure, which pressurized the reactor with nitrogen, posed a problem. Simple calculations revealed that this procedure only reduced the oxygen concentration inside the process to 15 percent volume, which exceeds the safe Limiting Oxygen Concentration (LOC). From a combustion engineering perspective, the inert gas must diminish the oxygen concentration to levels that are lower than the LOC. Estimating the LOC for unknown pyrolysis gas compositions is challenging, yet essential. To mitigate explosion risks, inert gas purging is highly important to prevent the formation of an ignitable mixture [227]. It is still worth noting that the pyrolysis process, which lacks oxygen in the reactor, is safer compared to conventional incineration methods [8]. A study conducted by Paladino et al. focuses on the hazard identification and human health risk assessment of a pilot-plant involved in catalytic pyrolysis of municipal waste plastic. The study followed three main routes which are: hazard identification, exposure assessment, and testing of pollutants transport models. The main

pollutants of concern are volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and dioxins. Four scenarios were considered to assess the potential environmental and human health impacts. These scenarios included start-up phases and continuous operation phases, with accidental releases of un-condensable gases or flue gases into the atmosphere. Exposure routes included inhalation of gases and ingestion of food and water near the plant site. The transport of pollutants in the atmosphere was simulated using a chemical spill risk mapper. The results indicated that the population is not at risk for dioxins and PCBs but emphasized the need for attention to non-condensable gas releases containing VOCs. Scenarios involving malfunctioning torches or VOC leakages from pipelines were considered, highlighting the importance of addressing these issues [233]. General practices can also be applied to minimize the impact on the environment and protect worker health. This includes careful controlling and monitoring of pyrolysis emissions. Hazardous gases and particulates generated during the process can be captured and neutralized by installing emission control equipment like scrubbers and filter units. In addition to guaranteeing compliance with safety regulations, real-time emission monitoring enables prompt adjustments when necessary. Solid and liquid residues are examples of residual by-products that need to be handled in compliance with environmental laws as well [234].

11. Economic study

With the continuing rise towards environmental sustainability and waste minimization, many economies tend to transform from being a linear economy to a more circular economy [235]. Therefore, it is relevant to review how pyrolysis can play a significant role in achieving a circular economy in sustainable medical plastic waste management. Conducting a general techno-economic assessment on various pyrolysis process designs can help validate the economic feasibility of the process guiding decisions on whether to develop it into an industrial project based on its feasibility and circular impact."

11.1. Pyrolysis as a circular solution

The circular economy can be defined in many ways; however, it can be simply described as an economic system that aims to minimize waste generation while maximizing resource utilization by producing long-lasting products [236]. In the long run, the economic model of “take--make-use-disposal” has been replaced with the “reduce, reuse, and recycle” model [237]. Pyrolysis of plastic waste can be considered as a circular solution that supports the transition to a circular economy while fostering the development of sustainable and environmentally friendly products [232]. This approach directly contributes to several United Nations Sustainable Development Goals (SDGs) for the 2030 vision including ending poverty (SDG 1) by promoting inclusive economic growth, and ending hunger (SDG 2) by ensuring responsible production practices. It also provides good health and well-being (SDG 3) by reducing environmental pollution. Clean water and sanitation (SDG 6) can be achieved by minimizing plastic waste contamination. Affordable and clean energy (SDG 7) can be obtained by converting waste into energy. Furthermore, it encourages decent work and economic growth (SDG 8) by creating jobs in the recycling and waste management sectors, fosters innovation and infrastructure (SDG 9) by advancing waste-to-energy technologies, and reduces inequalities (SDG 10) by promoting access to sustainable solutions. It also contributes to sustainable cities and communities (SDG 11) by reducing urban waste. The pyrolysis process of medical waste considers consumption and production (SDG 12) by closing the loop on plastic use, addresses climate action (SDG 13) by reducing greenhouse gas emissions, protects life below water (SDG 14) by preventing marine plastic pollution, and safeguards life on land (SDG 15) by reducing land-based plastic waste [233].

The design stage represents the pyrolysis process as in the means of converting medical plastic wastes into valuable products. Research and experimental procedures are carried out to achieve the most optimum conditions which vary between reaction parameters, catalyst type and loading, type of reactor used, mode of pyrolysis, and several other factors. Recently, the use of artificial intelligence has helped in creating a network [179,181] that can be used in assessing the optimum parameters to achieve a specific requirement such as a quantified amount of oil for instance. One must upscale from lab scale to industrial or large scale in the design process, and later on carry an economic analysis or a feasibility study to complete the full design of a pyrolysis plant which can then initiate the production of valorized products that need to achieve certain circular standards; longevity and sustainability [238]. The valorized products are then distributed to consumers for several applications. Specifically, oil can undergo fractional distillation to produce multiple volatile fractions, including pyrolysis diesel. To align with circular economy objectives, the pyrolysis diesel used by consumers should be more sustainable and environmentally friendly than conventional diesel. Oil blend with conventional can cause significant changes in the emission profile of the fuel as a whole. Fig. 16 shows emissions released from the combustion of kerosene, diesel and pyrolysis oil blend with diesel in the ratio 1:9 with respect to the break mean effective pressure (BMEP) where the blend may be cleaner burning fuel [239]. It can be observed that the blend produced negligible differences in carbon dioxide (CO_2) emissions, while nitric oxide (NO) emissions were higher than those of diesel alone. However, the blend reduced carbon monoxide (CO), hydrocarbon (HC), and smoke emissions compared to both diesel and kerosene.

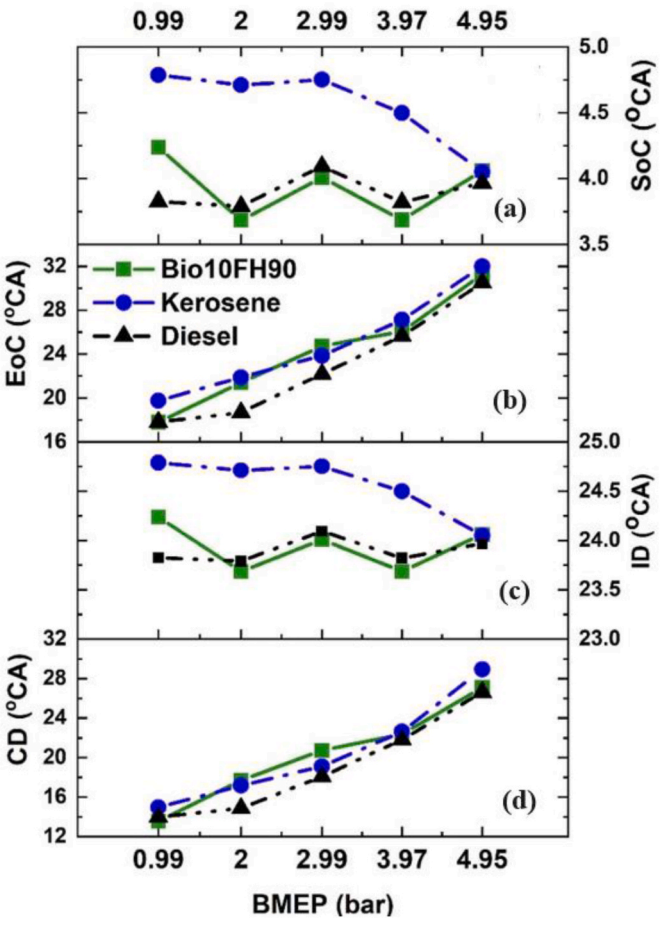

Fig. 16. Emissions of (a) CO, (b) CO_2, (c) HC, (d) NO, and (e) smoke [239].

Another form of environmental assessment was conducted using life cycle assessment (LCA) to analyze the CO_2 emissions of a proposed pyrolysis plant project to determine the net CO_2 emissions released per ton

of feedstock. After performing LCA on the project from the start of the plantation and harvesting until the utilization of the output for electricity in three scenarios; palm kernel shell (PKS)-medical protective clothing (MPC), empty fruit bunch (EFB)-MPC, and palm frond (PF)-MPC, the net emissions were defined as global warming potential (GWP) [145]. All scenarios had negative GWP values which were considered preferable with the scenario of using EFB-MPC as feedstock being the most environmentally friendly.

The loop was closed where consumers released medical plastic waste, especially from hospitals and medical applications, which was collected and recycled back to be processed through pyrolysis. In this case, medical plastic waste was considered a resource from a circular perspective. The production of plastics ever since the COVID-19 pandemic was around 1.6 million tons per day worldwide [240] resulting in the disposal of consequently large amounts of waste. The United States alone generates around 5.9 million tons of medical plastic waste per year [241]. Such waste should be treated since medical plastic waste may cause infectious diseases such as AIDs, hepatitis B, and C [242]. Therefore, applying pyrolysis as a method of medical waste management in circular transitioning is preferable to incineration or landfilling, as it reduces air pollution, suppresses the spread of viruses and microbes, and prevents the formation of leachates and microplastics that may cause bio-toxicity and other harmful effects on human health [243].

11.2. Economic analysis

Alongside Alongside sustainability and environmental impact, a project of medical pyrolysis plant must be evaluated based on its feasibility and profitability. Therefore, one must take into consideration the costs and benefits of the project. A case study in Malaysia was subjected to a techno-economic analysis which involved assessing the economic factors of a medical pyrolysis plant project. It involved setting assumptions that help in calculating techno-economic indicators such as the net present value (NPV), the payback period (PBP), and internal rate of return (IRR). The analysis consisted of two main sections; the costs, which were the input, and the profits (the output gained). The input was divided into fixed costs and variable costs. Fixed costs are usually constant, therefore described in USD, while variable costs are expenses that fluctuate in direct proportion to production volume or activity level. For instance, feedstock cost is a variable cost and it is described in USD/t. As for the output gained, this is what can be considered as generated profit. The outputs from the project were expected to be oil, electricity, and fee for the medical waste disposal service. The result of pyrolysis converted oil palm wastes mixed with medical protective clothing into oil, pyrolysis gas, and char where oil and condensable gases were collected as oil, while the residues were combusted to produce thermal energy which was then used to convert water to steam for the steam turbine to generate electricity. Consequently, the profits of the project came from the revenue of oil, generated electricity, and the medical waste disposal fee [145]. Although the techno-economic analysis made in the previous case study was valid, it can be reinforced with a cost-benefit analysis (CBA). It is a techno-economic analysis tool used to assess all of the benefits and costs of the project [244].

12. Future of artificial intelligence

Artificial intelligence (AI) has progressively been applied in many fields and industries around the world, and that does not exclude pyrolysis. It has been recently applied mainly in two ways; the Monte Carlo simulation [180,245], and the best-fit artificial neural network (ANN) [243]. The Monte Carlo simulation helps in studying the reaction mechanism and information on product output as a recent a study has used the Monte Carlo engine to study the thermal degradation of PS where the polymeric distributions were stored in the form of a tree data structure [245]. The most common AI method used is the best fit ANN which can be used to predict the yield of products and properties such as HHV [246]. It has been recently applied and achieved an overall prediction power of 99.99 % [181]. Fig. 17 shows the ANN which generally consists of three layers; the input layer, the hidden layer, and the output layer [247]. Each layer consists of neurons that present a certain parameter [246]. Input neurons usually present output properties reaction conditions such as temperature and pressure, while output neurons present product properties such as yield and HHV [246].

Designing the hidden layer is of immense importance for the performance of the ANN [246]. It is critical to choose the optimum number of neurons since a small amount of neurons may result in underfitting, while a large amount of neurons may cause overfitting and

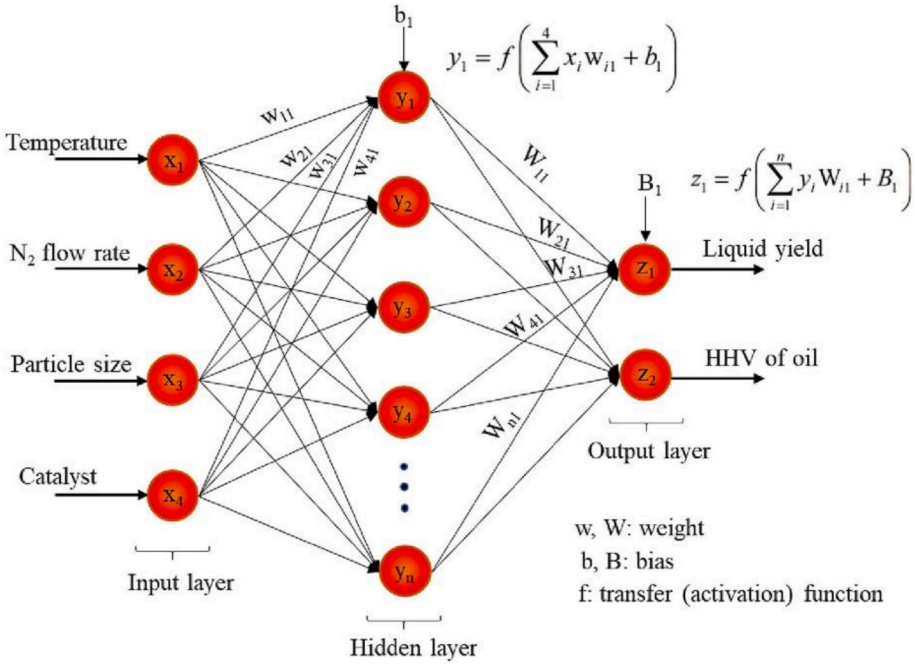

Fig. 17. Structure of an ANN model for oil yield and HHV prediction [246].

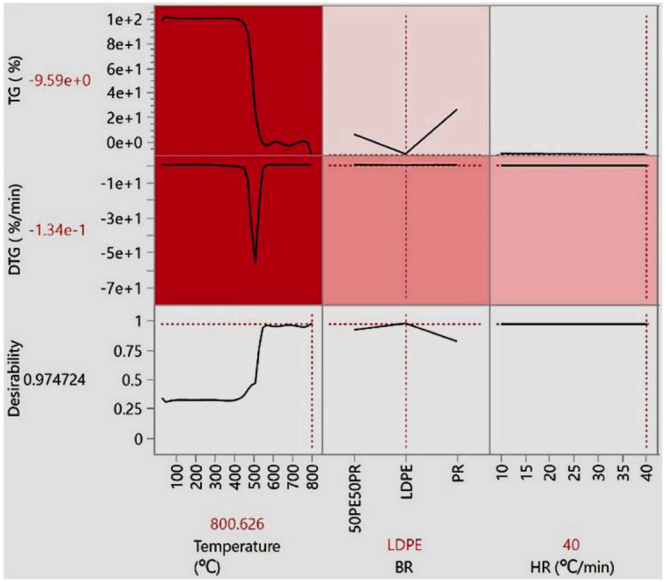

Fig. 18. Optimization of pyrolysis efficiency and relevancy of parameter condition for ANN and Monte Carlo simulations respectively [181].

computational cost. The performance of ANN may be assessed through various performance indicators including the coefficient of determination (R^2) and the root-mean-square error (RMSE) [181]. The parameters can be tuned for more efficient using optimization tools such as the Bayesian optimization tool [245]. Fig. 18 shows the optimization of the pyrolysis efficiency and the importance of each parameter according to the ANN and Monte Carlo simulations.

One study applied machine learning to evaluate the activation energy in the pyrolysis of waste plastics which is crucial for optimizing and scaling up the process. The model's input variables included feed characteristics from ultimate and proximate analysis such as carbon, nitrogen, sulfur, ash, fixed carbon, and moisture content. It also considered the type of feedstock (PP, LDPE, HDPE, PET, PS, PVC) and isoconversional methods for process kinetics, including Kissinger-Akahira-Sunose (KAS), Flynn-Wall-Ozawa (FWO), and Friedman Method (FR). Among the machine learning models tested (Random Forest, XGBoost, CatBoost, and AdaBoost), Random Forest proved to be the most accurate with R^2 value of 0.941 [248]. Machine learning algorithms have also proven effective in predicting key outcomes of the non-catalytic pyrolysis process for plastic waste. A study found that the Decision Tree model was the most accurate with R^2 value above 0.99 outperforming other models like Neural Networks (ANN), Support Vector Machines (SVM), and Gaussian Processes (GP). Predictions of liquid yields, liquid compositions, and gas compositions were more accurate when using input data from ultimate analysis compared to data based on plastic type. This approach is particularly valuable when the type of plastic waste is unknown, and only ultimate analysis data is available [249].

13. Conclusion

In the face of mounting environmental concerns and the urgent need for sustainable waste management practices, plastic pyrolysis has emerged as a beacon of hope, particularly in the context of medical plastic waste. This review paper explored the complex field of plastic pyrolysis applied to medical plastic waste including a wide spectrum of technological, environmental, and strategic considerations. The challenges associated with medical plastic waste are significant, from its intrinsic hazardous properties to its persistent resistance to degradation. However, the concept of converting this waste into valuable resources through pyrolysis offers a compelling solution that aligns with both ecological and economic aspirations. The integration of simulation technology, notably exemplified by Aspen Plus, brings a level of precision and efficiency to the pyrolysis process that was previously unattainable. By virtually navigating the complexities of thermal degradation and fluid dynamics, these tools empower researchers and industry professionals to optimize process conditions, maximize yields, and minimize energy consumption. This symbiosis of technology and science presents a pivotal advancement in the quest for sustainable waste-to-resource conversion. The infusion of artificial intelligence into medical plastic waste pyrolysis introduces a realm of possibilities that extend far beyond conventional methodologies. The real-time monitoring, predictive maintenance, and adaptive control capabilities that AI-driven systems offer foster safer operations and more flexible response mechanisms. As we move towards an era where automation and intelligence are central, the integration of AI and pyrolysis represents a significant advancement in achieving waste management objectives with improved efficiency. At its core, the concept of a circular economy serves as a guiding principle for our future. The integration of pyrolysis-derived products into this paradigm underscores the transformative potential of this approach. This review paper illuminated the multifaceted journey of plastic pyrolysis applied to medical plastic waste. It discussed the interplay of innovation, science, and strategy in shaping a more sustainable future. The path ahead necessitates not only technological advancements but also collaborative efforts among researchers, industries, policymakers, and the wider society. As we look to a future where waste is reframed as a resource, plastic pyrolysis stands as a beacon, illuminating the path towards a cleaner, greener, and more responsible world.

CRediT authorship contribution statement

Mohamed Bassyouni: Methodology, Conceptualization, Simulation, Data collection, Software, Visualization, Writing – original draft. **Reem Nasser:** Methodology, Conceptualization, Simulation, Data collection, Software, Visualization, Writing – original draft. **Moataz El-Bagoury:** Methodology, Conceptualization, Simulation, Data collection, Software, Visualization, Writing – original draft. **Islam Shaker:** Methodology, Conceptualization, Simulation, Data collection, Software, Visualization, Writing – original draft. **Attia M. Attia:** Methodology, Conceptualization, Simulation, Data collection, Software, Visualization, Writing – original draft. **Yasser Elhenawy:** Methodology, Conceptualization, Simulation, Data collection, Software, Visualization, Writing – original draft. **Dina Aboelela:** Methodology, Conceptualization, Simulation, Data collection, Software, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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