

CIRCULAR ECONOMY ENABLED BY INNOVATIVE RECYCLING TECHNOLOGIES¹Kristina BAZIENE

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Abstract

The circular economy provides a sustainable approach to tackling growing environmental challenges, particularly in waste management and resource depletion. This paper explores the role of circular economy objectives by converting waste into valuable products such as fuels, chemicals, and bioplastics. These technologies are assessed in terms of their environmental advantages, scalability, and economic feasibility. The study demonstrates how integrating such innovations can reduce dependence on virgin resources, decrease landfill usage, and cut carbon emissions. Real-world industrial applications are examined to show their scalability, economic practicality, and environmental impact. Ultimately, waste-to-value innovations are crucial for achieving circular economy goals, offering sustainable pathways for improving resource efficiency. While these technologies hold significant promise, further research, policy support, and technological advancements are needed to address challenges related to economic viability, regulatory obstacles, and large-scale implementation. Transforming plastic waste into valuable products offers a promising solution for both waste management and sustainable energy production. Technologies like pyrolysis provide practical options for reducing plastic pollution and decreasing reliance on fossil fuels. However, further improvements in process efficiency, economic feasibility, and environmental impact are necessary to enhance the commercial viability and scalability of these solutions. By integrating these innovations into the broader circular economy framework, we can make a meaningful contribution to a more sustainable and resource-efficient future.

Keywords: Circular economy, pyrolysis technology, waste to value technologies

1. INTRODUCTION

Circular economy are innovative systems and processes designed to transform waste materials into valuable products such as energy, fuels, chemicals, and raw materials. The waste to energy technologies aim to reduce waste, minimize environmental harm, and foster sustainability by converting discarded materials into useful resources. Waste-to-value technologies provide multiple benefits. First, resource recovery helps reclaim valuable materials and energy from waste, reducing the need for virgin resources. Second, they have a positive environmental impact by diverting waste from landfills and lowering greenhouse gas emissions, contributing to sustainability.

The concept of a circular economy is changing how we view renewable fuel production. Unlike the traditional linear model, which often leads to resource depletion and waste, a circular approach prioritizes sustainability and efficiency. In this model, the circular economy for renewable fuel production holds great potential. It drives innovation, reduces environmental harm, and strengthens security. By adopting this model, we can create a sustainable, resilient future where energy production is aligned with ecological balance.

The objectives of the study are to explore the application of plastic waste pyrolysis technologies within the circular economy framework, evaluating its potential as a sustainable and resource-efficient technology for plastic waste management and material recovery. The study aim is to understand how pyrolysis can be applied to plastic waste management. The objective is to find out if pyrolysis of plastic waste can be a green and

efficient way to deal with plastic, helping recycle materials instead of discarding them — supporting the goals of a circular economy.

2. LITERATURE REVIEW

The circular economy model has gained significant attention as a sustainable alternative to the challenges of the traditional linear economy. Unlike the "take, make, dispose" approach, the circular economy promotes the creation of systems that reduce waste, maximize resource efficiency, and establish closed-loop processes where products and materials are reused, recycled, or repurposed. The principles of the circular economy are particularly relevant in addressing the growing issue of plastic waste, which, if improperly managed, can cause severe environmental and ecological harm. In the context of plastic waste, the circular economy offers innovative solutions for converting plastic into renewable fuels.

Waste-to-value technologies play a key role in recovering valuable materials and energy from waste, thus reducing dependence on virgin resources. According to Rezanian [1], these technologies contribute to the circular economy by enhancing resource efficiency and sustainability [2]. The researcher of several groups [3, 4] highlight that implementing waste-to-value technologies can significantly reduce the carbon footprint associated with waste disposal.

The economic viability of waste-to-value technologies, which convert waste into valuable products like fuels, chemicals, or energy, is crucial for their widespread adoption. Technologies such as pyrolysis, gasification, and chemical recycling offer substantial potential in addressing global waste issues while creating economic opportunities. However, the success of these technologies hinges on several factors, including investment costs, operational efficiency, market demand for byproducts, and policy incentives. Awogbemi and others [5, 6, 7] note that although the capital costs for waste-to-value facilities can be high, the long-term benefits — such as reduced landfill use and the production of valuable byproducts — may justify the initial investment. Moreover, operational costs, including energy consumption, maintenance, and feedstock processing, must be factored in. For example, pyrolysis requires significant energy inputs, which can impact the economic feasibility of the waste to value technology if energy prices are high [8].

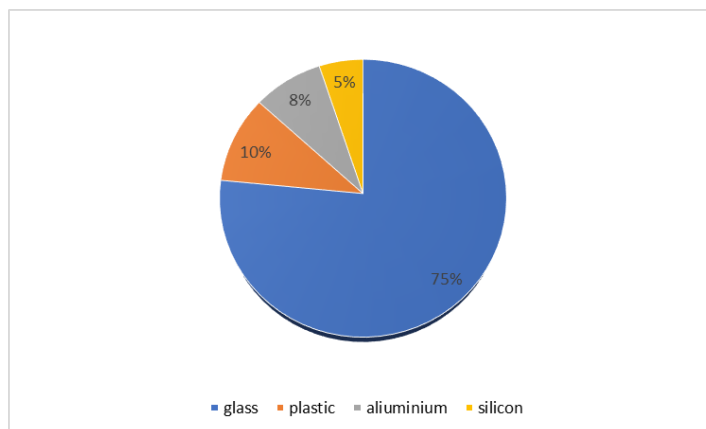


Figure 1 The composition of solar panels [9]

As waste-to-value technologies continue to mature and expand, they may benefit from economies of scale, which could lower costs and enhance profitability. Plastic waste is generated when polymer materials break down or are disposed of. The deterioration or discarding of plastic products contributes to the growing issue of plastic waste. Approximately 4 % of global oil and gas production is allocated to plastic manufacturing. Plastic waste arises when materials become obsolete or no longer usable [10]. The widespread use of plastics, driven by their versatility and affordability, significantly contributes to the accumulation of plastic waste. While

solar panels are key to advancing renewable energy, they also generate plastic waste due to the materials used in their construction and the challenges in recycling them. Solar panels, especially those utilizing crystalline silicon technology, are made up of various components **Figure 1**. The plastic parts, such as the backsheet made from polyethylene terephthalate (PET) and polyvinyl fluoride (PVF), are crucial for weatherproofing, but their presence complicates recycling efforts. These materials are difficult to separate and may degrade over time, raising environmental concerns [9].

Recent studies have extensively examined the potential of using pyrolysis to convert plastic waste into liquid oil, driven by growing concerns over plastic pollution and the rising need for sustainable waste management solutions. Pyrolysis is a promising method for transforming plastic waste into valuable liquid fuel, tackling both the environmental challenges of plastic waste and the energy demands tied to fossil fuels.

The pyrolysis process involves the thermal breakdown of plastic waste at high temperatures (usually between 300 °C and 900 °C) in the absence of oxygen. This decomposition breaks down complex polymer chains into smaller molecules, producing liquid oil, gases, and solid residue (char). The liquid oil obtained is rich in hydrocarbons and can be further refined to replace fossil fuels in engines or industrial applications [11].

Waste-to-value technologies are centered around converting plastic waste into valuable products, thereby supporting sustainable development by reducing waste, conserving resources, and fostering a circular economy. These technologies aim to close the plastic consumption loop by reusing or recycling plastic waste into new, useful products such as fuels, chemicals, and materials. The primary waste-to-value technologies for plastic are depicted in **Figure 2**.

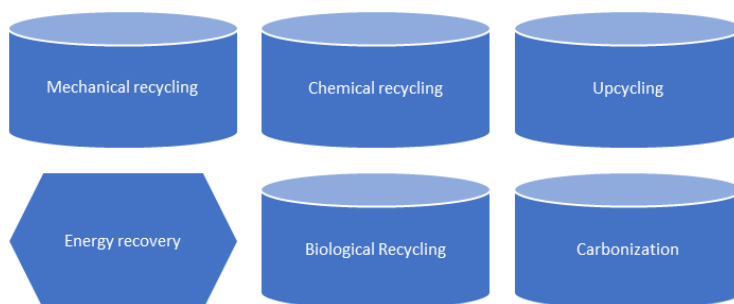


Figure 2 Plastic waste conversion technologies [11]

Upcycling refers to the process of transforming plastic waste into products of higher value. Energy recovery technologies, such as pyrolysis and gasification, convert plastic waste into energy (heat, electricity, or fuel) through thermal decomposition. Plastic carbonization involves converting plastic waste into carbon-rich materials like activated carbon, which can be used in energy storage, environmental cleanup, and organic synthesis applications.

Managing energy consumption and minimizing emissions are crucial for ensuring environmental sustainability throughout the waste-to-fuel process. The heat generated during pyrolysis can be recovered and reused to power the process or produce electricity. A life cycle assessment should be conducted to evaluate the environmental benefits of converting plastic waste to fuel, including: estimating the overall reduction in greenhouse gas emissions compared to landfill disposal or incineration; analyzing the net energy produced by the process versus the energy consumed during conversion; and assessing how much plastic waste is diverted from landfills, as well as the circular economy benefits of recycling plastic into fuel [12, 13, 14].

This study examines the feasibility and potential advantages of converting plastic waste into fuel through pyrolysis within the context of circular economy principles. By analyzing the technical, environmental, and

economic aspects of the pyrolysis process, the research assesses its viability as both a waste management solution and an energy recovery method.

3. METHODOLOGY OF RESEARCH

Heat transfer plays a crucial role in the reactor to efficiently break down plastics and achieve a high yield of plastic oil from the plastic vapor generated inside. The heating of the reactor can be done in several ways. One method is to use a burner that operates with gases like LPG, CNG, or biogases, and in some cases, solid fuels like wood and coal are used, especially in fixed-bed reactors. Alternatively, the reactor can be heated using electricity, with windings around the reactor that pass electricity to generate heat. Solar energy can also be utilized as a heating source. However, the main drawback of using electricity as a heating medium is that it may not provide sufficient temperature to produce gases from plastics efficiently. Microwave reactors are occasionally used, though less commonly, due to longer heating times, energy loss, and the need for specialized materials to construct the reactor.

SolidWorks was utilized as a simulation platform for designing and analyzing complex processes, including chemical reactions, heat transfer, and fluid dynamics. It was specifically used to simulate reactor designs that require detailed information on thermodynamics, fluid dynamics, and reaction kinetics, such as in pyrolysis. The primary parameter simulated was temperature, with three different temperatures for the reactor (450 °C, 500 °C, 600 °C) tested, as shown in **Figure 3**.

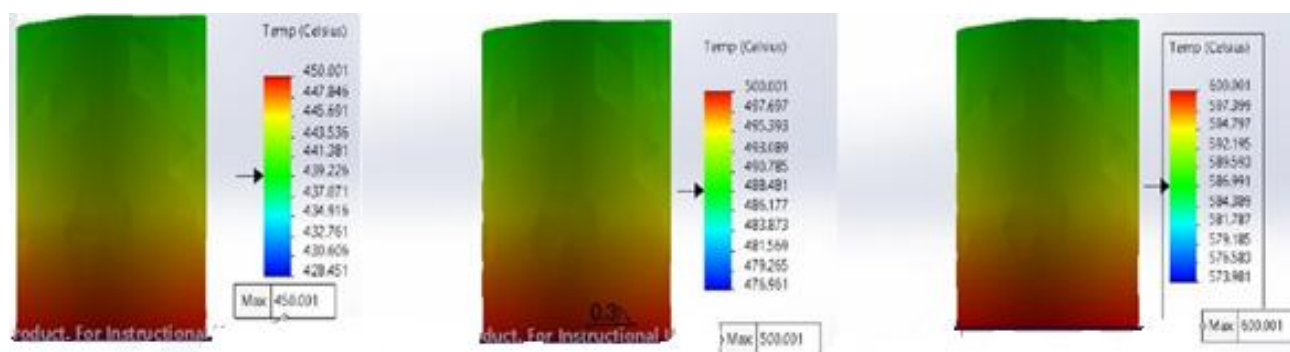


Figure 3 Heat distribution in a reactor with varying temperature settings.

Energy recovery technologies, such as pyrolysis and gasification, are processes used to convert plastic waste into energy forms like heat, electricity, or fuel by thermally decomposing plastics in controlled conditions.

Pyrolysis is a thermal decomposition process conducted in the absence of oxygen. When plastic waste is heated to high temperatures (typically between 350 °C and 800 °C), it breaks down into simpler chemical compounds. The products of pyrolysis include liquid oils, gases, and solid char. The liquid oil can be further refined into valuable fuels such as diesel, gasoline, and other petrochemical products, while the gases can be utilized for power generation. For the simulation, a mix of plastic waste was used, including polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET). The selected temperature range for the simulation was between 450 °C and 600 °C, with the precise temperature depending on the type of plastic.

4. RESULTS OF THE RESEARCH

After completing the reactor design and analysis in SolidWorks, the system is assumed to operate under ideal conditions with no heat loss. This assumption enables accurate estimation of internal temperature retention.

When LDPE plastic waste is loaded into the reactor, it reaches a thermal load of about 450 °C. Pyrolysis begins around 400 °C, triggering the production of pyrolytic vapors.

Table 1 outlines the plastic types used: LDPE (Low-Density Polyethylene), HDPE (High-Density Polyethylene), and PP (Polypropylene). In the reactor model, a base plate temperature of 450 °C is applied. To optimize thermal retention, the base plate is strategically placed beneath the reactor body, ensuring consistent heat distribution. This arrangement effectively promotes gas production while minimizing wax formation during pyrolysis [2].

The plastic pyrolysis system designed to convert LDPE into pyro-oil has been successfully validated through design and simulation in SolidWorks. Simulation data, supported by relevant research literature, confirm that this reactor model is suitable for laboratory-scale experiments and can serve as a reliable prototype for future experimental studies.

Table 1 The parameters used for simulation with various types of plastics

Samples	Material (plastic)	Melting temperature, °C	Temperature, °C	Temperature of pyrolysis, °C
a)	LDPE	110	450	250-380
b)	HDPE and PP	140	500	390-500
c)	Mixture	Depends on mixed plastics	600	380-550

The pyrolysis of plastic waste is a thermochemical process that decomposes polymers into smaller molecules in an oxygen-free environment, transforming plastic into valuable products like liquid fuels, gases, and char. The key aspects of plastic waste pyrolysis, categorized into technical, environmental, economic, and operational factors, are outlined below in **Table 2**.

Table 2 illustrates how plastic waste-to-value technologies (such as pyrolysis) are essential to the circular economy, fostering sustainability, minimizing waste, and creating economic opportunities. Technologies that transform plastic waste into valuable products (e.g., through recycling, upcycling, or energy recovery) play a crucial role in a circular economy by extending material lifecycles and reducing resource consumption. These technologies support circular economy principles, such as closing the material loop. In a circular economy, materials are kept in use for as long as possible. Plastic-to-value technologies, including mechanical recycling (melting and remolding plastics), chemical recycling (breaking polymers down into monomers or fuels), or upcycling (converting waste into higher-value products), enable plastic waste to re-enter the economy rather than being disposed of in landfills. This helps reduce the reliance on natural mineral resources.

Table 2 The parameters used for simulation with various types of plastics

	Technical	Environmental	Economic	Operation
Aspects/Description	Pyrolysis can be classified into the following types: Slow pyrolysis (operates at lower heating rates, resulting in higher char yield). Fast pyrolysis (involves rapid heating to maximize liquid oil production) Catalytic pyrolysis (uses catalysts to improve yield and quality of pyro-oil while	Emission Reduction helps reduce plastic buildup in landfills and oceans, and can lower CO₂ emissions compared to incineration or landfilling. The pyrolysis process generates	Pyrolysis oil can be processed into diesel, gasoline, or various chemicals. The gaseous by-products can be recycled for energy input. Several cost factors are involved in pyrolysis, including capital investment for	Feedstock preparation, which includes cleaning, drying, and shredding, is crucial for efficient pyrolysis. Additionally, mixed plastic streams may require sorting or dechlorination (removal of PVC).

	reducing the reaction temperature). Typically, thermoplastics such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), and mixed plastics (with pre-treatment to remove PVC/PET due to harmful emissions or low oil yield) are used in the process. Heat transfer efficiency and residence time are crucial factors in determining the quality of the output.	by-products such as a gas fraction (which can be used to fuel the process, minimizing external energy requirements) and solid residue (char), which can be utilized as a filler or adsorbent.	reactor setup and control systems, operational costs such as energy, labor, and feedstock preparation. Profitability is influenced by factors like oil prices, the availability of plastic waste, and potential subsidies.	Process efficiency relies on consistent heating, feed rate, and oxygen exclusion, while energy recovery from the gas fraction helps improve the overall energy balance.
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While converting plastic waste into fuel can help lower emissions, the process itself is not completely free of environmental impact. Abnisa with other researcher [15] reported that pyrolysis one of the leading technologies in this field has a carbon intensity of roughly 500 – 700 g CO₂ per kWh. Although this is less than that of many fossil fuel-based systems, there is still room for improvement, particularly in reducing emissions from energy inputs and process inefficiencies. Additionally, converting plastic waste into synthetic fuels can decrease the carbon footprint of waste treatment by up to 30 % compared to traditional disposal methods such as incineration or landfilling [8]. This reduction is largely due to avoided emissions from both plastic disposal and the extraction and processing of fossil fuels. According to Kevorkijan [16], converting one ton of plastic waste into synthetic fuel could offset as much as 2.3 tons of CO₂ that would otherwise be emitted through conventional oil refining and usage.

Plastic to fuel technologies represent a significant opportunity to tackle two major environmental issues simultaneously: plastic pollution and fossil fuel dependence. By converting post consumer plastic waste into synthetic fuels and other usable energy products, this approach contributes to a more circular and sustainable model for energy production and plastic waste management. Turning this waste into fuel not only diverts it from these damaging outcomes but also helps to reduce greenhouse gas emissions linked to both traditional waste treatment and fossil fuel use.

Waste itself is the key driver behind the evolution of waste to energy technologies within the circular economy model. Leveraging waste in this way directly addresses sustainability goals by providing a steady, year round supply of raw material for energy recovery. Going forward, research should focus on advancing and refining valorization strategies improving systems for waste collection, sorting, storage, and upgrading the quality of end products to further enhance the effectiveness and efficiency of plastic waste to fuel conversion.

5. CONCLUSION

Pyrolysis has proven to be an effective waste-to-energy technology, capable of reducing plastic waste in landfills while generating valuable products that can replace fossil fuels, thus helping lower carbon emissions. This process aligns with circular economy principles, which aim to close product life cycles through recycling and reuse.

Despite its potential, the widespread adoption of plastic waste-to-value technologies encounters several technical, economic, and regulatory hurdles. However, with continued research, technological progress, and supportive policy frameworks, these challenges can be addressed. Incorporating waste-to-value technologies into the circular economy provides a sustainable solution for managing plastic waste, reducing fossil fuel dependence, and combating environmental pollution.

Transforming plastic waste into valuable products offers a promising strategy for both waste management and sustainable energy production. Technologies such as pyrolysis, gasification, and chemical recycling present effective solutions to reduce plastic pollution and reliance on fossil fuels. Nonetheless, further advancements in process efficiency, economic viability, and environmental impact reduction are essential for making these technologies commercially feasible and scalable. By embedding these innovations into the broader circular economy, we can make significant contributions to a more sustainable and resource efficient future.

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