A COMPREHENSIVE REVIEW ON PYROLYSIS OF WASTE MATERIALS: PROCESSES, PRODUCTS, AND APPLICATIONS

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ABSTRACT

Today pyrolysis operates as a fundamental waste-to-energy process because it transforms numerous waste materials into beneficial products of biochar and bio-oil together with syngas while maintaining low oxygen levels. The review offers a comprehensive analysis which investigates feedstock composition as well as operational temperature and heating parameters because these factors determine the quantity and attributes of produced materials. The research looks at waste materials such as plastics as well as biomedical waste and electronic waste through pyrolysis and reinforces how innovative reactors must be designed together with pre-treatment techniques to handle dangerous substances. A detailed review focuses on the Dual-Stage Thermochemical Reactor which includes pre-treatment methods designed to enhance product quality with safety standards for the environment. The research investigates applications of pyrolysis products while discussing challenges with these applications to boost sustainable development and circular economy practices. The existing improvements in both process optimization and catalytic systems demonstrate potential for building a commercial industrial waste management system based on pyrolysis while maintaining higher environmental cleanliness standards.

Key Words: Thermochemical conversion, Dual-stage reactor, Bio-oil, Circular economy.

INTRODUCTION

As previously noted, pyrolysis has the potential [1] for waste management and energy recovery and offers a modern alternative to traditional disposal methods. This process, which captures carbon dioxide and converts it into biochar, syngas and bio-oil, involves the heating of organic materials in the absence of oxygen [2,3,4]. Unfortunately, standard pyrolysis approaches often lack the capability to remove harmful constituents like heavy metals, chlorine, and acidic gases. These limitations pose the risk of secondary contamination and restrict widespread applicability. This work addresses these challenges through the design of a Dual-Stage Thermochemical Reactor with an Advanced Pre-Treatment System that selectively removes harmful substances before pyrolysis. It aims at maximizing the quality of end pyrolysis products while guaranteeing safer disposal of wastes through novel gas-cleaning systems combined with pre-treatment processes [5].

Efficiency in pyrolysis depends on variables such as temperature, residence duration, heating rate, and feedstock composition. The removal of heavy metals and chlorine in this project is accomplished through a pre-treatment step whereby trash is heated to 200-300 degrees Celsius. A natural scrubber is employed afterwards to clear the gases emitted [6,7]. The waste is turned into charcoal, pyrolysis oil and syngas in an oxygen-less pyrolysis reactor heated to 400-600 degrees Celsius. [8,9]. Screens with gas scrubbers and activated carbon filters, along with a cyclone separator, are also designed to provide low emission standards and even greater control of harmful emissions [10]. Such technology makes the system economically feasible, adaptable, and environmentally friendly, which makes it suitable for industrial waste treatment processes.

Waste management is taken a step further with pyrolysis as it converts waste into valuable resources, making it pivotal to the circular economy [11, 12]. Enhanced agricultural productivity, carbon sequestration in conjunction with reduced greenhouse gas emissions are the benefits obtained from the use of biochar, which is frequently used as a soil amendment and is one of the primary byproducts of bioenergy production [13, 14]. An alternative biofuel, pyrolysis oil, assists in the development of renewable energy [15, 16]. The mixture of hydrogen, carbon monoxide, and methane is known as syngas and is utilized for producing power and industrial heating [17, 18]. The Dual-Stage Thermochemical Reactor maximizes these product outputs and ensures better reaction efficiency and feedstock purity.

Even with its advantages, the widespread use of pyrolysis still faces challenges like its high energy use, variability of feedstock material, and emission control inefficacies [19]. Integrating a pre-treatment system with gas-cleaning technology will, hopefully, mitigate these particular obstacles and allow pyrolysis to become a cleaner, more sustainable hazardous waste management method. Given the growing global demand for sophisticated waste management systems, this novel approach to pyrolysis is capable of bridging the divide between waste reduction and the supply of clean energy and is maskable as a renewable invention.

Types of Waste used in Pyrolysis.

The waste products suitable for pyrolysis include plastic trash, biomass, rubber, municipal solid waste (MSW), biomedical waste and electronic debris (e-waste). The distinct features of these waste materials control the product properties along with their generation quantities during the pyrolysis process [20]. Plastic-based waste generates mostly liquid fuels through the process while biomass waste output includes biochar for agricultural use. When conducting e-waste pyrolysis operators can recover metal values and extract hydrocarbons together with the generation of carbon black and high-energy pyrolysis oil from discarded tires [21].

1. Pyrolysis of plastics

The different chemical compositions of plastic materials differ from the standard descriptions found in proximate analysis. Proximate analysis refers to the assessment method that measures four chemical characteristics of plastics through moisture content analysis and examination of fixed carbon content and volatile matter and ash content determination.[22]. The two primary factors affecting the production rate of liquid oil during pyrolysis are volatile matter composition along with mineral residue. Plenty of ash in the process diminished the amount of liquid oil while boosting both gaseous outputs and char development while volatile matter elevated liquid oil production.[23] The measurements indicate that plastic ash content remains low although every plastic sample shows exceptional volatility. Results indicate plastics should produce significant yields during thermal decomposition in accordance with the liquid oil production method known as pyrolysis. Further discussions will emphasize important parameters from the pyrolysis process regarding the formation of liquid because the proximate analysis shows promising results [24].

1.1. Polyethylene terephthalate (PET)

The use of PET has become widespread for food packaging due to its popularity among plastic makers producing containers for drinks such as fruit juice containers, soft drink bottles and mineral water. Its natural characteristics allow PET to serve as an excellent material for lightweight pressure-resistant storage containers with large capacity. PET serves multiple purposes through its production in electrical insulation components as well as printing sheets and magnetic tapes and X-ray and other photographic film and various additional applications [25]. A mass usage of PET materials would lead to excessive PET waste accumulation in landfills and disposal sites. The standard approach to handling collected plastic waste involved PET waste recycling.

The increased frequency of collecting heavy plastic containers results in higher transportation costs. Conducting recycling on PET waste requires multiple colour and grade separations before processing which renders the recovery system ineffective and expensive. The investigation of alternative PET recovery methods including the pyrolysis technique led researchers to study the produced yield from this process. Cepeliogullar and Putun conducted research into using PET in pyrolysis for generating liquid oil through a fixed-bed reactor at 500 C. The experimental conditions utilized nitrogen gas as the sweeping gas at a heating rate of 10 C/min.

The researchers obtained less liquid oil compared to the gaseous product yields. At 76.9 weight percent the gaseous product had no solids, and 23.1 weight percent of liquid oil was recovered from the process. The gas chromatography–mass spectroscopy (GC–MS) examination showed benzoic acid occupied 49.93% of the oil composition. Benzoic acid in pyrolysis oil caused deterioration of fuel quality because its corrosive nature destroys the fuel properties [26].

The industrial operation of benzoic acid faces difficulties because this general sublime material can lead to clogging in heat exchangers and pipes [27,28]. Fakhrhoseini and Dastanian [achieved a somewhat elevated liquid oil production at similar heating conditions and operating temperature. Liquid oil made up 39.89 percent of the final weight along with a gaseous portion of 52.13 percent and a 8.98 percent solid residue. Among the products of PET pyrolysis liquid oil reached between 23 and 40 weight percent as did gaseous products in the range of 52 to 77 weight percent. Resulting data from PET pyrolysis indicates it would be the most suitable material for reaction-based gaseous product generation to obtain energy needed for heating the reactor until it reaches its required temperature [29].

1.2. High-density polyethylene (HDPE)

HDPE exists as a high strength material through its extensive linear structure outside limited branches and deep crystalline state. HDPE finds extensive application because of its remarkable strength in creating toys as well as oil containers and milk bottles along with detergent bottles for multiple items. Plastic waste stands as the third-biggest plastic material category within municipal solid waste (MSW) and contains approximately 17.6% of different applications [30]. HDPE wastes show excellent potential for pyrolysis because different operating parameters allow the material to produce noteworthy liquid volumes. Researchers have extensively studied the yield of products produced through HDPE pyrolysis using different operational conditions [29].

Research on HDPE pyrolysis was conducted through experiments in a micro steel reactor. The micro steel reactor heated the materials between 300 and 400 C when using a heating rate of 5–10 C/min. Since the researchers used nitrogen gas as their fluidizing medium throughout the process. Investigatory findings demonstrated that liquid obtained 80.88 weight percent product yield together with maximum total conversion at 350 C. The solid residue weight percentage declined to 0.54 percent at the highest temperature condition of 400 C although it still remained high at 300 C where the weight percentage reached 33.05 percent[31] Together with temperature ranges of 400 to 550 C HDPE producers operate semi-batch reactors.

A high weight percentage of 24.75 for gaseous products along with 79.08 wt% liquid yield was observed at 550 C but wax started dominating the product fraction when the temperature reached between 500 and 550 C. The pyrolytic process generated an oil with dark brown hues that had boiling range from 82 to 352 C and showed no formation of solid deposits. The researchers developed an oil mixture of diesel, kerosene, and petrol which fulfilled conventional fuel characteristics according to Table 2. The HDPE pyrolytic oil contains a minimum of 0.019% sulphur content which establishes its ecological usefulness [32]. the HDPE pyrolysis in a batch reactor at 550 C.

The reaction produced 84.7% weight of liquid oil with 16.3% weight of gaseous products. Higher temperature levels resulted in higher liquid oil production according to experimental findings.

A drawback was observed in this system despite other success points. The process exceeded its maximum thermal degradation point thus raising temperature levels generated extra gaseous products while simultaneously decreasing liquid oil yield. Mastral and associates [33]. The scientists running the HDPE pyrolysis at 650 C in a fluidised bed reactor obtained gaseous products amounting to 31.5 weight percent and liquid oil products amounted to about 68.5 weight percent. The transformation of the liquid into gaseous form indicates its gasification process. The material turns into a gas after heating it above 550 degrees Celsius [34].

1.3. Polyvinyl chloride (PVC)

The production process of PVC stands apart from other plastics since it combines 57% industrial-grade salt transformed into chlorine with 43% carbon drawn from oil and natural gas ethylene [35]. The high fire-safe properties of PVC stemming from chlorine content prove this material an outstanding selection for electrical insulation. PVC functions as a versatile material because it accepts a wide range of additives for use. Wood or metal frames used together with PVC form common building elements while PVC insulation covers wires and cables. Additional applications include footwear, synthetic leather, food foil and medical equipment as well as blood bags and car interiors as well as packaging and credit cards and various additional items.

Few scientists have studied PVC pyrolysis in written publications due to its dangerous chemical outputs during heating processes at high temperatures. The batch reactor used to pyrolyze PVC operated at temperature ranges from 225–520 C under a heating rate of 10 C/min. Under vacuum and a total pressure of 2 kPa the experiment took place. The production of liquid oil during the experiment had a low yield which ranged from 0.45 to 12.79 percent by weight while temperature levels were rising. The produced tar accumulated to values exceeding the amount of generated liquid oil and reached a maximum of 19.6 weight percent. The experiment primarily produced a chemical substance named hydrogen chloride (HC) [36]. PVC yields very minimal liquid oil during pyrolysis which proves that PVC was not the optimal material for this process.

During the waste analysis less than 3% of accumulated PVC products constituted the total plastic waste share [30]. The production of hazardous substances including HCl combined with chlorobenzene compounds in the pyrolysis liquid leads to environmental toxicity. A PVC dichlorination process served to lower the chlorine content in liquid oil during the process. The achievement of this process can be attained through various techniques which encompass stepwise pyrolysis and catalytic pyrolysis and pyrolysis with adsorbents that are added within the PVC sample. The industry experienced a major drawback because PVC pyrolysis needed additional expenditures to perform a dichlorination process [30].

1.4. Polypropylene (PP)

The saturated hydrocarbon-chained linear polymer knows strong chemical along with heat resistance properties. PP maintains its structure as a solid material when exposed to temperatures below 160 C because HDPE does melt under this condition. Its density is lower. Its superior hardness and rigidity surpasses HDPE thus the plastics industry selects this material as their preferred choice. PP represents 24.3% of plastic waste materials within the plastic waste category that contains the highest amount of plastics in MSW [30]. The application range of materials includes flowerpots alongside office files and pails while automobile bumpers and carpets and furniture and storage boxes are additional items among many others.

PP pyrolysis operates as a waste management approach to collect energy because commercial PP usage heightens each year. Different researchers have investigated PP pyrolysis under various conditions to study the production alongside the characteristics of liquid oil [37]. They executed PP pyrolysis tests inside a miniature steel reactor within the temperature range of 250–400 C. The investigation team discovered that 300 C yielded optimal liquid oil yields equivalent to 69.82 weight percent while achieving complete conversion of 98.66%. When the temperature reached 400 C, both weight percent solid residue and product conversion rate decreased from 1.34% to 5.7% and 98.66% to 94.3% respectively.

The results indicated that when temperatures increased coke production became more dominant in the reaction process. The process takes place at 380 C for PP pyrolysis when compared to typical operating conditions. The experiment generated higher liquid amounts reaching 80.1 weight percent together with 6.6 weight percent gaseous byproducts and 13.3 weight percent solid residue [38]. The reaction of PP at 500 C led to the production of over 82.12 weight percent liquid. Rising the temperature beyond 500 C resulted in reduced liquid production. The research conducted by Demirbas involved PP pyrolysis in a batch reactor at 740 C resulting in 48.8% liquid products and 49.6% gaseous products together with 1.6 weight percent char [29].

1.5. Low-density polyethylene (LDPE)

The numerous branches within LDPE reduce intermolecular forces and lead to decreased tensile strength and material hardness. The structure of LDPE becomes less crystalline through its side branching and this makes it more workable so it exhibits greater ductility than HDPE. The excellent waterproof capability of LDPE allows it to be widely used for plastic bags and packaging materials and trash bags among other items. LDPE waste has become the second-biggest plastic waste in MSW after PP because these items appear regularly in our daily lives [30].

The researchers conducted LDPE pyrolysis using nitrogen as fluidizing gas in an experimental run of 20 minutes at 500 C reactor temperature with 10 C/minute heating rate in a fixed-bed reactor. Scientists discovered that the process produced 95 weight percent liquid products together with minimal gas products and trace amounts of char while obtaining 93.1 weight percent liquid oil [33].

A batch reactor operated at 550 C with a heating rate of 5 C/min performed the experiment at a different time period. Several researchers have studied LDPE pyrolysis at working temperatures below 500 C[39]. The production of liquid oil would increase by utilizing pressure during the process at lower temperatures in the reactor system. According to Onwudili et al. [34] the pyrolysis of LDPE at 425 C took place within a pressure-controlled batch reactor under pressures ranging from 0.8 to 4.3 MPa. The obtained products consisted of 89.5% liquid oil with 10 weight percent gaseous products and 0.5 weight percent char from the experimental setup. The outcome of future pyrolysis product analysis depends on pressure applications as a result [40].

1.6. Polystyrene (PS)

The liquid petrochemical provides styrene monomers that lead to the production of PS. A single chain of hydrocarbon molecules forms the basis where phenyl rings connect next to each atomic carbon. PS itself has no colour but receives its aesthetic qualities through additional colouring agents. PS has become one of the most popular polymers because of its thermal stability and acceptable durability along with strength and low weight which allows industries such as toys electronics construction and food packaging and medicine to adopt it for various usages.

The extensive quantity of PS waste accumulated in MSW during each year becomes evident through various industrial applications. The roadside recycling program does not accept PS items because it only permits people to reuse glasses, papers, cans and certain types of plastic. Most people choose to throw foam food packaging into the general trash even though there exists a plastic recycling container. Low density polystyrene foam material known as PS exists in the general trash because collecting it for recycling does not prove economically feasible nor does the waste separation process work well. The pyrolysis process represents the sole possibility to utilize all PS waste because it transforms the material to produce valuable oil that avoids permanent landfill storage [40].

A batch pressurised autoclave reactor maintains chemical decomposition of PS for an hour using temperatures between 300–500 °C. Retort conditions operated between 0.31 MPa to 1.6 MPa pressure with 10 C/min heating rate. Pyrolysis experiments at 425 C produced a superior weight percentage (97.0) of liquid oil as the main product. The highest production level of petrol reached 2.5 weight percent while petrol generation remained minimal [41]. PS underwent fluidised bed reactor pyrolysis between the temperature range of 450 and 700 C. Among the experimental conditions the highest weight percent of liquid oil reached 98.7 at 600 C. The liquid oil production at 450 C with a weight percentage of 97.6 received comparable positive assessments as the higher quantity by 1.1 weight percentage. The primary focus on energy conservation led people to choose colder temperatures as a way to minimize energy bills. Demirbas [36] reported that PS pyrolysis produced 89.5 weight percent liquid oil when performing in a batch reactor at 581 C. The research demonstrated that running PS pyrolysis above 500 C would produce sub-optimal liquid oil yields so this mode of operation should be avoided [42].

2. Pyrolysis of Biomedical Waste

Waste management strategies became extremely difficult due to growing biomedical waste generation which poses serious questions about improper disposal risks. Health risks in communities arise when biomedical waste spreads as an infection. Massive medical waste requires effective and safe waste processing methods to reduce health threats in human populations [42,43].

The pyrolytic gas conversion of SW/SBW produced three main end products using different tools as well as materials and chemicals. The research materials of disposable syringes and saline bottles originating from hospitals and clinics in Khulna city were obtained for pyrolysis studies in Bangladesh. The researchers cleaned the wastes thoroughly by washing them with detergent followed by water to remove all physical and impure components attached to the biological waste. Following cleaning procedures, the raw materials underwent solar drying then personnel used scissors to slice them into small fragments [45]. The production of BMW at BMW combines biological and medical procedures in their research and service delivery for disease diagnosis and prevention and treatment processes.

Medical facilities together with their associated emergency rooms and nursing homes along with clinics produce biomedical waste frequently throughout their operations. The calorific value of BMW lies between 12,550 kJ/kg and 16,740 kJ/kg depending on average measurements [46]. The rising accumulation of BMW poses a severe threat to human beings along with environmental harm. The composition of such waste types shows extensive variation which makes precise identification impossible. Particular methods need to be utilized to recycle this waste material [47]. Per treatment studies medical waste becomes subject to incineration at rates of 59-60% while steam sterilization (autoclaving) handles 37–20% of these wastes and alternative treatment techniques including landfilling and microwave and plasma pyrolysis contribute to only 4-5% disposal.

The disposal of materials mentioned in BMW requires incineration as the primary worldwide waste management approach for explosive materials such as papers and polyvinyl chloride polymers along with abandoned equipment. The engineering approach of incineration allows practitioners to destroy medical waste organic components through high-temperature thermal oxidation above 900 C to 1200 C. The production of extremely hazardous dioxins and toxic compounds like benzo(a)pyrene and furans at cremation sites creates potential health concerns for the persons involved. The autoclave relies on a steel enclosure with a self-locking door which integrates steam entry and exit pipelines through hatches to bear high pressure and temperature conditions. The healthcare waste industry considers microwave technology for clinical waste treatment to be an improved method compared to incinerators. Steam-based procedures enable sterilization through electromagnetic wave frequencies between radio and infrared which use either wet waste contents or additional steam [48].

The process of electric arc plasma surpasses waste incineration by achieving superior ecological and sanitary-hygienic safety through extensive atmospheric emission reductions of dioxins and benzo[a]pyrene together with furans along with a decrease in slag and ash products. Plasma generates powerful heat which allows proper elimination of all waste categories from hazardous waste to biomedical waste to municipal solid waste. Electric power serves as the only disadvantage for plasma generation operations within the plasma gasification process. The produced syngas serves as a foundation material that enables the production of ammonia and methanol and hydrogen as well as power generation through fuel cells or gas turbines or leads to liquid fuel through the Fischer-Tropsch process [49].

3. Pyrolysis of Electronic Waste (E Waste)

Landfills became the disposal destination for electronic and electrical products including mobile phones and TVs and computers. The inclusion of hazardous substances such as CFCs together with PCBs and Pb and Hg and others poses severe risks to the environment. The European Commission maintained the WEEE Directive under the codenamed 2002/96/EC during multiple years of development. The directives entered into effect on February 13, 2003 while national laws of UE members needed implementation before August 13, 2004. The directive requires recovering between 70 to 80 percent of electrical and electronic equipment items. WEEEs composed of numerous material types make them difficult to recycle (metals, glassware, rubbers, plastics, etc.).

The recycling of non-metallic components such as plastics and rubbers found in WEEEs remains without an obvious alternative and experts focus mainly on metal recovery. Plastic waste from WEEs represents sixteen percent of total WEEs yet Western Europe accumulated nine hundred thousand tons of plastic trash in 1997 and scientists project this number will increase to one million four hundred thousand tons by this decade [50]. This investigation involved selecting four actual WEEE stream specimens as test materials. Two main criteria determined the selection of samples because these wastes needed to contain higher concentrations of polymers while also facing impractical recycling possibilities. The following details the chosen samples' origin and makeup: The majority of copper and aluminium elements are separated from wires through flotation methods before WEEE processing facilities collect the remaining polyethylene (PE) wire mass as waste.

Through this process a main polyethylene product emerges but some copper and aluminium remain inside the material. The WEEE processing facility generates Table phones waste after magnetic components separation and table phone grinding (including base and card phone and wire). WEEE recycling plants obtain these phones in their mutilated state after the magnetic component’s removal process ends. Circuit boards which are printable consist of combined numerous technical components alongside substantial metal content [51]. The majority of copper and aluminium elements are separated from wires through flotation methods before WEEE processing facilities collect the remaining polyethylene (PE) wire mass as waste [52]. Through this process a main polyethylene product emerges but some copper and aluminium remain inside the material. The WEEE processing facility generates Table phones waste after magnetic components separation and table phone grinding (including base and card phone and wire) [53].

WEEE recycling plants obtain these phones in their mutilated state after the magnetic component’s removal process ends. Circuit boards which are printable consist of combined numerous technical components alongside substantial metal content. The FTIR Nicolet Impact 410 apparatus was used to perform FTIR investigations in order to gather data regarding the functional groups and, consequently, the polymers included in the WEEE samples [54]. It was challenging to identify polymers and generate suitable spectra from the samples due to their complexity (complex mixture of several polymers and other components), and quantitative information could not be extracted. Actually, the PE wire sample provided absolutely no suitable spectrum. The three more samples' FTIR spectra—printed circuit boards, cell phones, and table phones [55].

Pyrolysis Process and Mechanism:

The thermochemical separation process of pyrolysis takes place at elevated temperatures throughout an atmosphere free of air. The method finds widespread use in converting biomass alongside plastic and other organic materials to obtain biochar alongside bio-oil and syngas as valuable products. The classification of pyrolysis divides into three main elements which consist of heating rate together with operational temperature and processing duration. The dividing lines in pyrolysis are defined through the four main classifications which include slow pyrolysis and fast pyrolysis together with flash pyrolysis and catalytic pyrolysis.

1. Slow Pyrolysis

The process of slow pyrolysis happens within temperature ranges of 300 to 700°C with heating rates at 0.1–1°C/s alongside extended residence durations between minutes and hours. Biochar production through this process maintains substantial feedstock quantities as solid carbon therefore it is mainly used to create biochar [56]. Several studies indicate that slow pyrolysis produces more biochar than alternative techniques during the production process. The excellent qualities of the resulting product transforms biochar into a valuable material for adsorption processes while making it suitable for carbon sequestration techniques and serving as a soil amendment solution [57,58]. Research indicates that biochar quality can reach its maximum by adjusting key regulatory factors such as feedstock composition together with temperature and duration during the pyrolysis process [59].

2. Fast Pyrolysis

Fast pyrolysis primarily aims to optimize bio-oil generation to use as chemical feedstock alongside renewable fuel [60]. A study demonstrates that fast pyrolysis generates bio-oil from 75% of lignocellulosic biomass while syngas and biochar constitute the remaining product portions [61]. The fast pyrolysis bio-oil product contains high oxygen content that reduces its energy density and stability characteristics. The researchers studied fractional condensation together with hydrodeoxygenation along with co-pyrolysis with hydrogen-rich materials as approaches to enhance bio-oil quality [62,63].

3. Flash Pyrolysis

To operate flash pyrolysis at advanced levels researchers, apply temperatures from 450 to 1000°C while maintaining peak heating speeds above 1000°C/s and keeping the reaction time under 1 second [64]. This technology aims to boost the number of liquid products by diminishing the formation of char. Research indicates that flash pyrolysis effectively turns microalgae and waste plastics into valuable hydrocarbon products [65]. Bio-oil production both in quantity and quality has received improvement through innovative reactor technology implementing fluidized beds and microwave-assisted systems [66, 67].

4. Catalytic Pyrolysis

Bio-oil quality receives improvement through catalyst-assisted pyrolysis alterations of reaction pathways which selectively generates beneficial hydrocarbon products [68]. Bio-oil oxygen content reduction and aromatic hydrocarbons such as benzene, toluene, and xylenes (BTX) production happen through this technique [69]. The characteristics of bio-oil and deoxygenation process performance have been greatly improved using HZSM-5 zeolite-based catalysts through extensive research studies [70]. The main obstacles in catalytic pyrolysis require innovative approaches to resolve catalyst regeneration processes along with coke-deposition issues [71, 72].

Key Process Parameters:

1. Temperature:

Temperature stands as an essential operational variable in pyrolysis which controls the way organic chains break during the cracking process. The polymer structure stays intact through Van der Waals forces acting between molecules to stop their breakdown. An increase in system temperature speeds up molecular vibrations and makes molecules escape more likely from the object surface. The energy output from Van der Waals forces exceeds bond enthalpy within the C–C chain link to result in carbon chain destruction [73]. The thermal degradation characteristics of plastics become evaluable through the use of thermogravimetry analyzers. The analyzer creates dual plot distributions consisting of thermogravimetry analysis (TG) curve and derivative thermogravimetry analysis (DTG) curve. The TG curve measures weight changes of substances while they are in contact with time at different temperatures [74].

The DTG curve features degradation transformation peaks which indicate the stages of process degradation through peak counting [74]. Cepeliogullar and Putun [75] studied PET pyrolysis and identified that PET starts to decompose at 400 °C while the temperature ranges from 200–400 °C resulted in limited weight loss. The maximum weight reduction of the material happened at 427.7 °C. The analysis revealed no substantial variations after the temperature exceeded 470 °C. The authors determined that PET undergoes thermal degradation in the temperature range between 350–520 °C. According to Chin et al. [76] thermal degradation of HDPE started between 378–404 °C before finishing between 517–539 °C which researchers determined through thermogravimetric analysis (TG) at heating rates between 10–50 °C/min. The study showed that higher heating rates would speed up weight loss reactions. The research by Marcilla et al. [77] revealed that HDPE reached its fastest degradation point at 467 °C. Researchers need to factor in this essential temperature limit during their pyrolysis work to optimize their liquid production results. Major weight loss in PVC occurs in two different temperature areas according to Cepeliogullar and Putun's findings [75].

During the temperature range from 260 °C to 385 °C the actual weight loss exceeded 62.25% of the original weight. During the temperature interval of 385 °C to 520 °C the weight loss amounted to about 21.74% of the original material weight. The material showed near minimum weight loss of 1.62% when the temperature reached 800 °C. The experts determined PVC undergoes degradation between 220 °C and 520 °C [75]. LDPE pyrolysis led to the initial development of liquid oil between 360 to 385 °C according to Marcilla et al. [78]. The maximum amount of liquid product was produced within the temperature range 469 – 494 °C. The production of oil from LDPE started at 410 °C according to the research findings of Onwudili et al. [79]. The conversion of oil remained incomplete when a brown waxy substance formed during the reaction below 410 °C. Researchers determined that LDPE liquid yield reached its highest value when using 425 °C as the temperature parameter.

The study produced by Marcilla et al. [80] showed that 550 °C stood as the optimal temperature for producing maximum liquid oil output. Rising temperatures from 600 °C reduced the amount of liquid product that was acquired [81]. The thermal decomposition process of LDPE takes place between temperatures of 360–550 °C. The thermal degradation threshold of PP occurred at a lower temperature than HDPE. The research by Jung et al. [82] showed that temperature variations in a fluidized bed reactor affected HDPE and PP decomposition through DTG curve analysis by demonstrating principal decomposition occurrences between 400 to 500 °C. The PP fraction initiated its weight loss process at temperatures that remained below 400 °C before the HDPE fraction commenced its loss. The maximum temperature of degradation for PP reached 447 °C yet HDPE required 467 °C to complete decomposition and lose the most weight according to Marcilla et al. [77]. The rapid degradation rate of PP occurs due to its structural makeup since half the carbon atoms are tertiary carbon bondage that accelerates tertiary carbocation formation [82]. The degradation process for PS led to the lowest temperature among all plastic kinds. Onwudili et al. [79] conducted studies on PS pyrolysis within batch reactors but they reported reactions would not begin until reaching 300 °C. At the lower temperature condition of 350 °C PS fully transformed into a thick opaque dark oil according to their results. The research team obtained the maximum amount of liquid oil at a temperature setting of 425 °C yet elevated the temperature to 581 °C which caused liquid oil production to decrease and generate more gaseous products [83].

The thermal degradation temperature for PS usually falls between 350–500 °C. Studies show that temperature directly impacts reaction rates because it affects the composition of liquid and gaseous and char product outputs from all previously discussed plastics. The temperature requirements depend intensely on the selected end products. Gaseous or char products can only be obtained at thermal temperatures beyond 500 °C. The production of liquid-based products requires temperature ranges between 300 and 500 °C according to suggestions which are equally applicable to all plastics.

2. Residence Time:

The average time duration for which catalyst particles spend inside the reactor affects product distribution according to research [84]. An increased reaction time enables greater conversion of primary substances into stable thermally produced products that include low molecular weight hydrocarbons and non-condensable gases [85]. Product distribution remains unaffected by residence time when the process reaches a specific temperature point. Mastral et al. [86] investigated how delaying time and heating levels affected the distribution of products obtained from HDPE thermal decomposition in a fluidized bed reactor. Research findings demonstrated that longer residence time (2.57 seconds) reached maximum liquid production levels when the temperature remained below 685 degrees Celsius. When the operating temperature exceeded 685 °C the length of residence time produced no significant variation in the yields from both liquid and gaseous products.

3. Heating Rate:

Sources of thermal impact function as primary controlling factors in pyrolysis outcomes because they affect both reaction speeds and determine both biomass degradation structures and other organic materials. The speed of heating decides both the production rates of biochar and bio-oil and syngas from the material. The production of biochar achieves optimal results when heating progresses at a speed between 0.1 and 1°C/s to enable full secondary reaction involvement [87]. Biochar maintains elevated quantities of fixed carbon while forming better porous arrangements which develop advantageous conditions for bettering soil quality and increasing storage capabilities and absorption features [88]. Premium bio-oil results occur through fast pyrolysis heat rates between 10 to 200 °C/s because it controls volatile second-order breakdown reactions and reduces char formation production [89]. The production of bio-oil increases at heating rates above 50°C/s because research shows this fast thermal breakdown simultaneously leads to suppressed gas degradation [90]. Flash pyrolysis depends on heating speeds above 1000°C/s to pull volatile compounds right away for producing significant amounts of syngas together with minimal leftover solid matter [91]. The specific amount of heat serves to achieve optimal results across various feedstock types where proper heating temperatures enable cellulose and hemicellulose decomposition from lignocellulosic biomass [92] and plastic waste mixtures and algal biomass need distinct heating conditions for successful liquid fuel generation [93]. The heat management process in pyrolysis systems relies on different reactor types such as fixed-bed and fluidized-bed and microwave-assisted reactors to achieve optimal heating rates [94]. The control of heating rates remains key to modifying pyrolysis operations since it enables targeted product generation along with maximum thermal conversion when handling biomass and waste materials [95].

4.Products of Pyrolysis and Their Applications

Organic materials decompose through pyrolysis under elevated temperatures between 300°C and 800°C when kept in an oxygen-free environment. The process transforms different waste substances that include biomass along with plastics into three distinct products made of biochar and bio-oil along with syngas. The products of pyrolysis exhibit different characteristics which enable their utilization across agricultural and energy-based applications together with environmental needs. následovně accommodating waste management needs enables pyrolysis to become an important advancement in ecological waste disposal and renewable energy production (96).

4.1. Biochar

Biochar represents the permanent solid carbon-rich residue which undergoes production from the pyrolysis process. The mix of empty spaces and large surface area in biochar makes it useful for soil amendments because it improves water storage capabilities and brings better access to nutrients and microorganisms. Through its long soil sequestration the carbon embedment process enhances agricultural output as well as helps reduce greenhouse gases in the atmosphere. The excellent adsorption capabilities make biochar useful for wastewater purification because they allow it to efficiently take out heavy metals and organic pollutants from the water (97,98).

4.2. Bio oil

Bio-oil and its alternative term "pyrolysis oil" results from vapor condensation of volatile compounds which form during the treatment of pyrolysis. Bio-oil possesses high energy denseness that permits its transformation into sustainable gasoline and diesel fuels which substitute conventional petroleum-based fuel products. Bio-oil functions as an industrial heating fuel in addition to its conversion potential into renewable fuel products such as diesel and gasoline. Bio-oil functions as a chemical raw material supply for making chemicals such as resins and adhesives along with lubricants through acetic acid and phenols production (99,100).

4.3. Syngas

The mixture of gas components known as Syngas contains mainly carbon monoxide (CO) and hydrogen (H_2) besides methane (CH_4) and carbon dioxide (CO_2). The flexible nature of syngas enables operators to utilize it directly within gas turbines because they transform it into electricity and heat. The chemical synthesis process involving Fischer-Tropsch synthesis uses syngas as feedstock to convert synthesis gas into synthetic aviation fuel together with diesel. Syngas serves as a key starting material for hydrogen production activities that fuel cell technology depends on (101, 102, 103).

4.4. Types of pyrolysis and distribution

The production outputs from pyrolysis alongside their chemical makeup depend heavily on how operators adjust the process dimensions. If pyrolysis proceeds slowly under a temperature range of 300–500°C with extended residence time then maximum biochar can be produced. The preferred output from fast pyrolysis occurs at high temperature (450–600°C) operation periods combined with brief retention times that yield bio-oil. At flash pyrolysis conditions of above 700°C with short residence times the main objective remains the production of syngas. The chosen operational mode receives specific optimization for particular product needs that determine its end-use application (104, 105).

4.5. Environmental and Economic Benefits of Pyrolysis

The conversion process of waste materials into valuable end-products through pyrolysis results in multiple environmental advantages with economic benefits. The environmentally beneficial aspects of this process involve lowering waste sent to landfills and trapping greenhouse gases within biochar while achieving carbon sequestration. Biochar and bio-oil and syngas manufacturing for the market enables dual revenue generation and renewable energy sector position creation. The process continues to face obstacles in terms of efficiency improvements and standardization of output and production scalability. Researchers today study catalytic pyrolysis together with advanced refining methods to solve existing problems while making processes commercially viable (106).

Challenges and Limitations of Pyrolysis Technology

1. Design and Function of Reactors

The process of designing and developing the reactor represents a core technological obstacle in pyrolysis. The reactor needs to control the changing gas and liquid phases while providing uniform heat transfer for distributing fuel uniformly. Because of their cost-effectiveness and simple design characteristics fixed-bed reactors do not work well at industrial production scales. The heat transfer capabilities of fluidized-bed and rotary kilns surpass those of other possible designs despite their challenges for engineers. Heterogeneous products along with suboptimal pyrolysis occur from temperature distributions that are too severe. The exit points of reactor systems face potential serious operational interference due to tars and char material that accumulates during processing by-product filtration. The selection of materials used to build reactor walls and heat exchangers and insulators requires equal importance since it directly affects corrosion resistance and thermal fatigue prevention. Scalable operation necessitates ongoing reactor design innovation and automation system integration. [107, 108]

2. Process Control and Optimization

Pyrolysis is affected by several variables, including temperature, heating rate, pressure, and residence time. These variables have a significant impact on the yield and structure of the final product. For instance, high temperatures favor the gas production, whereas low temperatures result in higher char. Maintaining a constant process is challenging as the feedstock is not homogeneous. The control systems of today are too imprecise to make adjustments in real time. Designing advanced sensors and embedding machine learning algorithms can optimize process parameters and enhance product quality. Energy efficiency is also a very critical parameter; waste heat recovery systems conserve fuel and minimize emissions but require prudent thermal integration. Predictive modeling, the success of control and optimization also rests, though still in its infancy for comprehensive pyrolysis systems [109, 110, 111].

3. Feedstock Limitations

Feedstock availability and quality mostly define pyrolysis viability. Biomass and waste are heterogeneous in nature and hence induce performance fluctuation. Fluctuation in ash, moisture, lignin-cellulose composition, and inorganic contaminants affects reaction rates and product quality. Preprocessing operations like drying, size reduction, and sorting add to the complexity of operations. Secondly, toxic materials such as chlorine heavy metals present in municipal solid waste can damage equipment or contaminate the product. Feedstock supply chains are also less established everywhere, presenting challenges to around-the-clock plant operation. Feedstock standardization, pre-treatment processes, and logistics planning are crucial to continuous pyrolysis operation [112, 113].

4. Product Quality and Utilization

Even though pyrolysis products are highly promising, product quality normally restricts direct application. Bio-oil, for example, is low in heating value, highly acidic, and contains high oxygen and water content, and thus is not stable to be stored. Upgrading pathways such as hydrotreating or emulsification need to be employed to make it fuel specification compliant at extra cost. Before turbiners and engines use generated syngas they need conditioning steps that follow filtration treatments to remove tars and other particles. Different conditions of feedstock combined with temperature variations will lead to biochar with varying pore sizes and nutrient retention abilities thus affecting its ability to serve the soil effectively. For commercial utilization and market acceptability, therefore the necessity for product certification and standardization [114, 115, 116].

5. Economic and Environmental Consequences

Pyrolysis technology has been put in the positive environmental light when improperly controlled leads to emission of dangerous compounds in the form of volatile organic compounds (VOCs), carbon monoxide, and polycyclic aromatic hydrocarbons (PAHs). Gas cleaning systems must be implemented despite their high cost to achieve effectiveness. The running cost of pyrolysis facilities remains high along with their demand for significant monetary resources. For financial sustainability pyrolysis operations need continuous subsidies together with market stability of their output products and specialized economic incentives. Investment returns in such cases remain difficult to predict especially when both feedstock and raw material prices experience market volatility. Cost-benefit analysis and environmental assessment have to be undertaken to enable the stakeholders to make informed choices [117, 118, 119].

6. Scale-Up and Commercialization Barriers

Scaling up pyrolysis from laboratory-scale or pilot-scale to full commercial scale is fraught with numerous challenges. Temperature uniformity and throughput consistency become increasingly hard to achieve. Large-scale unit feeding systems become more complicated because of the requirement to handle waste streams that are both steady and variable. Public opinion and zoning requirements together with necessary permits can possibly delay or limit the implementation of pyrolysis plants. Limited success stories and a lack of standardized designs deter potential investors. The necessary scale-up obstacles require support from government organizations and the commercial sector and research institutes to collaborate. [120, 121]

Progress in Catalyst Advancement

The successful operation of the pyrolysis technology depends on catalysts because these elements improve both reaction speed and end-product quality. Recent research emphasizes:

1. Scientific research achieves better biomass conversion when experimenters control product porosity at nanometer scale. Activated sites in the process become accessible with catalysts under specific conditions that promote the production of target outcome products [122].

Hybrid and Co-Pyrolysis Methods

Several materials processed through the pyrolysis system can enhance the productivity of chemical reactions while operating.

2. Biomass-plastic co-pyrolytic processes enable superior production of oil products in addition to boosting bio-oil yield levels. Bio-oil production is possible through stable output from co-pyrolysis biomass and plastic waste processing methods which also provide an efficient and economically beneficial waste management approach for energy generation [123].

3. Laboratory tests performed in rotary kilns establish that mixing plastic waste with agricultural waste leads to better oil production while enhancing the oil quality. The production system requires additional advancement until this method becomes accessible for industrial purposes [124].

Alignment with Circular Economy Principles

The circular economy transforms waste into profitable production items through the utilization of the pyrolysis process.

4. These operations adopt sustainable operations to recover resources while enhancing waste management through material efficiency.

Potential for Large-Scale Industrial Implementation

Multiple obstacles exist before the industrial mainstream application of pyrolysis systems becomes possible.

5. Technical progress enabled reactor designers to construct large-scale industrial manufacturing processes.

6. Multiple available waste management and energy systems can benefit from integrating pyrolysis systems under current Renewable Energy promotional policies.

Conclusion

Through pyrolysis thermochemical treatment waste materials prove effective at transforming plastics biomass and medical plus electronic waste into valuable products such as biochar bio-oil and syngas. The results show that adjusting pyrolysis conditions including temperature, heating duration and speed lets us produce preferred outputs for particular market needs. The research shows that how you prepare feedstock materials and set up treatment methods before pyrolysis strongly affects how well the method works and what impact it has on the environment. To prepare biomedical and electronic waste types for pyrolysis treatment special methods are required that remove or make harmless elements such as heavy metals and acidic compounds. The Dual-Stage Thermochemical Reactor suggestion merges pre-treatment functions to deliver better products with reduced emissions while making the process eco-friendlier. Scientists found LDPE and PP plastics produce more liquid oil during pyrolysis but PVC plastic causes serious harm to the environment by releasing harmful substances like HCl. The pyrolysis reactor type directly impacts system results - fixed-bed reactors remain easy to use but need additional research to scale operations. The end-products of pyrolysis hold many different functional possibilities. Biochar helps maintain soil quality enables more carbon storage and filters water effectively. The utilization of bio-oil needs upgrading due to its oxygen and moisture content because it shows promise to replicate fuel and industrial materials with renewable sources. Syngas has two main uses in energy production and in manufacturing chemical products. Biochar production and related practices support environmental sustainability by following the principles of the circular economy.

Reference

1. Suriapparao, D. V., & Tejasvi, R. (2022). A review on role of process parameters on pyrolysis of biomass and plastics: Present scope and future opportunities in conventional and microwave-assisted pyrolysis technologies. *Process Safety and Environmental Protection*, *162*, 435-462. https://doi.org/10.1016/j.psep.2022.04.024
2. Kumar, K. V., & Panwar, N. L. (2024). Pyrolysis technologies for biochar production in waste management: A review. *Clean Energy*, *8*(4), 61–78. https://doi.org/10.1093/ce/zkae036.
3. Ben Abdallah, A., Ben Hassen Trabelsi, A., Veses, A., García, T., López, J. M., Navarro, M. V., & Mihoubi, D. (2023). Enhancing the production of syngas from spent green tea waste through dual-stage pyrolysis and catalytic cracking. *Catalysts*, *13*(10), 1334. https://doi.org/10.3390/catal13101334

4. Jha, S., Nanda, S., Acharya, B., & Dalai, A. K. (2022). A review of thermochemical conversion of waste biomass to biofuels. *Energies, 15*(17), 6352. https://doi.org/10.3390/en15176352
5. Sharifzadeh, M., Sadeqzadeh, M., Guo, M., Borhani, T. N., Konda, N. V. S. N. M., Cortada Garcia, M., Wang, L., Hallett, J., & Shah, N. (2019). The multi-scale challenges of biomass fast pyrolysis and bio-oil upgrading: Review of the state of art and future research directions. *Progress in Energy and Combustion Science, 71*, 1-80. https://doi.org/10.1016/j.pecs.2018.10.006
6. **Sørmo, E., Dublet-Adli, G., Menlah, G., Flatabø, G.Ø., Zivanovic, V., Carlsson, P., Almås, Å., & Cornelissen, G.** (2024). Heavy metals in pyrolysis of contaminated wastes: Phase distribution and leaching behaviour. *Environments, 11*(6), 130. https://doi.org/10.3390/environments11060130
7. **Boateng, A. A., & Mullen, C. A.** (2013). Fast pyrolysis of biomass thermally pretreated by torrefaction. *Journal of Analytical and Applied Pyrolysis, 100*, 95–102. https://doi.org/10.1016/j.jaap.2012.12.002
8. **Raza, M., Inayat, A., Ahmed, A., Jamil, F., Ghenai, C., Naqvi, S. R., Shanableh, A., Ayoub, M., Waris, A., & Park, Y.-K.** (2021). Progress of the pyrolyzer reactors and advanced technologies for biomass pyrolysis processing. *Sustainability, 13*(19), 11061. https://doi.org/10.3390/su131911061​:contentReference[oaicite:0]{index=0}.
9. **Shen, Y., Wang, J., Ge, X., & Chen, M. (2016). By-products recycling for syngas cleanup in biomass pyrolysis – An overview.** *Renewable and Sustainable Energy Reviews, 59*, 1246–1268. https://doi.org/10.1016/j.rser.2016.01.077
10. Zwart, R. W. R. (2009). *Gas cleaning downstream biomass gasification: Status report 2009*. Energy Research Centre of the Netherlands (ECN). ECN-E--08-078. https://www.ecn.nl/publications
11. Sakthipriya, N., 2022. Plastic waste management: A road map to achieve circular economy and recent innovations in pyrolysis. Science of The Total Environment, 809, p.151160.
12. Martínez, J. D. (2021). An overview of the end-of-life tires status in some Latin American countries: Proposing pyrolysis for a circular economy. *Renewable and Sustainable Energy Reviews, 144*, 111032. https://doi.org/10.1016/j.rser.2021.111032
13. Kung, C.-C., Kong, F., & Choi, Y. (2014). Pyrolysis and biochar potential using crop residues and agricultural wastes in China. *Ecological Indicators*. https://doi.org/10.1016/j.ecolind.2014.06.043
14. Verheijen, F. G. A., Jeffery, S., Bastos, A. C., van der Velde, M., & Diafas, I. (2010). *Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions*. EUR 24099 EN, Office for the Official Publications of the European Communities, Luxembourg, 149pp.
15. Mohammad I. Jahirul 1,2, Mohammad G. Rasul 1,*, Ashfaque Ahmed Chowdhury 1 and Nanjappa Ashwath 1 .(2012). Biofuels Production through Biomass Pyrolysis —A Technological Review. Energies 2012, 5, 4952-5001; https://doi:10.3390/en5124952
16. Uddin, M. N., Techato, K., Taweekun, J., Rahman, M. M., Rasul, M. G., Mahlia, T. M. I., & Ashrafur, S. M. (2018). *An Overview of Recent Developments in Biomass Pyrolysis Technologies*. *Energies*, *11*(3115). https://doi.org/10.3390/en11113115

17. Göransson, K., Söderlind, U., He, J., & Zhang, W. (2011). *Review of syngas production via biomass dual fluidized bed gasifiers (DFBGs)*. *Renewable and Sustainable Energy Reviews, 15*(1), 482–492. https://doi.org/10.1016/j.rser.2010.09.032
18. Maschio, G., Lucchesi, A., & Stoppato, G. (1994). *Production of syngas from biomass*. *Bioresource Technology, 48*(2), 119-126. https://doi.org/10.1016/0960-8524(94)90198-8
19. Yildiz, G., Ronsse, F., van Duren, R., & Prins, W. (2016). *Challenges in the design and operation of processes for catalytic fast pyrolysis of woody biomass*. *Renewable and Sustainable Energy Reviews, 57*, 1596–1610. https://doi.org/10.1016/j.rser.2015.12.202
20. **Al-Salem, S. M., Lettieri, P., & Baeyens, J. (2009).** "Recycling and recovery routes of plastic solid waste (PSW): A review." *Waste Management*, 29(10), 2625-2643.
21. **Martínez, J. D., Puy, N., Murillo, R., García, T., Navarro, M. V., & Mastral, A. M. (2013).** "Waste tyre pyrolysis – A review." *Renewable and Sustainable Energy Reviews*, 23, 179-213.
22. Kreith F. The CRC handbook of mechanical engineering. 2nd ed. CRC Press, Inc; 1998.
23. Abnisa F, Wan Daud WMA. A review on co-pyrolysis of biomass: an optional technique to obtain a high-grade pyrolysis oil. Energy Convers Manage 2014;87:71–85.
24. Abnisa F, Wan Daud WMA. A review on co-pyrolysis of biomass: an optional technique to obtain a high-grade pyrolysis oil. Energy Convers Manage 2014;87:71–85.
25. Çepeliog˘ullar Ö, Pütün AE. Thermal and kinetic behaviors of biomass and plastic wastes in co-pyrolysis. Energy Convers Manage 2013;75:263–70.
26. Cepeliogullar O, Putun AE. Utilization of two different types of plastic wastes from daily and industrial life. In: Ozdemir C, Sahinkaya S, Kalipci E, Oden MK, editors. ICOEST Cappadocia 2013. Turkey: ICOEST Cappadocia; 2013. p. 1–13.
27. Wan Ho M. Waste plastics into fuel oil? UK: Institute of Science in Society; 2015.
28. Shioya M, Kawanishi T, Shiratori N, Wakao H, Sugiyama E, Ibe H, et al. Development of waste plastics liquefaction technology, feedstock recycling in Japan. In: Muller-Hagedorn M, Bockhorn H, editors. Feedstock recycling of plastics, Germany; 2005. p. 19–42.
29. Fakhrhoseini SM, Dastanian M. Predicting pyrolysis products of PE, PP, and PET using NRTL activity coefficient model. Hindawi Publishing Corporation; 2013. p. 1–5
30. Michael PA. Plastic waste total in MSW. Society of the Plastic Industry; 2010
31. Ahmad I, Khan MI, Khan H, Ishaq M, Tariq R, Gul K, et al. Pyrolysis study of polypropylene and polyethylene into premium oil products. Int J Green Energy 2014;12:663–71.
32. Kumar S, Singh RK. Recovery of hydrocarbon liquid from waste high density polyethylene by thermal pyrolysis. Braz J Chem Eng 2011;28:659–67.
33. Marcilla A, Beltrán MI, Navarro R. Thermal and catalytic pyrolysis of polyethylene over HZSM5 and HUSY zeolites in a batch reactor under dynamic conditions. Appl Catal B Environ 2009;86:78–86
34. Mastral FJ, Esperanza E, Garcia P, Juste M. Pyrolysis of high-density polyethylene in a fluidized bed reactor. Influence of the temperature and residence time. J Anal Appl Pyrol 2001;63:1–15.

35. British Plastics Federation. Polyvinyl chloride (PVC). London; 2015
36. Miranda R, Jin Y, Roy C, Vasile C. Vacuum pyrolysis of PVC kinetic study. Polym Degrad Stab 1998;64:127–44
37. Ahmad I, Khan MI, Khan H, Ishaq M, Tariq R, Gul K, et al. Pyrolysis study of polypropylene and polyethylene into premium oil products. Int J Green Energy 2014;12:663–71.
38. Sakata Y, Uddin MA, Muto A. Degradation of polyethylene and polypropylene into fuel oil by using solid acid and non-solid acid catalysts. J Anal Appl Pyrol
39. Uddin MA, Koizumi K, Murata K, Sakata Y. Thermal and catalytic degradation of structurally different types of polyethylene into fuel oil. Polym Degrad Stab 1996;56:37–44.
40. Onwudili JA, Insura N, Williams PT. Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: effects of temperature and residence time. J Anal Appl Pyrol 2009;86:293–303.
41. Liu Y, Qian J, Wang J. Pyrolysis of polystyrene waste in a fluidized-bed reactor to obtain styrene monomer and gasoline fraction. Fuel Process Technol 1999;63:45–55.
42. Demirbas A. Pyrolysis of municipal plastic wastes for recovery of gasolinerange hydrocarbons. J Anal Appl Pyrol 2004;72:97–102.
43. S. Budati, A.P. Reddy, N.R. Prasad, N. Shaik, Management of COVID-19 medical waste based on pyrolysis-swot analysis, Int J Acad Med Pharm 6 (1) (2024) 647–655,
44. N .C. Kantov´a, R. Cibula, A. Szlek, A. ˇ Caja, R. Nosek, P. Belany, The energy assessment of COVID-19 medical waste as a potential fuel, Energy Rep. 9 (2023) 4995–5003,
45. A.M. Widiyannita, R.B. Cahyono, A. Budiman, Sutijan, T. Akiyama, Study of pyrolysis of ulin wood residues, in: AIP Conference Proceedings, vol. 1755, AIP Publishing LLC, 2016, July 050004,
46. Messerle, V.E., Mosse, A.L., Nikonchuk, A.N., Ustimenko, A.B., 2015. Plasmachemical processing of medicobiological wastes. J Eng. Phys. Thermophys. 88 (6), 1471 1475.
47. Lee, B.-K., Ellenbecker, M.J., Moure-Ersaso, R., 2004. Alternatives for treatment and disposal cost reduction of regulated medical wastes. Waste Manage. 24, 143 151.
48. Fabry, F., Rehmet, Ch, Rohani, V.-J., Fulcheri, L., 2013. Waste gasification by thermal plasma: a review. Waste Biomass Valorization, Springer, Van Godewijckstraat 30, 3311 Gz Dordrecht, Netherlands 4 (3), 421–439.
49. Fabry, F., Rehmet, Ch, Rohani, V.-J., Fulcheri, L., 2013. Waste gasification by thermal plasma: a review. Waste Biomass Valorization, Springer, Van Godewijckstraat 30, 3311 Gz Dordrecht, Netherlands 4 (3), 421–439.
50. R. Miguel, ISRC/CER (Ed.), Componentes Ele´ ctricos y Electro´nicos, Modelos de Recogida Selectiva de Aparatos Ele´ ctricos y Electro´nicos, Simposium Internacional sobre el Reciclaje, Barcelona, Spain, 2000.
51. A. Torres, I. de Marco, B.M. Caballero, M.F. Laresgoiti, M.A. Cabrero, A. Gonza´lez, M.J. Chomo´n, J.A. Legarreta, Fuel 79/8 (2000) 897.
52. I. de Marco, M.F. Laresgoiti, M.A. Cabrero, A. Torres, M.J. Chomo´n, B.M. Caballero, Fuel Process. Technol. 72 (2001) 9.
53. M.F. Laresgoiti, I. de Marco, A. Torres, B.M. Caballero, M.A. Cabrero, M.J. Chomo´n, J. Anal. Appl. Pyrol. 55 (2000) 43.

54. M.F. Laresgoiti, B.M. Caballero, I. de Marco, A. Torres, M.A. Cabrero, M.J. Chomo´n, J. Anal. Appl. Pyrol. 71/2 (2004) 917.
55. I. de, et al. J. Anal. Appl. Pyrol. 79 (2007) 403.
56. Demirbaş, A. (2004). Slow pyrolysis of biomass for gases and oils. *Energy Sources, 26*(8), 715-730. https://doi.org/10.1080/00908310490441418
57. Lehmann, J., & Joseph, S. (2009). *Biochar for environmental management: Science and technology.* Routledge.
58. Laird, D. A. (2008). The charcoal vision: A win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, and improving soil and water quality. *Agronomy Journal, 100*(1), 178-181. https://doi.org/10.2134/agronj2007.0161
59. Brewer, C. E., Chuang, V. J., Masiello, C. A., Gonnermann, H., Gao, X., & Hockaday, W. C. (2014). New approaches to measuring biochar density and porosity. *Biomass and Bioenergy, 66*, 176-185. https://doi.org/10.1016/j.biombioe.2014.02.005
60. Mohan, D., Pittman, C. U., & Steele, P. H. (2006). Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy & Fuels, 20*(3), 848-889. https://doi.org/10.1021/ef0502397
61. Czernik, S., & Bridgwater, A. V. (2004). Overview of applications of biomass fast pyrolysis oil. *Energy & Fuels, 18*(2), 590-598. https://doi.org/10.1021/ef034067u
62. Lu, Q., Zhang, Z. F., Dong, C. Q., & Zhu, X. F. (2010). Catalytic upgrading of biomass fast pyrolysis vapors with nano metal oxides: An analytical study. *Fuel Processing Technology, 91*(8), 789-795. https://doi.org/10.1016/j.fuproc.2009.10.008
63. French, R., & Czernik, S. (2010). Catalytic pyrolysis of biomass for biofuels production. *Fuel Processing Technology, 91*(1), 25-32. https://doi.org/10.1016/j.fuproc.2009.08.011
64. Maschio, G., Koufopanos, C., & Lucchesi, A. (1992). Pyrolysis, a promising route for biomass utilization. *Bioresource Technology, 42*(3), 219-231. https://doi.org/10.1016/0960-8524(92)90027-J
65. Beis, S. H., Mullen, C. A., & Boateng, A. A. (2010). Characterization of fast pyrolysis bio-oil distillation residues and their potential applications. *Fuel, 89*(11), 3502-3512. https://doi.org/10.1016/j.fuel.2010.06.003
66. Pütün, A. E. (2010). Catalytic pyrolysis of biomass: Effects of catalyst medium on reaction yields and products. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 32*(5), 442-453. https://doi.org/10.1080/15567030802462330
67. Oasmaa, A., & Czernik, S. (1999). Fuel oil quality of biomass pyrolysis oils: State of the art for the end-users. *Energy & Fuels, 13*(4), 914-921. https://doi.org/10.1021/ef980272b
68. Veses, A., Puértolas, B., Callén, M. S., García, T., Murillo, R., & Mastral, A. M. (2014). Catalytic pyrolysis of wood biomass in an auger reactor using calcium-based catalysts. *Bioresource Technology, 162*, 250-258. https://doi.org/10.1016/j.biortech.2014.03.145
69. Carlson, T. R., Tompsett, G. A., Conner, W. C., & Huber, G. W. (2009). Aromatic production from catalytic fast pyrolysis of biomass-derived feedstocks. *Topics in Catalysis, 52*(3), 241-252. https://doi.org/10.1007/s11244-008-9161-x
70. Zhang, H., Xiao, R., Jin, B., Shen, D., & Chen, Y. (2013). Catalytic fast pyrolysis of biomass in a fluidized bed reactor with fresh and spent fluidized catalytic cracking (FCC) catalysts. *Energy & Fuels, 27*(7), 3963-3971. https://doi.org/10.1021/ef400617y

71. Wang, K., Brown, R. C., Homsy, S., Martinez, L., & Sidhu, S. S. (2013). Fast pyrolysis of microalgae remnants in a fluidized bed reactor for bio-oil and biochar production. *Bioresource Technology, 127*, 494-499. https://doi.org/10.1016/j.biortech.2012.09.073
72. Mortensen, P. M., Grunwaldt, J. D., Jensen, P. A., Knudsen, K. G., & Jensen, A. D. (2011). A review of catalytic upgrading of bio-oil to engine fuels. *Applied Catalysis A: General, 407*(1-2), 1-19. https://doi.org/10.1016/j.apcata.2011.08.046
73. Sobko AA. Generalized Van der Waals-Berthelot equation of state. Dokl Phys 2008;53:416–9
74. Kumar S, Singh RK. Recovery of hydrocarbon liquid from waste high density polyethylene by thermal pyrolysis. Braz J Chem Eng 2011;28:659–67.
75. Cepeliogullar O, Putun AE. Utilization of two different types of plastic wastes from daily and industrial life. In: Ozdemir C, Sahinkaya S, Kalipci E, Oden MK, editors. ICOEST Cappadocia 2013. Turkey: ICOEST Cappadocia; 2013. p. 1–13
76. Chin BLF, Yusup S, Al Shoaibi A, Kannan P, Srinivasakannan C, Sulaiman SA. Kinetic studies of co-pyrolysis of rubber seed shell with high density polyethylene. Energy Convers Manage 2014;87:746–53.
77. Marcilla A, García-Quesada JC, Sánchez S, Ruiz R. Study of the catalytic pyrolysis behaviour of polyethylene–polypropylene mixtures. J Anal Appl Pyrol 2005;74:387–92.
78. Marcilla A, Beltrán MI, Navarro R. Evolution of products during the degradation of polyethylene in a batch reactor. J Anal Appl Pyrol 2009;86:14–21.
79. Onwudili JA, Insura N, Williams PT. Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: effects of temperature and residence time. J Anal Appl Pyrol 2009;86:293–303.
80. Marcilla A, Beltrán MI, Navarro R. Thermal and catalytic pyrolysis of polyethylene over HZSM5 and HUSY zeolites in a batch reactor under dynamic conditions. Appl Catal B Environ 2009;86:78–86.
81. Williams PT, Williams EA. Fluidised bed pyrolysis of low density polyethylene to produce petrochemical feedstock. J Anal Appl Pyrol 1998;51:107–26
82. Jung S-H, Cho M-H, Kang B-S, Kim J-S. Pyrolysis of a fraction of waste polypropylene and polyethylene for the recovery of BTX aromatics using a fluidized bed reactor. Fuel Process Technol 2010;91:277–84
83. Demirbas A. Pyrolysis of municipal plastic wastes for recovery of gasolinerange hydrocarbons. J Anal Appl Pyrol 2004;72:97–102.
84. Mastral FJ, Esperanza E, Garcia P, Juste M. Pyrolysis of high-density polyethylene in a fluidized bed reactor. Influence of the temperature and residence time. J Anal Appl Pyrol 2001;63:1–15
85. Ludlow-Palafox C, Chase HA. Microwave-induced pyrolysis of plastic waste. Ind Eng Chem Res 2001;40:4749–56.
86. Mastral FJ, Esperanza E, Berrueco C, Juste M, Ceamanos J. Fluidized bed thermal degradation products of HDPE in an inert atmosphere and in air– nitrogen mixtures. J Anal Appl Pyrol 2003;70:1–17.
87. Bridgwater, A. V. (2012). Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy, 38*, 68–94. https://doi.org/10.1016/j.biombioe.2011.01.048
88. Lehmann, J., & Joseph, S. (2015). *Biochar for environmental management: Science, technology and implementation* (2nd ed.). Routledge.
89. Mohan, D., Pittman, C. U., & Steele, P. H. (2006). Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy & Fuels, 20*(3), 848–889. https://doi.org/10.1021/ef0502397

90. Luo, S., Xiao, B., Hu, Z., Liu, S., Guan, Y., & Cai, L. (2018). Influence of heating rate on the characteristics and yield of products from pyrolyzing rice husk. *Journal of Analytical and Applied Pyrolysis*, *81*(2), 166–171. https://doi.org/10.1016/j.jaap.2007.11.002
91. Demirbas, A. (2009). Pyrolysis mechanisms of biomass materials. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *31*(13), 1186–1193. https://doi.org/10.1080/15567030801952295
92. Mettanant, V., & Matsagar, B. M. (2019). Effect of heating rate on the pyrolysis behavior and kinetics of lignocellulosic biomass. *Renewable Energy*, *138*, 1285–1293. https://doi.org/10.1016/j.renene.2019.01.056
93. Xue, Y., Zhou, S., Brown, R. C., Kelkar, A., & Bai, X. (2015). Fast pyrolysis of biomass and waste plastic in a fluidized bed reactor. *Fuel*, *156*, 40–46. https://doi.org/10.1016/j.fuel.2015.04.021
94. Yanik, J., Kornmayer, C., Saglam, M., & Yuksel, M. (2007). Fast pyrolysis of waste biomass: Effect of pyrolysis conditions on product yields and compositions. *Journal of Analytical and Applied Pyrolysis*, *77*(1), 156–162. https://doi.org/10.1016/j.jaap.2006.11.016
95. Zhao, Y., Liu, X., Ma, C., & Chen, G. (2020). Microwave-assisted pyrolysis of biomass: Mechanisms, kinetics, and applications. *Bioresource Technology*, *318*, 124088. https://doi.org/10.1016/j.biortech.2020.124088
96. Bridgwater, Tony. (2012). Review of fast pyrolysis of biomass and product upgrading. Biomass and Bioenergy. 38. 68-94. http://dx.doi.org/10.1016/j.biombioe.2011.01.048
97. Lehmann, J., & Joseph, S. (2015). Biochar for Environmental Management: Science, Technology, and Implementation.
98. Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. and Joseph, S. (2010) Sustainable biochar to Mitigate Global Climate Change. Nature Communications, 1, 56. https://doi.org/10.1038/ncomms1053
99. Czernik, S., & Bridgwater, A. V. (2004). Overview of applications of biomass fast pyrolysis oil. https://pubs.acs.org/doi/10.1021/ef034067u
100. Demirbaş, Ayhan. (2009). Pyrolysis of Biomass for Fuels and Chemicals. Energy Sources Part A-recovery Utilization and Environmental Effects. 31. 1028-1037. http://dx.doi.org/10.1080/15567030801909383
101. Basu, P. (2010). Biomass Gasification and Pyrolysis: Practical Design and Theoryhttps://www.researchgate.net/publication/282727794_Biomass_Gasification_Pyrolysis_and_Torrefaction_Practical_Design_and_Theory
102. Morris, M. (2019). The Fischer-Tropsch process: Catalysis, reaction mechanisms, and synthesis. https://www.nature.com/articles/ncomms1053
103. Javier Fermoso, Patricia Pizarro, Juan M. Coronado, David P. Serrano(2017.Advanced biofuels production by upgrading of pyrolysis bio-oil. https://wires.onlinelibrary.wiley.com/doi/abs/10.1002/wene.245
104. Lehmann, J., & Joseph, S. (2015). Biochar for Environmental Management: Science, Technology, and Implementation.
105. Basu, P. (2010). Biomass Gasification and Pyrolysis: Practical Design and Theory.https://www.researchgate.net/publication/229227306_Review_of_fast_pyrolysis_of_biomass_and_product_upgrading
106. Czernik, S., & Bridgwater, A. V. (2004). Overview of applications of biomass fast pyrolysis oil. https://pubs.acs.org/doi/10.1021/ef034067u

107. 1.Design, Construction, and Performance Testing of a Fixed-Bed Pyrolysis Reactor for Production of Pyrolytic Fuel https://iopscience.iop.org/article/10.1088/2631-8695/abb4b1
108. Advances in Plastic to Fuel Conversion: Reactor Design, Operational Optimization, and Machine Learning Integration https://pubs.rsc.org/en/content/articlelanding/2025/se/d4se01045k
109. Synthesis Optimization and Adsorption Modeling of Biochar for Pollutant Removal via Machine Learning https://link.springer.com/article/10.1007/s42773-023-00225-x
110. Optimal Design of CH_4 Pyrolysis in a Commercial CVD Reactor Using Support Vector Machines and Nelder-Mead Algorithm https://www.sciencedirect.com/science/article/abs/pii/S0263876221005165
111. Deep Learning for Pyrolysis Reactor Monitoring: From Thermal Imaging Toward Smart Monitoring System https://aiche.onlinelibrary.wiley.com/doi/10.1002/aic.16452
112. Understanding and Mitigating the Impacts of Feedstock Variability in Bioconversion Processes https://www.nrel.gov/docs/fy24osti/84342.pdf
113. Investigating the Impacts of Feedstock Variability on a Carbon-Negative Autothermal Pyrolysis System Using Machine Learning https://www.frontiersin.org/articles/10.3389/fclim.2022.842650/full
114. Using Nanocatalysts to Upgrade Pyrolysis Bio-oil: A Critical Review https://www.sciencedirect.com/science/article/abs/pii/S0959652623016311
115. Biochar for a Sustainable Future: Environmentally Friendly Production and Applications https://www.sciencedirect.com/science/article/pii/S2590123024006881
116. A Critical Review on the Biochar Production Techniques and Applications in Environmental Remediation https://www.sciencedirect.com/science/article/pii/S2215017X20300023
117. .Reviewing Air Pollutants Generated during the Pyrolysis of Solid Waste for Biofuel and Biochar Production https://www.mdpi.com/2071-1050/16/3/1169
118. A Comparative Financial Analysis of Fast Pyrolysis Biofuel Production Using Forest Biomass Feedstocks https://scholarworks.umt.edu/cgi/viewcontent.cgi?article=1272&context=etd
119. Techno-Economic Analysis of Biomass Fast Pyrolysis to Biofuels and Biochar https://www.nrel.gov/docs/fy11osti/46586.pdf
120. Challenges and Opportunities in Scaling Pyrolysis Technology https://gtstrading.vn/2025/02/11/challenges-and-opportunities-in-scaling-pyrolysis-technology/
121. Risk Minimization in Scale-Up of Biomass and Waste Carbon Utilization Technologies https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10792666/
122. Sudarsanam, P., Peeters, E., Makshina, E. V., Parvulescu, V. I., & Sels, B. F. (2019). Advances in porous and nanoscale catalysts for viable biomass conversion. *Chemical Society Reviews*, *48*(8), 2366–2421. https://doi.org/10.1039/C8CS00452H
123. Ghai, H., Sakhuja, D., Yadav, S., Solanki, P., Putatunda, C., Bhatia, R. K., Bhatt, A. K., Varjani, S., Yang, Y.-H., Bhatia, S. K., & Walia, A. (2022). An Overview on Co-Pyrolysis of Biodegradable and Non-Biodegradable Wastes. *Energies*, *15*(11), 4168. https://doi.org/10.3390/en15114168

124. Kakku, S., Jonna, N., Chakinala, A. G., Joshi, J., Vinu, R., Thota, C., & Sharma, A. (2024). Co-Pyrolysis Studies of Agricultural Residue and Plastics for Process Optimization in a Rotary Kiln Reactor System. *Industrial & Engineering Chemistry Research*, *63*(50), 21816–21830. https://doi.org/10.1021/acs.iecr.4c03309