

A Review of the Life Cycle Analysis for Plastic Waste Pyrolysis

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Abstract

Pyrolysis is a rapidly expanding chemical-based recyclable method that complements physical recycling. It avoids improper disposal of post-consumer polymers and mitigates the ecological problems linked to the production of new plastic. Nevertheless, while there is a consensus that pyrolysis might be a crucial technology in the years to come, more discussions are needed to address the challenges related to scaling up, the long-term sustainability of the process, and additional variables essential to the advancement of the green economy. Herein, it emphasizes knowledge gaps and methodological issues in current Life Cycle Assessment (LCA), underlining the need for standardized techniques and updated data to support robust decision-making for adopting pyrolysis technologies in waste management strategies. For this purpose, this study reviews the LCAs of pyrolytic processes, encompassing the complete life cycle, from feedstock collection to end-product distribution, including elements such as energy consumption, greenhouse gas emissions, and waste creation. Hence, we evaluate diverse pyrolysis processes, including slow, rapid, and catalytic pyrolysis, emphasizing their distinct efficiency and environmental footprints. Furthermore, we evaluate the impact of feedstock composition, process parameters, and scale of operation on the overall sustainability of pyrolysis-based plastic waste treatment by integrating results from current literature and identifying essential research needs. Therefore, this paper argues that existing LCA studies need more coherence and accuracy. It follows a thorough evaluation of previous research and suggests new insights into methodologies and restrictions.

Keywords

Plastics, Thermal Recycling, Carbon Dioxide Emissions, Life Cycle Evaluation, Pyrolysis

1. Introduction

Plastics are thermally stable substances that are thermally generated [1]. They are one of humanity's most prevalent synthetic materials, and their broad use has eased many facets of modern life. There is a large variety of polymers, each with distinct features that make them perfect for use. Polymers like polyethylene (PE), polypropylene (PP), vinyl chloride (PVC), and polyethylene terephthalate (PET) are highly sought-after chemical compounds, followed by polystyrene (PS) and polyurethane (PUR). The packaging industry has been the most important in terms of use, comprising about 40% of the total [2]. Thermal plastic is a polymer derived from petroleum-based products that can be easily sculpted into various forms to fulfill diverse requirements. Still, it has also caused a tremendous environmental crisis—approximately 80% of the 8300 million metric tons of plastic made before 1950 remains alive within our garbage dumps, streams, or seas [3]. If the present rates persist, the situation is projected to use twenty percent in the year 2050, along with consuming fifteen percent of our planet's aggregate fossil funds [4]. On an annual basis, 95 percent of plastic wrapping supplies, costing approximately USD 80 - 120 billion, are employed for only one function and are discarded as garbage afterward [5]. Consequently, considerable manufacture of recyclable items with crude oil implies a critical scarcity of natural resources, contributing to enormous financial and material loss. Further, since over 99 percent of the material is created by and manufactured employing power gained via petroleum and coal, it is identified as a substantial as well as the rising driver of planetary climate change [6].

In light of the rise of public focus on plastic waste, recycling plastic has become an easy commercial operation [7] [8] [9] [10]. For this explanation, most businesses today are in a situation where they have to offer and declare “plastic recycling regulation” [11]. This helps enlighten consumers about the problem of plastic, but it sometimes indicates that proper remedies have been adopted. It is crucial to underline that alternative items will not replace 83 percent of plastic components utilized now [12], implying that recyclable technology needs to be created and deployed to lessen the surrounding costs arising from irresponsibly abandoned postconsumer. They are possible to recycle and reuse as starting points for the development of additional goods [13]. Waste treatment techniques may be split into recyclable materials, chemical recycling, and energy recovery. Here a difference is created between post-industrial and post-consumer application, mechanical recycling typically involves the primary choice; nevertheless, owing to certain fundamental restrictions, recyclable chemicals provide the sole practicable recycling alternative in numerous cases [5] [14] [15].

Even though it is clear that nylon recycling rates are still abysmal, it remains apparent that recent firms and technology are developing in this sector to assist in raising recycling rates [16] [17]. For example, chemical recycling technologies may enable the recuperation of the majority of the organic value of material, which represents the key feature of the cyclic economy. Numerous merit papers

of review have been released over the past decade, indicating the relevance and advantages of pyrolysis for reusing postconsumer plastic materials compared with alternative final stages of life methods [5] [16]-[44]. Nonetheless, specific technologies used economically can be considerably distinct from the ones typically employed for pursuing scientific inquiries, which might postpone innovation in the field.

Pyrolytic systems, such as Agilyx's fastener reactors, can process 50 tons daily. The scientific study focuses on bench-scale power plants employing thermogravimetric measurements and micro pyrolysis. However, variables including plastic waste, contaminants, reactor design, performance, carrier gases, and operating pressures have yet to be completely overlooked. Debates on perceptual characterization and cooperation with mathematical frameworks have been restricted, making improvement and management duties more challenging [36] [42] [45]; at the same time, most scientific research concentrates on bench-scale power plants, employing thermogravimetric measurements and micro pyrolysis [17] [44]. However, the influence of plastic waste, pollutants, reactor architecture, performance, carrier gases, and operating pressures on the process has been largely disregarded. Additionally, debates on the subjective characterization of the deterioration, with the cooperation of theoretical kinematic frameworks, have become constrained, leaving designing and carrying out improvement and management duties more challenging [45] [46] [47].

Life cycle assessment (LCA) is commonly employed to discover solutions with minimal ecological effect [48]. LCA includes a life cycle inventory (LCI), which tracks resources and pollutants released throughout the process [49]. The life cycle impact assessment (LCIA) component examines these data flows considering projected consequences across various areas, notably environmental toxicity, resource utilization, and climate change [50]. LCIA findings show probable harms to primary ecosystems, such as human well-being, ecological effectiveness, and biodiversity. Enhancing plastics' life cycle is crucial to conserving fossil fuels and resources, lowering uncontrolled plastic litter discharge into the ocean, and reducing plastic waste. Three steps involve tackling industry changes in plastics production, enhancing recycling, and recovering petroleum ether [51]. A couple of papers have been released concentrating on postconsumer pyrolysis of plastic and should, undoubtedly, be encouraged [52] [53] [54]. LCA assessments may statistically analyze carbon dioxide emissions, process toxicity, plus the advantages of recycled or virgin initial products like naphtha, liquified natural gas. They also emphasize the benefits of reused hydrocarbon feed flow and other pertinent aspects [55] [56] [57].

However, the lack of industry information and established collections of experimental data make creating a solid lifetime inventory and assessing the associated LCA models easier [58] [59]. Pyrolysis results may need to be more consistent owing to dependency on experimental equipment, inferring reproducibility difficulties, and explaining the apparent dispersion of data in scientific re-

search [5] [60]. LCA specialists may utilize existing data inappropriately owing to a lack of expertise about the recycling process and the enormous number of factors. For instance, utilizing pyrolysis data higher than 600°C, which is not frequent in commercial contexts, might lead to misleading conclusions. Additionally, the pyrolysis process relies on numerous parameters impacting item yields, resulting in skewed LCA stock [5] [60]. Furthermore, many critical concerns remain unaddressed due to varied industrial and academic environments. Assessments of waste disposal, polymer combustion, and physical reuse in chemical recycling studies sometimes neglect the complementing nature of mechanical recycling. Landfill waste collection and cremation are hazardous to the natural world and do not benefit postconsumer material, causing skewed findings in technical rival research [61].

To draw attention to several of the mentioned aspects, the rest of this section briefly examines the pyrolysis process and LCA experiments focus on the chemical recovery of polymeric materials. This section's major objective is to highlight the approaches most often to conduct the previously released life cycle analysis (LCA) studies and suggest areas for increasing uniformity and the representation of additional studies.

2. Pyrolysis Mechanism

Pyrolysis is a thermal and pressure-driven process that disintegrates complex polymer molecules into fewer and simpler ones. The process yields natural gas, petroleum, and char, resulting in significant value in manufacturing and factories. Researchers picked it because of its capacity to create vast amounts of liquid oil at a reasonable temperature [62]. Pyrolysis is versatile, allowing modifications in process parameters to optimize the product's output. The obtained liquid oil may be utilized without upgrading or modification in numerous applications [63]. Pyrolysis is a green technique that avoids contamination of water and utilizes gaseous by-products to compensate for the entire energy used by the plant [64]. The process handling approach is easier and more adaptable than conventional recycling processes since it doesn't involve a rigorous screening step, making it more straightforward to implement.

2.1. Various Types of Pyrolysis Processes

Pyrolysis procedures comprise diverse methods, such as slow, rapid, flash, catalytic, and vacuum pyrolysis, each having specific functioning circumstances and processes. Three primary kinds of pyrolysis procedures for biomass or plastic waste are distinguished by their combustion percentage, temperature, and vapor retention duration.

2.1.1. Slow Pyrolysis

Also called non-isothermal, it happens at moderate temperatures (350 to 550 Celsius), with one to 10°C/min warming charges and a more extended air resi-

dence period [65]. The primary outcome of the slow burn is firm leftover, dubbed tar, as a slow temperature rise that favors solid formation among several parallel-competitive reactions [66]. It usually produces oily liquid outputs of over 95 wt% from plastic trash [64]. Oil combustion has a thermal conductivity equal to standard diesel fuel (approximately 45 MJ/kg) and may be employed in diesel engines with simple modifications [65].

2.1.2. Fast Pyrolysis

Isothermal fast pyrolysis typically occurs between 500°C and 700°C. The raw material's heat intensity may reach above 1000°C/min, and the duration of the gas residence can sometimes be several seconds [67]. Rapid pyrolysis promotes fluid generation, and depending on the kind of substrate, fluid production might unexpectedly reach up to 90% of the polymeric material's breakdown [68].

2.1.3. Flash Pyrolysis

Flash pyrolysis, or Ultra-fast, involves heating the input to temperatures over 700°C, with high heating rates and gas stay times within the millisecond interval [66]. Flash pyrolysis may create more huge fuel outputs than rapid pyrolysis for biomass feedstocks. However, it varies from plastic garbage since it generates more gas than other items [69]. The byproducts derived during the pyrolysis of recyclable materials can be divided into fluid, solid residue, or gas [70].

2.1.4. Thermal Cracking

Thermal cracking or Pyrolysis is a thermal breakdown technique that occurs when polymers are subjected to high temperatures (often around 350°C and 900°C). This breaks down the components and produces fluid, gas, and charred char. The fuel is usually derived via the condensable component of the unstable item [71]. Thermal pyrolysis is a thermo-chemical treatment (TCT) process including the decrease of paraffin, isoparaffins, olefins, naphthenes, and aromatics in aqueous solutions, requiring temperatures up to 900°C owing to bond breakage and weakening [72]. This technique's physical parameters of the liquid fuel generated principally vary with the plastic category [73]. **Table 1** offers an overview of a few of the characteristics of fluid fuel originating through the pyrolysis of multiple polymers.

Table 1. Several features of fluid resulting from the pyrolysis of monoplasic input.

Polymer type	Volume 40°C (g/cm ³)	Thickness at 40°C (cSt)	Flash point (°C)	Calorific data (MJ/kg)	Appearance	References
HDPE	0.80 - 0.92	2.42 - 2.52	40 - 48	45.40	Lighter oil, Brown	[74]
LDPE	0.76 - 0.80	1.65 - 1.80	50	39.10	Lighter oil, Brown	[75]
PP	0.76 - 0.80	2.72	31 - 36	40	Lighter oil, Yellow	[76]
PET	0.08 - 0.90	NA	NA	28.20	Lighter oil, Brown	[77]
PS	0.85 - 0.86	1.4 at 50°C	28	43.00	Lighter oil, dark brown	[22]

NA: are not accessible for research.

2.1.5. Microwave Pyrolysis

Microwave pyrolysis (microwave-assisted pyrolysis) involves microwave heating of dielectric material. Microwaves interact with diverse materials in three ways: via conductors, perfect barriers, or absorbed and decaying according to their dielectric properties. In semiconductors, heat is produced via magnet-induced molecular rupture. Plastic microwave pyrolysis absorbs microwave radiation and delivers heat to plastic [71]. The uniformity of heat dispersion in microwave-induced pyrolysis is determined by physical features and absorbent volume ratio. Compared to thermal and enzymatic pyrolysis, it may be utilized to create value-added chemicals and fuels [78]. The method tries to heat polymer compounds effectively and correctly. However, due to weak dielectric factor loss, polymers cannot absorb microwave radiation. Absorbent materials like tire shreds and silicon carbide [79], carbon atoms [80], and iron fit [81] are required to assist in plastic pyrolysis. **Table 2** offers statistics on the yield, absorption-to-polymer proportion, operation duration, and electromagnetic efficacy for five plastic kinds employing tires instead of lignite as an electromagnetic absorbent.

Table 2. The relationship between microwave energy and output utilizing polymers as an electromagnetic absorbent [82].

Material	Electromagnetic energy spectrum (KW)	Period (min)	Absorbent-polymer percentage	Solid form (wt%)	Fluid (wt%)	Gas form (wt%)
HDPE	3.0	75	1:2	0.40	83.92	15.68
PP	3.0	68	1:2	15.89	70.82	13.29
PVC	3.0	21	1:2	14.69	3.44	81.87
PET	1.80 - 3.0	40	2.51	38.20	35.32	26.48
PS	3.0 - 6.0	59	1:2	6.83	89.25	8.92

2.1.6. Catalytic Pyrolysis

Catalytic pyrolysis is a method that includes heating polymeric substances without the presence of oxygen and utilizing a catalyst to break down them. Typical catalysts used in plastic material pyrolysis include silica-alumina [83], natural zeolites [84], fluid cracking catalytic (FCC) [85], and mobile categorization of materials (MCM-41) [86]. Zeolite-based catalysts are powerful owing to their excellent acid resistance. Two-phase catalytic breakdown employing silica-alumina and HZSM-5 zeolite may enhance gas output and octane number, but the reverse arrangement doesn't help. Staged catalysis may turn waste plastic into gasoline-range chemicals, yielding C2 (mostly ethene), C3 (usually propene), and C4 (mostly butene, butadiene) gases [87]. Clays were found to be inactive but could degrade polyethylene at greater temperatures, giving 70% liquid products and heavier ones. Catalysts such as zeolites (ZSM-5, Y-zeolite), FCC, and MCM-41 are utilized to increase the pyrolysis process efficiency, target particular reactions, minimize temperature and time requirements, as well as improve the nutritional value of pyrolysis items [22].

2.1.7. Vacuum Pyrolysis

Within vacuum pyrolysis, the procedure occurs under a controlled environment

where the pressure is dropped below the level of the atmosphere. By working under vacuum circumstances, the boiling point of the reaction outcomes decreases, resulting in more effective isolation and gathering. This approach provides various benefits over traditional pyrolysis methods, including lower energy usage, increased output production, and the capacity to treat a more extensive variety of raw materials.

2.2. Parameters Affecting the Pyrolysis Process

The process parameters in plastic pyrolysis, including temperature, power plants, strain, residence duration, catalyst, lubricating gas, and pace, may affect a combination of final products such as fluid oil, gases, and ashes. Adjusting these variables could give the desired outcome.

2.2.1. Temperature

Temperature is a critical aspect of decomposition due to the controls of the breaking reaction of polymer chains. The Van der Waals attr pulls molecules together, preventing collapse. As temperature rises, vibrations become more evident, and molecules evaporate off the surface. This happens once the heat generated by the force produced by Van der Waals overcomes the resistance of the C-C connect, resulting in the breakdown of the corresponding carbon strand [88].

The thermogravimetry analyzer might be employed to evaluate the heat deterioration of plastics. It includes two graph types: a thermogravimetry analysis (TG) slope and a derivative thermal gravity assessment (DTG) slope. It indicates the material's shift in weight dependent on temps and duration, while the DTG graph delivers information on the degradation stage [89]. The following **Table 3** offers a detailed description of the thermal decomposition behavior of PET, HDPE, PVC, and LDPE plastics, showing the heat ranges at which significant deterioration occurs and essential discoveries from relevant research.

Table 3. Overview of the thermal degradation behavior of plastic.

Plastic Type	Thermal Degradation Temperature Range (°C)	Major Findings	References
PET	350 - 520	Degradation begins beyond 400°C, with the most substantial loss of weight at 427.7°C	[90]
HDPE	378 - 539	Degradation starts at 378°C - 404°C, maximum degradation rate at 467°C	[91] [92]
PVC	220 - 520	Significant reductions in weight between 260°C - 385°C (62.25%) and 385°C - 520°C (21.74%)	[90]
LDPE	360 - 550	Liquid oil formation starts at 360°C - 385°C, highest yield around 469°C - 494°C	[93] [94]
PP	400 - 500	Major decomposition within 400°C - 500°C, maximum degradation at 447°C	[92] [95]
PS	350 - 500	Complete deterioration into viscous oil about 350°C, maximum fluid oil state at 425°C	[96] [97]

2.2.2. The Pressure and Residence Period

Accordingly, the placement of product options, pressure, and residence time should be handled, particularly at temperatures under 450°C [21]. The experiment by Murata *et al.* [98] demonstrated that pressure strongly affects the resulting gas and the carbon amount spacing among the fluid output at temperatures above freezing. Pressure directly impacts the scission rate of C-C linkages in polymers, boosting dual bond growth and residence duration at lower temperatures. However, this impact becomes less visible when temperatures near 430 C. Mastral *et al.* [99] observed that prolonged residence time boosts liquid yield at temperatures below 685 C but less at higher temperatures. The research discovered that pressure and residence duration in plastic pyrolysis are influenced by temperature. They impact product dispersion at temperatures below freezing but less at elevated levels, thereby raising operational costs.

2.2.3. Reactor Type and Configuration

The reactor type considerably impacts the combination of polymers plus catalysts, residence duration, heat transmission, and the effectiveness of the reaction in getting the intended output. Most lab-scale plastic pyrolysis is accomplished in batch, semi-batch, or continuous-flow reactors such as fluidized bed, fixed-bed reactor, and conical spouted bed reactor.

- **Batch and semi-batch reactor**

Batch reactors are enclosed devices that do not allow for introducing or removing reactants or products while a reaction occurs. They achieve excellent efficiency of conversion by maintaining reactants in the reactor for prolonged durations. Nevertheless, these methods have limitations, such as uncertain results, expensive workforce requirements, and challenges in achieving mass creation [100]. Semi-batch reactors provide concurrent reactant input and product removal, providing versatility in reaction selectivity. Nevertheless, they possess comparable labor costs to batch reactors, making them appropriate for production on a modest scale. These reactors are preferred because they are simple and allow easy operation parameter control [75] [101]-[109]. Pyrolysis is often conducted within 300 - 800 degrees Celsius for thermal and catalytic processes. Researchers incorporate catalysts into polymers to enhance hydrocarbon production and improve product refinement. Nevertheless, this process has limitations, including creating excessive coke on the enzyme's terrain, decreased effectiveness, and difficulty removing leftovers from the catalytic after the experiment.

The stirrer in batch reactors promotes fluid oil production via the enhancing interaction of catalysts and polymers. Abbas-Abadi [110] and Kyong [111] [112], revealed that semi-batch reactors with stirrers are ideal for the process due to parameter management. In contrast, batch reactors are inappropriate for catalytic burning owing to potential ash accumulation. **Figure 1** shows the schematic batch with the stirrer components.

- **Fixed and fluidized bed reactor**

Fixed-bed reactors are vital for plastic pyrolysis owing to their simplicity and

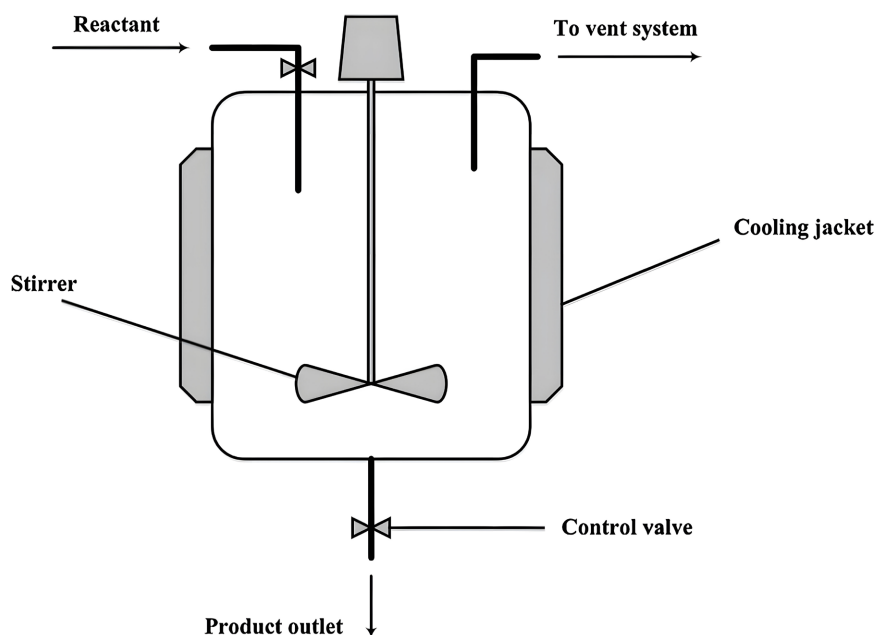


Figure 1. Description of the batch reactor using stirrer components [21].

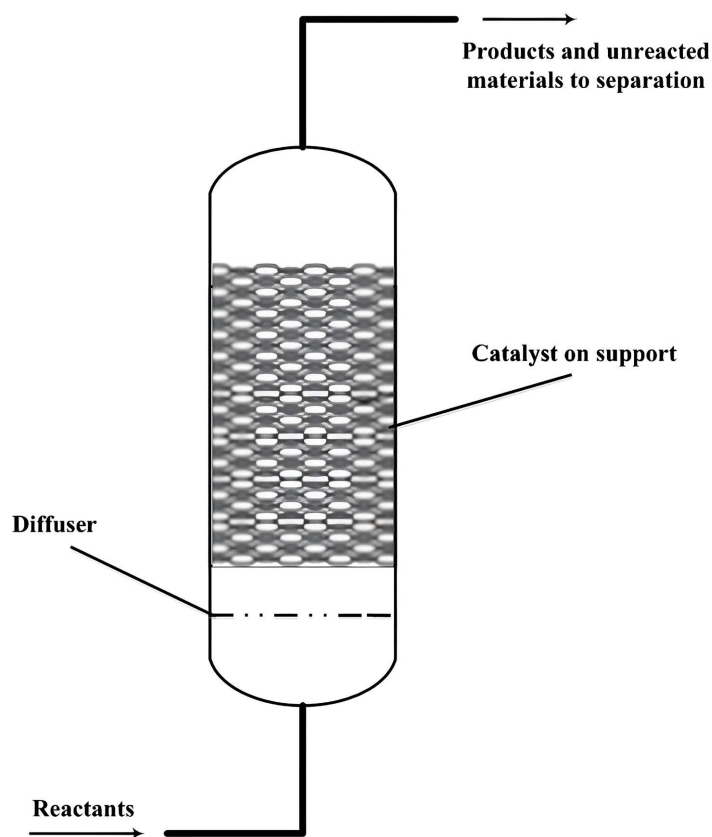


Figure 2. Illustration of fixed-bed device [21].

capacity to manage uneven particle sizes. However, they encounter limitations, including restricted surface area and uncertain process conditions. Fluidized bed reactors alleviate difficulties by allowing greater mobility to the catalyst and

more significant contact areas, minimizing unpredictability, and boosting heat transfer. The catalyst in the fixed-bed device is usually palletized and organized in a stationary bed, as shown in **Figure 2**. Research investigations generally employ fixed-bed reactors for plastic pyrolysis, [90] [113] [114] [115] [116] [117], frequently as secondary reactors owing to the ease of product feeding [118]. A fluidized bed reactor is a more flexible and cost-effective alternative to fixed-bed reactors due to its improved access to the catalyst [119], wider surface area, and better heat transfer, as depicted in **Figure 3**. Researchers recommend using fluidized bed devices in the catalytic cracking of polymers owing to their flexibility, which requires less continuous operation and avoids frequent feedstock charge compared to fixed bed reactors [120]-[127].

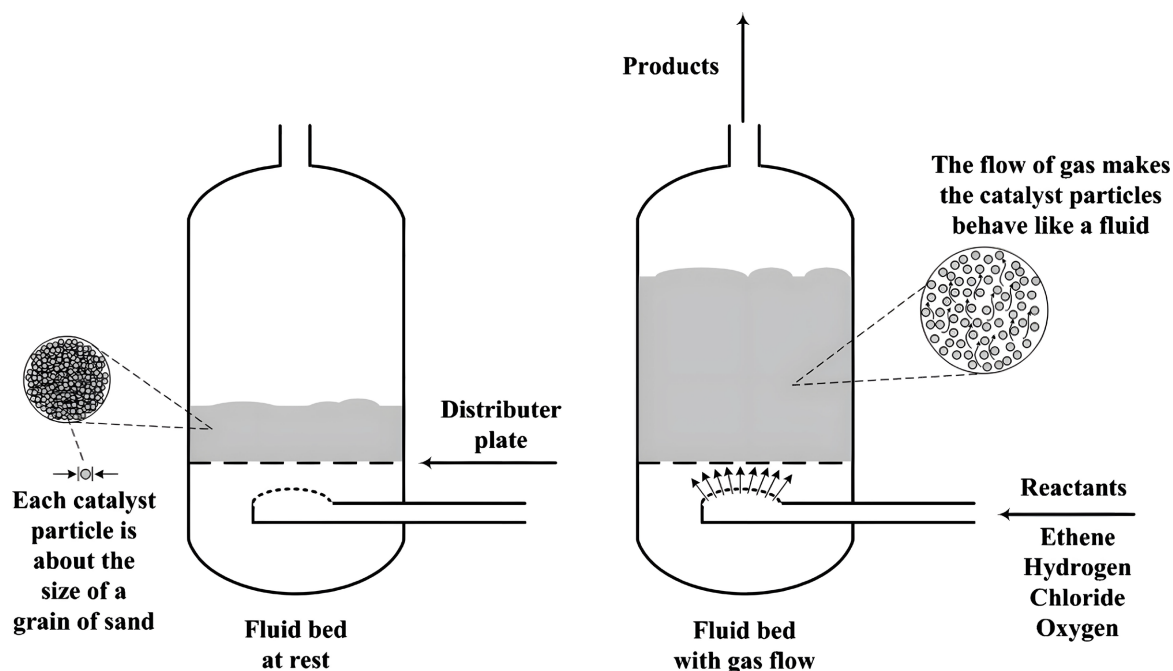


Figure 3. Model of fluidized bed device [21].

- **The Conical spouted bed reactor (CSBR)**

The (CSBR) is a flexible device that can tolerate substantial particle changes and densities [118]. Multiple investigators were adopting CSBR for their destructive cracking of material testing [128]-[133]. Olazar *et al.* [128] discovered CSBR exhibited fewer losses and bed segregation compared to bursting fluidized beds and substantial heat transfer between phases. However, technical restrictions, such as catalyst being fed, stimulation, and output gathering, render it less desirable to handle sticky materials. Study [133] employed CSBR for HDPE pyrolysis with HY zeolite catalyst at 500°C, resulting in a 68.7 wt% gasoline fraction (C5 - C10), despite the high operating expense of the complicated design that required pumps, and the method was illustrated in **Figure 4**.

- **Microwave-assisted technology**

The microwave absorbent gathers radiation from microwaves to deliver suffi-

cient heat to attain the degrees of heat necessary for widespread pyrolysis [135]. Microwave radiation provides benefits over classical pyrolysis, including quicker heating, more incredible output velocity, and decreased production costs. The material is directly exposed to electromagnetic radiation via chemical interaction, eliminating the need for immediate heating [136]. Microwave heating provides benefits, but needs help in industry research owing to the necessity to characterize the dielectric characteristics of the processed waste stream. The efficacy relies on material qualities, such as the tiny dielectric strength of plastics. Using carbon as an electromagnetic collector throughout pyrolysis might maximize the intake of energy and thermal conversion in a reduced timeframe [135]. The possible variance in heating efficiency for each material has been a critical worry for corporations.

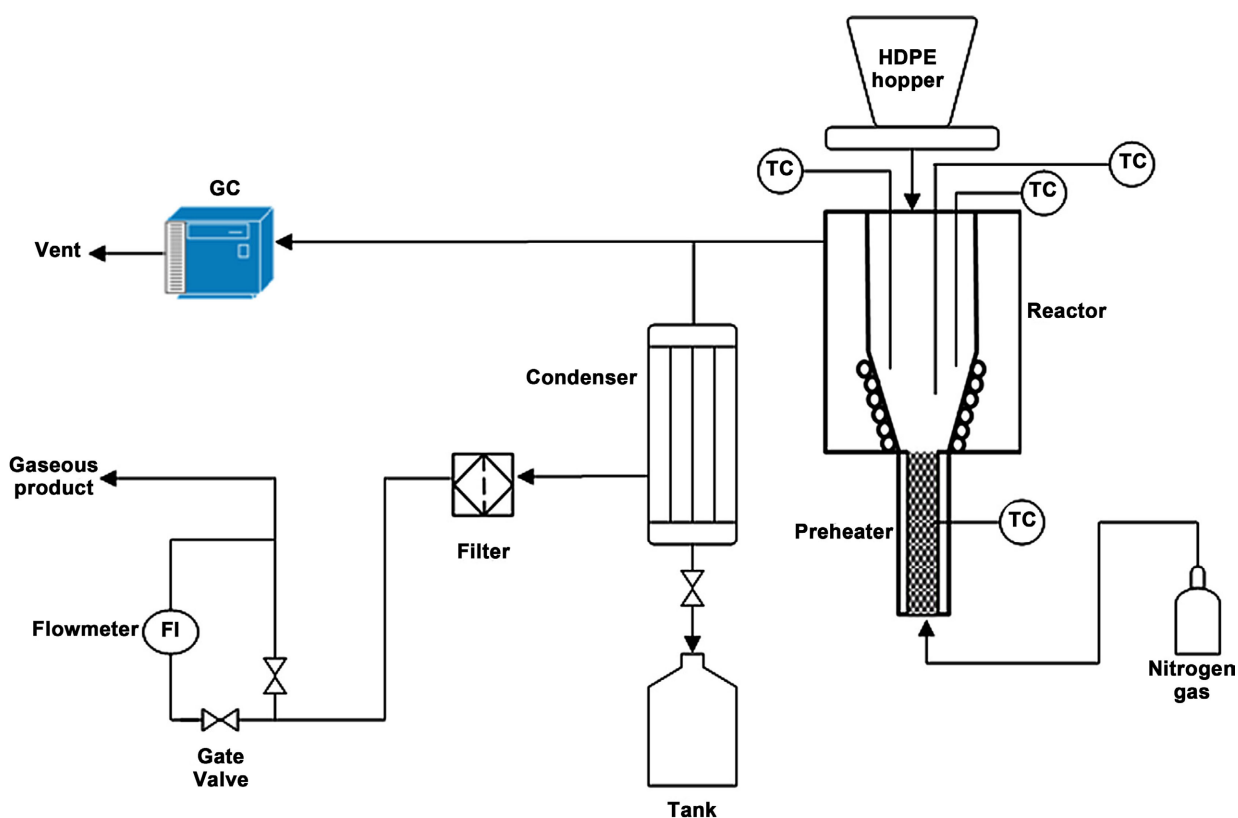


Figure 4. Schematic synthesizing pyrolysis of high-density polyethylene (HDPE) using a zeolite enzyme in a CSBR system [134].

2.2.4. Catalysts

Catalysts, both uniform and heterogeneous, promote product dispersion, selectivity, and yields in industries like polyolefin pyrolysis. Uniform catalysts like AlCl_3 are typically utilized [137] [138]. Nevertheless, the catalyst that is most often used is diverse because of its ability to quickly separate the fluid product mixture of the solid catalytic.

- **Zeolite catalyst**

Zeolites are crystalline aluminosilicate sieves containing pore spaces and can

have ion abilities [139] [140]. Zeolite, a multidimensional frame with oxygen atoms joining tetrahedral sides, is created by altering $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios. The ratio impacts zeolite reactivity and pyrolysis results. HZSM-5 zeolite significantly impacts HDPE pyrolysis output, with acidic catalysts more active in breaking waxes and creating light olefins. Decreases in the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio improve the synthesis of simple hydrocarbons and perfumes. Other zeolite catalysts include HUSY and HMOR. Garforth, Al-Salem *et al.* [141] observed that HZSM-5, a better zeolite catalyst, beat HUSY and HMOR in HDPE pyrolysis, with a minimal residue left of 4.53 wt%, outperforming other materials in optimizing total product transformation.

- **FCC catalyst**

FCC catalyst combines zeolite particles and a non-zeolite acidic substrate termed silica-alumina with binding agents [138] [142] [143] [144]. Zeolite-Y has served as a key feature of FCC catalysts for more than forty years due to its strong selectivity for products and heating equilibria [145]. FCC catalyst is extensively used in chemical treatment to convert dense oil components into lighter fuel and LPG portions [145]. The FCC catalyst is generated from commercial FCC operations in energy facilities, which is efficient and may be regenerated in pyrolysis. Kyong *et al.*'s [111] investigation of abandoned FCC catalysts in the decomposition of HDPE, LDPE, PP, and PS at 400 °C indicated that each of the plastics generated more than eighty-weight percent liquid oil, with PS being especially concentrated. The rejected catalyst displayed high catalytic activity and was cost-effective as a reused catalyst.

- **Silica-alumina catalyst**

Silica-alumina is an irregular enzyme comprised of Bronsted acid spots plus Lewis acid locations. Its acid content is governed by the molecular fraction of $\text{SiO}_2/\text{Al}_2\text{O}_3$. Unlike zeolite, silica-alumina's acidity is assessed against a high ratio of $\text{SiO}_2/\text{Al}_2\text{O}_3$, suggesting an enhanced degree of acidity. SA-1 and SA-2 are commercially available silica-alumina [146]. Uddin, Kasar, *et al.* [147] studied the impact of SA-2 on HDPE and LDPE pyrolysis, finding similar results to Sakata *et al.*'s findings. Uddin *et al.* observed that SA-2 substantially effects HDPE and LDPE pyrolysis, with HDPE being more resistant owing to its linear chain.

2.2.5. Type and Rate of Fluidizing Gas

Fluidizing gas, including nitrogen, helium, argon, ethylene, propylene, and hydrogen, is used for plastic pyrolysis to transfer vaporized materials, with sensitivity varying based on the size of its molecules. AbbasAbadi *et al.* [148] discovered that carrier gas molecular size impacts product composition and temperature, and reactivity affects coke production. Ethanol, ethylene, helium, and propylene are the most prevalent, with ethylene offering greater liquid output and fewer coke forms. Nitrogen is often used in plastic pyrolysis owing to its ease of handling and safety, but helium is seldom utilized due to restricted supplies and higher prices. Fluidizing flow rate also affects product distribution, with the lowest flow rate lowering degradation rate rapidly and lengthy contact time

promoting coke precursor formation.

3. Life Cycle Assessment (LCA) Methodology

Life Cycle Assessment (LCA) is an approach that assesses the ecological effect of an item or operation across its complete life cycle, from virgin item extraction to the latter stages of life elimination [149]. The LCA approach to analyzing the ecological effect of pyrolysis procedures for plastic waste has been continually enhanced in methodology, databases, and software. It facilitates comparing approaches, detecting environmental hotspots, helping decision-making, and encouraging sustainable waste management practices.

3.1. Components of an LCA

- **Goal and scope definition**

The first step entails explicitly identifying the aim and breadth of the LCA research. The intent describes the intended use of such an assessment, such as comparing various goods or detecting environmental hotspots. The scope specifies the system limits, including the functional unit (for instance, the quantity of goods or services being assessed) and the lifespan cycle stages must be included [150]. The purpose and scope give a basis for the whole assessment.

- **Life cycle inventory (LCI)**

The LCI implies generating a complete inventory of inputs, outputs, and activities related to the lifespan cycle stages indicated in the scope. It comprises data collection on substances, the extraction process, energy usage, greenhouse gases, waste creation, transportation, and other pertinent factors [150]. The LCI assesses the system's external inputs and outputs, generating a thorough inventory record.

- **Life cycle impact assessment (LCIA)**

The inventory data is examined to identify the possible ecological consequences of the system under consideration. This entails using characterisation criteria to turn the inventory data into effect categories such as ozone depletion, global warming, toxicity to humans, etc. LCIA methodologies may vary, but they usually try to quantify and analyze the possible environmental impacts associated with the life cycle phases and emissions listed in the LCI [150].

- **Interpretation.**

Interpretation entails evaluating and interpreting the findings of the LCI and LCIA to develop conclusions and make educated judgments. It involves analyzing the assessment's strengths, weaknesses, and uncertainties and identifying the primary contributors to environmental consequences. The interpretation step generally incorporates sensitivity analysis, scenario analysis, and identification of improvement opportunities [150]. The outcomes of the interpretation influence decision-making, promote communication and inform the creation of initiatives to minimize environmental consequences. **Figure 5** shows a framework of LCA modified from the ISO 14040 standard. We can see the resume of the different parts in the following figure.

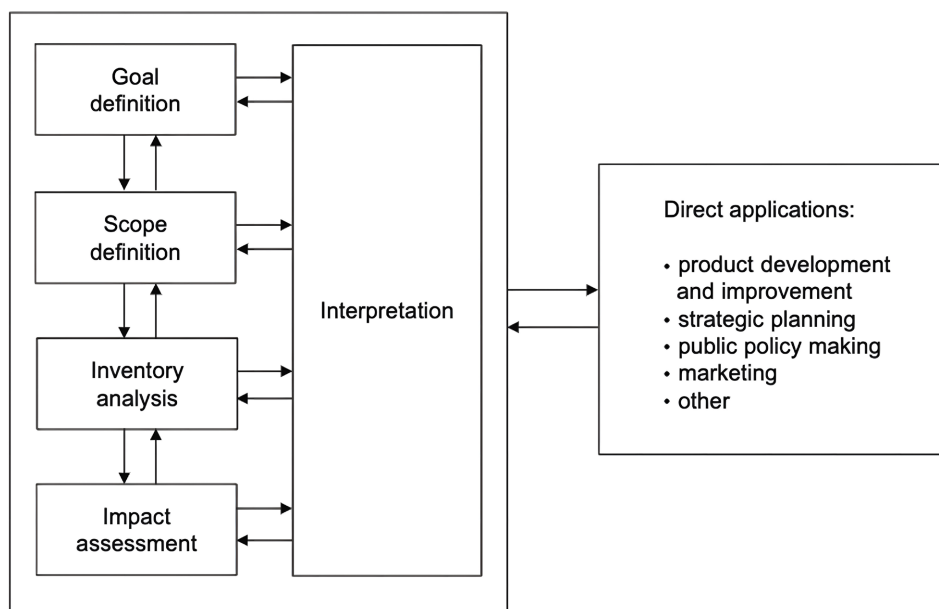


Figure 5. The frame of LCA adapted to the ISO 14040 norm.

3.2. Overview of the Various Effect Categories Evaluated in LCAs of Pyrolysis

LCAs of pyrolysis methods evaluate numerous impact categories to determine their environmental impacts. **Table 4** offers a synopsis of some of the primary impact categories frequently evaluated in LCAs of pyrolysis.

Table 4. Overview of the LCI and LCIA types of LCA [151].

	Category of Effects/Inventories	Description	Unit	LCIA/LCI Methods
LCI Categories	Energy requirement total	Assess all energy from the point of removal: outcomes encompass non-renewable as well as renewable energy sources	MJ	Average power assessment
	Demand for nonrenewable power	Monitors the fossil and nuclear power from the point of collection	MJ	Average power assessment
	Sustainable energy consumption	Assess the hydroelectric, sunlight, wind power, and other green energy, including landfill gas consumption.	MJ	Average power assessment
	Solid refuse by pounds	Counts amount of fuel, process, and postconsumer trash to a particular destiny (e.g., landfill, WTE) for eventual burial on a weight base	kg	Compound waste material component
	Use Of water	Groundwater outflows are dissipated and integrated into goods and garbage moved to new waterways or discharged into the sea after use	L	Average water usage inventory
LCIA Categories	Climate change potential	Represents the heat-trapping ability of the greenhouse gasses—important emission levels: CO ₂ fossilized material, CH ₄ .	kg CO ₂ equivalents (eq)	IPCC in 2013 GWP100a
	Acidification capacity	Determines the neutralizing impact of chemicals on their surroundings. Major emissions: SO ₂ , NO NH ₃ , HF, HCl, H ₂ S	kg SO ₂ eq	TRACI v2.1

Continued

Eutrophication capacity	Assesses repercussions from a high load of micro-nutrients to the surroundings. Significant greenhouse gases: NH ₃ , COD, NOX and BOD, P and N molecules Analyses stratospheric the loss Of ozone. Notable emissions: CFC chemicals and halons	kg Neq	TRACI v2.1
Ozone reduction potential	Measures stratospheric ozone depletion. Important emissions: CFC compounds and halons	kg CFC-11 eq	TRACI v2.1
Smog production Capacity	Establishes the development of reactive chemicals (e.g. tropospheric Ozone) that cause damage to human health and plants. Important emissions: NOx, NMVOC, BTEX, C ₂ H ₆ , COH10, CH ₄ , C ₃ H ₈ , C ₆ H ₁₄ , acetylene, Et-OH, formaldehyde	kg O ₃ eq	TRACI v2.1

3.3. Review of Existing LCAs

Table 5 compiles some of the past Life Cycle Assessment investigations concerning the recycling of chemically processed polymers. The main emphasis is on pyrolysis, whereas other methods such as electromagnetic combustion, gasification, and hydrolysis are considered impractical owing to technological constraints [38] [39] [40] [43]. Neither solvent degradation nor enzyme breakdown were explored due to their unsuitability for polymers such as polyethylene and polypropylene [152] [153]. However, LCAs may enhance existing processes, and it is essential to advocate for their implementation.

Acidification potential (AP), Aquatic toxicity (FAETP), Climate change - Global Warming potential (GWP100), Climate Change (CC), Climate Change Potential (CCP), Cumulative Energy Demand (CED), Eutrophication Potential (EP), Fossil Resources scarcity (FRE), freshwater ecotoxicity (FETP), human toxicity (HT), ionizing radiation (IRP), land use (LOP), marine ecotoxicity (ME/METP), Marine Eutrophication (ME), Metal Depletion (MD), Mineral Resource scarcity (SOP), ozone depletion (ODP), particulate matter formation (PMFP), Photochemical Oxidation Potential (POP), Photochemical Ozone Formation (POFP), Photochemical Ozone Formation (HOFP), human health, abiotic resource depletion fossil fuels ((ADP-fossil)), Terrestrial Acidification (TA/TAP), Terrestrial Ecotoxicity (TETP), terrestrial eutrophication (ET), Water Consumption (WC), Heavy Vacuum Residue(HVR), Ultralow Sulfur Diesel (ULSD)

4. LCA Evaluations of Polymeric Pyrolysis and Recommendations

Among the eighteen research studies reported in **Table 5** claimed the use of proprietary details [156] [157] [170] [171], rendering an unbiased, critical assessment of the suggested LCA evaluations impossible. Investigations of the effectiveness of large-scale chemical recycling systems are based on laboratory-scale information that lacks a direct correlation to real-world industrial efficiency. Several studies use process simulators to describe pyrolysis units like transformation, output, or balanced reactors, depending on practical informa-

tion and the lack of theoretical foundations. **Table 5** underlines the necessity for crucial information on pyrolysis settings in reported investigations. Since outputs ranged from 65 toward 85 wt%, due to apparent variability, it is hard to compare results. To assess components, findings, and impacts, investigators should disclose reactor type, heat, time of residence, and if the technique is thermal degradation or catalysis (or incorporates catalytic amplification of pyrolysis chemicals) because these are vital aspects [34]. Unless expressly mentioned, the pressure level is usually average, which could influence dynamical ranks and vapor-liquid equilibrium.

Table 5. LCA experiments concerning polymer Pyrolysis.

Year	Statistics	Categories of AVC	Investigation	Damage types ^a	Inputs	reactor	T (°C)	P	time	Carrier gas	cat	item	coproduct	process fuel	circular economy
2005 [154]	NA	Attributional Framework extension	landfill incineration, mechanical recycling, pyrolysis, hydrocracking	WC, GW, power and raw oil use, natural complex air discharge, Manufacturing of waste	PE, PET	fluidized bed (BP cracking technology)	NA	NA	NA	no	NA	45% wax, 26.5% naphtha	14.7% gases (C3 - C4); 7.6% sand and coke; 5.7% CaO/CaCl ₂	0.212 MJ/t feed (electricity), 0.131 MJ/t feed (naphtha)	no
2012 [155]	fixed bed	attributional	fossil-based gas, and diesel products, incineration, landfilling	CED, ADP, AP, EP, GWP, OOP, POFP	PE	c	450	NA	NA	NA	no	1 kg gasoline, 0.09 kg diesel, 1.50 kg gas fraction	0.17 kWh/2.94 kg PE, 17.52 MJ/2.94 kg PE	no	
2014 [155]	pilot (50 kg/h)	attributional with framework extension	incineration, landfill, hydrogenation	GWP, AP, POCP, EP	PE + PP (83%), PVC (2%), PS	fluidized bed (BP cracking technology)	500	NA	NA	no	no	45% wax, 26.5% naphtha	14.7% gases (C3 - C4); 4% CaO, 1.7% CaCl ₂	0.212 MJ/ton feed (electricity), 0.131 MJ/t feed (naphtha)	yes
2017 [156]	industrial (24 - 265 t/day)	attributional (Without framework extension)	conventional ULSD fuel	fuel energy use, WCP, GWP	LDPE (33%), HDPE (25%), PP (42%)	NA	NA	NA	NA	no	no	67% condensable liquid (80% diesel, 20% naphtha)	21% gases (used for electricity/heat); 12% char (landfilled)	13% natural gas, 87% electricity	no
2018 [157]	laboratory (recycling technology)	attributional with framework extension	incineration, landfill, naphtha-based (BAU), crude-oil (refinery-feed)	GWP, ADP-fossil FAETP	generic, dry plastic waste	fluidized bed	NA	NA	NA	N2	NA	Plaxx	gas item (Used for energy producer)	NA	no
2019 [158]	c	attributional with framework extension	landfill, incineration	AP, CCP, POP, EP	PE, PP, PS, PU, and PET	NA	600	NA	NA	no	NA	65% Diesel	6.5% Solid waste	18.3 MJ natural gas/ton of mixed plastic garbage; 106 MJ electricity/t of mixed plastic garbage	no
2019 [159]	c	attributional (without framework extension)	incineration, mechanical recycling, gasification, landfill	CC, TA, and particulate material creation	40% PE, 17% PVC, 12% PP, 4% PS, 4.8% PET, and 22.2% others	NA	NA	NA	NA	no	NA	NA	NA	1.9 MJ natural gas per kg waste; 0.49 MJ syngas/kg for mixed plastic	no
2019 [160]	c	significant	mechanical recycling	GWP, human toxicity, POFP, TA, ET	PP (<2% PVC)	NA	NA	NA	NA	no	no	77% pyrolysis oil	12% gas ("steam", used as heat production); 8% solid waste	40 kWh/858 kg PP (electricity mix); 1278 MJ/858 kg PP (natural gas)	yes
2019 [161]	Laboratory (0.40 - 0.60 mg) (Extrapolated using Aspen Hysys)	attributional (Without framework extension) (mass allocation)	fossil-based ethylene, propylene, and aromatics	GWP	HDPE	fluidized bed	650	NA	NA	helium (1 kg/h)	NA	4.3% methane, 20.1% ethylene, 13.4% propylene, 3.7% aromatics	52.6% low molecular weight hydrocarbons, 5.2% high molecular weight hydrocarbons	333 kWh/ton; HDPE; natural gas, 2.20 GJ/t HDPE; self-sustained methane (purge combustion), 3.10 GJ/ton HDPE	yes

Continued

2020 [162]	c	attributitional with framework extension	mechanical recycling, incineration, energy recovery in cement kilns, refinery feedstock, fuel production, monomer production	GWP, ADP-fossil	HDPE, LDPE, PP, PS, PET	NA	NA	NA	NA	no	NA	0.846 kg ethylene/kg HDPE; 0.828 kg ethylene/kg LDPE; 0.846 kg propylene/kg PP	waste residues (0.1 kg/kg HDPE; 0.1 kg/kg LDPE; 0.1 kg/kg PP)	2.3 - 2.8 MJ/kg plastic	yes
2020 [163]	laboratory (0.3 mg)	attributitional with framework extension	naphtha-based (BAU), incineration, and landfill	CC, TA, WC, FE, ME, FRE	PE	flash gas pyrolyzer	1000	1 bar	20 s	He	no	4.62 C ₂ H ₄ (for 1 mol PE)	1.17 C ₃ H ₆ + 0.07 C ₃ H ₄ + 0.09 C ₄ H ₈ + 0.59 C ₄ H ₆ + 1.66 CH ₄	27.8 MW	yes
2020 [164]	industrial (7.5 kt/a pyrolysis oil) (BASF)	attributitional with framework extension	incineration, mechanical recycling, naphtha-based (BAU)	GWP, AP, EP, HOF, ADP fossil, human toxicity (BASF method)	mixed plastic waste (33% PP, 51% PE, 16% PS)	NA	NA	NA	NA	NA	NA	70% pyrolysis oil	gas (used for internal energy recovery); char	c	yes
2020 [14]	pilot	attributitional with framework extension	incineration, gasification, hydro pyrolysis	cc	mixed plastics	NA	NA	NA	NA	NA	NA	NA	NA	c	c
2020 [165]	laboratory (extrapolated using Aspen)	attributitional without framework extension	landfilling, incineration, mechanical recycling, gasification	CC, ODP, TA, FETP, ME, HT, POFP, PMFP, TETP, METP, IRP, etc. (ReCiPe method)	PP	NA	500	1 atm	NA	N ₂	no	15.7 wt % gases, 82.8 wt % oil	1.6 wt % ash	c	yes
2021 [166]	industrial (5000 t/y) (Plastic Energy)	attributitional with framework extension	incineration, mechanical recycling, naphtha-based (BAU)	GWP, AP, EP, HOF, ADP fossil, human toxicity (BASF method)	mixed plastic waste	Semi-batch reactor	NA	NA	NA	no	NA	71% pyrolysis oil	7.8% char (lignite substitute); impurities (incinerated); HVR (Fossil HVR substitute)	10 kg/ton pyrolysis oil (natural gas); 3260 MJ/t pyrolysis oil (electricity)	yes
2021 [167]	laboratory (2 g) (Extrapolated using Aspen)	significant	effect on market dynamics	GWP, ADP-fossil, etc.	HDPE	fluidized bed	600	1 bar	NA	N ₂	HZSM5	naphtha, aromatics, gasoline, diesel	ethylene, propylene, propane, 1-butene, i-butene, butane	high temperature heating energy provided by natural gas	yes
2021 [168]	c	attributitional with framework extension	polymers, incineration, gasification, mechanical recycling, dissolution, hydrolysis	LOP, CC, HT, ME, ODP, PMFP, POP, TA, TETP, WC	PP, PE, PET, PS, etc.	NA	700	NA	NA	NA	NA	50% paraffin, 10% lubricating oil, 40% gases/char	NA	NA	yes
2021 [169]	pilot (PS, 50 kt; polyolefins: 120 kton)	attributitional with framework extension	mechanical recycling, incineration	resource consumption, global warming impact	PE, PP, PS	NA	350	NA	NA	NA	NA	naphtha, slack wax, styrene	NA	NA	yes

Damage-types^a—abbreviations.

In addition, the fundamental presumptions of the recommended analytical methods need to be more visible. For instance, Zhao and You [167] performed pyrolysis tests using 2 grams of high-density polyethylene (HDPE) and figured out the findings would be consistent for furnaces with two tons per hour capacity. Nevertheless, the variations in product and component outputs in bigger reactors resulting from thermal and mass transfer effects plus projected improvements in unit architecture remain unknown. It is recognized that both sides of the process impact product quality and LCA ratings [30] [68] [172]

[173] [174]. As an illustration, melting a polymer substance in the extruder might remove hydrochloric acid and need less energy. The pyrolysis products may be further fractured using catalysts in a later reactor, changing the product's properties. However, as the expanded form of **Table 1** illustrates, many studies need to discuss or investigate these processes.

Concerning the nature of LCA, a great deal of research utilized a strategy that focused on system growth along with features [53]. Although his method helps assess technology, most employ it to study "avoided impacts" (such as the avoidance of using fossil fuels) or to contrast recycling chemical technologies with traditional recycling methods or cremation. Nonetheless, it has been uncommon in this industry to divide the effect categories to understand pyrolysis's social and environmental repercussions in a given location. The fundamental, unspoken assumption is that recycling conditions are the same everywhere, which is untrue. Some authors state that they followed the ISOs but still need to reveal the methodology they used in their research, even though they knew it was necessary to indicate the method utilized (attributional or consequential, with or without system expansion) [154] [168] [169] [175] [176].

Ensuring uniformity in the approach and documentation of technique and data is of utmost importance in pyrolysis life cycle assessments (LCAs), as divergent procedures might impede the comparability and reliability of study findings. It is crucial to establish universal criteria for disclosing and ensuring the quality of data, as well as promoting collaboration among academics, industry participants, and regulatory bodies.

Chemical recycling is economically feasible but confronts challenges due to inadequate process parameters and the loss of plastic. A more extensive carbon mass balance could reduce environmental impact and enhance the regenerative qualities of plastic pyrolysis. Byproducts can be used for internal power rehabilitation, however, comparability with integrated renewable energy sources like sunshine is sparse. These investigations could help to explore the consequences of lowering emissions of greenhouse gases or correspond to current patterns for electricity-powered breakers [177]. Studies indicate that it is possible to transform the exhaust into valuable compounds known as chemicals of high value (HVCs) rather than burning the gas. This process would lead to low CO₂ pollution, namely 0.2 tons of CO₂ per ton of plastics. Using fresh fossil fuel would result in 2.3 tons of CO₂ emissions [178].

However, while previous studies have mostly focused on examining the impact of emitting greenhouse gases, it is equally important to consider other significant repercussions when assessing and mitigating ecological costs [166]. In particular, even with the more straightforward "widespread substance flow evaluation" [178], Experts in chemical recycling technologies must determine the effectiveness of using a catalyst to alter product combinations and reaction rates and whether carrier gas can minimize mass and heat transfer limitations, considering scientific scores and the lack of addressed problems in published materials.

Finally, LCAs should consider not only ecological factors but also financial viability and implications for society. They should consider life cycle costs, benefits, such as employment and community engagement. This holistic approach may facilitate developing and implementing pyrolysis technologies that promote environmental sustainability and social equity. LCA studies still need to incorporate social elements of operations, such as the impact on underprivileged communities and refuse collectors' activities. This is crucial as societal repercussions of disposal ground, landfill, and hazardous emissions have been discreetly treated. Although there is no agreement for S-LCAs [179]-[184] exploratory studies and recommendations can be beneficial [185] [186] [187] [188] [189].

5. Conclusions

The research study evaluates the possible uses of polymer pyrolysis for recovering chemicals, focusing on the importance of reliability and effectiveness in capturing and using carbon and integrating clean energy sources. It highlights the significance of evaluating the environmental effects of chemical recycling technologies compared to other technical options, such as mechanical recycling, waste disposal, and burning. Additionally, it suggests investigating various operational frameworks for chemical recovery, such as implementing many small pyrolysis units to reduce waste delivery or consolidating waste processing in ample plants.

Many studies have been done on the LCAs of plastics. Chemical specialists and mechanical engineers have actively maintained the LCA inventory to enhance the reliability of life cycle analyses (LCAs). By integrating LCA with process simulation tools, a comprehensive analysis may be conducted to understand the efficiency and sustainability of the pyrolysis process. Nevertheless, it is essential to recognize the diversity in pyrolysis reactor designs and combinations. Comprehensive information on LCAs is crucial for evaluating and enhancing chemical processes, particularly when scaling up the system.

Furthermore, it is essential to assess the financial viability of pyrolysis since the economic factors will substantially impact the acceptance and expansion of this recycling technique. The issue is the need to thoroughly analyze publicly available information and combine the results of different investigations. This emphasizes implementing consistent and transparent reporting standards in LCA research.

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Conflicts of Interest

The authors maintain their independence along with no obvious conflicting

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