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Harnessing Pyrolysis for Circular Economy: Bio-Oil Production from Post-Consumer Plastic Waste

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Abstract
Post-consumer plastic waste creates major environmental and economic challenges globally due to poor disposal methods such as landfilling and incineration, leading to pollution and resource depletion. A circular economy framework presents a sustainable approach to managing plastic waste by promoting reuse, recycling, and resource recovery. Pyrolysis, a heat-induced decomposition process conducted in an oxygen-limited environment, emerges as a promising solution for transforming non-recyclable plastics into valuable materials like bio-oil, syngas, and char. This technology can process mixed and contaminated plastic waste, generating bio-oil suitable for energy production or as a chemical feedstock, thus reducing reliance on fossil fuels. Furthermore, pyrolysis aligns with circular economy principles by reclaiming resources, reducing environmental impact, and promoting sustainable industrial methods. Despite its potential, challenges such as high energy demands and fluctuations in feedstock continue to exist, requiring further technological advancements. Case studies from Europe and Japan demonstrate successful applications of pyrolysis, showcasing its integration into global waste management frameworks. Therefore, pyrolysis serves as a crucial method for addressing plastic pollution and fostering a circular economy model.

Keywords: Post-consumer plastic waste; Circular economy; Pyrolysis technology; Bio-oil production; Sustainable waste management

Introduction
Post-consumer plastic waste poses major environmental and economic issues worldwide. Inappropriate disposal of plastics, like landfilling and burning, leads to

serious environmental problems, such as soil and water contamination, greenhouse gas release, and damage to wildlife (Geyer et al., 2017). Furthermore, microplastics from the breakdown of plastic products gather in ecosystems, threatening human health and biodiversity (Rochman, 2018). From an economic standpoint, the poor management of plastic waste leads to a waste of valuable resources that could be reused, with an estimated annual loss of $80–120 billion attributed to unrecycled plastics (World Economic Forum, 2016). Even with improvements in recycling methods, recycling rates today continue to be low, as merely 9% of worldwide plastic waste is effectively recycled, while the remainder is either improperly handled or burned (Jambeck et al., 2015).

The circular economy represents a forward-thinking method for sustainable waste management that emphasizes minimizing waste, repurposing materials, and recycling resources to establish a closed-loop system. In contrast to the conventional "take-make-dispose" approach, the circular economy focuses on reducing resource extraction and environmental damage while enhancing material value through ongoing use (Ellen MacArthur Foundation, 2015). This model is particularly significant for handling plastic waste, as it encourages approaches like rethinking product designs for longevity, improving recycling technologies, and transforming waste into valuable assets like energy or bio-oil (Geissdoerfer et al., 2017). Through the adoption of these practices, the circular economy aids in decreasing reliance on fossil fuels, minimizing greenhouse gas emissions, and tackling the escalating issue of plastic pollution, providing a more sustainable and economically feasible alternative to conventional waste management systems (Kirchherr et al., 2017).

Pyrolysis represents a cutting-edge and hopeful method for transforming plastic waste into valuable items such as bio-oil, providing a sustainable response to the worldwide plastic waste issue. During this procedure, plastic waste is subjected to heat in an oxygen-free setting, resulting in the decomposition into smaller molecules and generating bio-oil, syngas, and char (Butler et al., 2011). This technique is extremely adaptable and can handle various plastic types, such as polyethylene and polypropylene, which are challenging to recycle through conventional methods (Achilias et al., 2007). Bio-oil generated through pyrolysis holds considerable promise as an alternative energy source that can be processed into fuels or chemicals, thus lessening reliance on fossil fuels (Miandad et al., 2016). Furthermore, pyrolysis conforms to the principles of a circular economy by reclaiming resources from waste and lessening the environmental impact of plastics (Al-Salem et al., 2009).

Post-Consumer Plastic Waste: A Global Challenge

Plastic waste has emerged as a major worldwide issue, with more than 400 million tons of plastic generated each year, of which merely 9% is successfully recycled. The remainder is either landfilled, burned, or contributes to environmental pollution (Geyer et al., 2017). Conventional recycling techniques encounter challenges like contamination, reduced plastic quality through recycling processes, and economic inefficiencies, hindering the efficient management of the increasing plastic waste volume. Inappropriate waste disposal leads to serious environmental problems, such as soil and water pollution, greenhouse gas emissions from burning waste, and the buildup of microplastics in both marine and land ecosystems, endangering wildlife and human health. Tackling these issues necessitates creative approaches such as pyrolysis and state-of-the-art recycling methods to reclaim resources and reduce the ecological effects of plastic waste (Hopewell et al., 2009).

Pyrolysis: A Promising Solution
Pyrolysis represents a promising method for handling plastic waste by transforming it into useful products like bio-oil, syngas, and char. The technique consists of heating plastic waste in an oxygen-free setting, decomposing long polymer chains into smaller molecules via thermal degradation (Butler et al., 2011). This technique is especially efficient for plastics that are challenging to recycle by conventional means, like polyethylene and polypropylene. Pyrolysis provides versatility since it is capable of processing mixed plastic waste, minimizing the requirement for thorough sorting (Achilias et al., 2007). Based on the operating circumstances, pyrolysis can be categorized into three types: slow, fast, and catalytic. Slow pyrolysis takes place at lower temperatures and extended residence times, resulting in increased char production. In contrast, fast pyrolysis functions at elevated temperatures and reduced residence times to optimize bio-oil yield. Catalytic pyrolysis employs catalysts to improve the reaction, leading to better yield and quality of bio-oil (Miandad et al., 2016).
In comparison to alternative plastic waste management techniques such as incineration and mechanical recycling, pyrolysis presents unique benefits. Burning waste results in resource depletion and releases toxic pollutants, whereas mechanical recycling frequently reduces the quality of plastics with every iteration (Hopewell et al., 2009). Pyrolysis not only generates energy but also yields bio-oil, which can be processed into fuels or utilized as a raw material for the chemical sector, advancing resource recovery and principles of a circular economy (Al-Salem et al., 2009). Moreover, the method produces syngas that can serve as an energy source for powering pyrolysis facilities, improving energy efficiency. Even with its promise, issues like elevated energy demands, variability in feedstock, and economic viability must be tackled through continuous research and technology improvements. Pyrolysis serves as a viable solution for addressing the increasing plastic waste issue and provides avenues for incorporating waste management within a circular economy model.

Bio-Oil Production through Pyrolysis
Bio-oil is a significant liquid product derived from the pyrolysis of plastic waste, primarily composed of hydrocarbons, oxygenated materials, and aromatic compounds. The properties and composition differ based on the kind of plastic utilized as feedstock and the conditions during the pyrolysis process (Butler et al., 2011). For example, polyethylene (PE) and polypropylene (PP) mainly produce aliphatic hydrocarbons owing to their basic linear structures, whereas polystyrene (PS) generates aromatic compounds due to its benzene ring composition (Achilias

et al., 2007). The elevated energy density of bio-oil, akin to that of traditional fuels, renders it appropriate for uses like heating, generating electricity, or as a raw material for refining operations. Nevertheless, its chemical intricacies and contaminants like chlorine from polyvinyl chloride (PVC) can create obstacles for immediate use without additional processing (Miandad et al., 2016).

The kind of plastic waste has a major impact on the quantity and quality of bio-oil generated. PE and PP usually lead to high bio-oil yields owing to their reduced oxygen levels and less complex polymer structures, while plastics such as PS offer a greater aromatic content, enhancing the oil's heating value (Al-Salem et al., 2009). Conversely, mixed plastic waste typically causes fluctuations in bio-oil quality, since various plastics decompose at different speeds and yield distinct compounds (Hopewell et al., 2009). This underscores the significance of choosing feedstock and pre-sorting in attaining reliable outcomes in bio-oil production.

Process parameters such as temperature, residence time, and catalyst utilization are crucial for enhancing bio-oil production efficiency. Typically, elevated temperatures boost bio-oil yield and assist in the decomposition of polymer chains; however, excessive heat can promote gas production instead (Butler et al., 2011). In the same way, brief residence times in rapid pyrolysis enhance the production of liquid products, while extended times encourage secondary reactions that may reduce the quality of bio-oil. The inclusion of catalysts like zeolites or silica-alumina enhances the selectivity of target hydrocarbons, diminishes impurities, and decreases the oxygen level in the bio-oil (Miandad et al., 2016). By meticulously regulating these parameters, pyrolysis can be adjusted to generate bio-oil with favorable characteristics for industrial uses, establishing it as an essential process for attaining sustainable management of plastic waste.

Potential Applications of Bio-Oil in Energy Production and Chemical Industries

The new fuel emerging from the pyrolytic processes of biomass, bio-oil, is the best and most important renewable source of fuel that can easily replace the fossil fuels. Apart from the other energy sources available, bio-oil can also be applied for the production of electricity and heating. Any fuel used for boilers or turbines, or furnaces, may be substituted by bio-oil for the production of electricity and heat. It can also be utilized in vehicles without modification of engines and thus serve as a cheap solution to greenhouse gas emissions during use by upgrading through refining to biodiesel or synthetic fuels. Bio-oil can serve in co-firing for power plant use with coal in some regions and thus reduce emissions as well as provide a transition to cleaner energy sources (Bridgwater, 2012). Biomass pyrolized oil is an important feedstock in the chemical industry due to its various organic compounds, such as phenols, acids, and ketones. All of these products can be processed and applied to resin, adhesive, and specialty chemical production. For example, these bio-oil-derived phenolic resins are quite significant for fabrication of plywood and insulation products. Bio-oil can also be converted into hydrogen for fertilizers, clean energy systems, and fuel cells. Moreover, by opening doors to using bio-oil for producing biodegradable plastics, it still becomes another promising raw material source toward reducing plastic pollution. It will provide a sustainable partial replacement for energy in the chemical industry, so now bio-based economy shifts are focusing on bio-oil itself (Huber et al., 2006).

Challenges in Refining Bio-Oil for Commercial Use

Although it promises much, it has several challenges on its way towards refining bio-oil for commercial applications. First off, its high moisture content reduces energy density and combustion efficiency, which constitute the main hurdle to its commercial application. Water could technically be removed at high costs, serving as a barrier to large-scale adoption. Bio-oil consists mainly of corrosive materials-especially acidic compounds-that can wreck conventional storage and processing equipment. The refining processes are further complicated by the presence of impurities such as ash and metals, as these contaminants deactivate catalysts used during upgrading. By way of example, bio-oils show thermal unstable behavior, meaning that, under high temperatures, they degrade or polymerize and as such they can be very difficult to handle and store. Stabilization can be achieved by such means as hydrotreating, but hydrotreating is expensive because it requires high-pressure hydrogen. Besides, there are no standardized quality indicators for bio-oils, which will slow down their inclusion in commercial markets. Economic viability is another challenge as refining processes remain very energy consumptive and expensive to implement. Without any governmental subsidy or incentive, bio-oil is unable to compete with the low price of fossil fuels. To tackle these issues and release the potential of bio-oils, it is important to scale up production and improve the measures of refining technologies (Elliott et al., 2007).

Integration of Pyrolysis into the Circular Economy

Pyrolysis plays a significant role in advancing the circular economy by converting plastic waste into valuable products like bio-oil, syngas, and char. This process enables resource recovery and waste valorization, addressing the global plastic pollution crisis while reducing dependency on fossil fuels (Butler et al., 2011). Unlike traditional recycling methods, which are limited by plastic degradation and contamination, pyrolysis can process mixed and non-recyclable plastics, creating a sustainable solution for managing diverse waste streams (Hopewell et al., 2009). By turning plastic waste into bio-oil, pyrolysis contributes to a closed-loop system where discarded materials are transformed into new resources, aligning with circular economy principles of reducing waste and reusing materials (Achilias et al., 2007).

Generating bio-oil via pyrolysis provides economic and environmental advantages within a circular economy model. From an economic perspective, bio-oil acts as a substitute for traditional fuels, lowering expenses linked to the extraction and refining of raw materials. Its application in energy production and as a chemical feedstock generates new income opportunities and enhances industrial sustainability (Miandad et al., 2016). From an environmental perspective, pyrolysis decreases landfill reliance, reduces greenhouse gas emissions relative to incineration, and lessens the ecological impact of plastic waste (Al-Salem et al.,

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2009). Moreover, the energy produced from syngas during pyrolysis can fuel the process, enhancing its energy efficiency and self-sustainability. These advantages render pyrolysis a feasible approach for combining waste management with sustainable resource use.

Numerous effective case studies demonstrate the ability of pyrolysis to meet circular economy objectives. For instance, in Europe, a BASF-run pyrolysis facility processes mixed plastic waste to generate pyrolysis oil, which is subsequently employed as a raw material in the production of new plastics, showcasing closed-loop recycling (BASF, 2021). Likewise, a pilot initiative in Japan aims to transform unusable plastics into fuels and chemicals, alleviating waste management problems and generating useful resources (Murugan et al., 2008). These instances illustrate how pyrolysis can be successfully applied on both small and large scales, facilitating wider use in global waste management systems. With advancements in technology, incorporating pyrolysis into circular economy frameworks is expected to be a crucial element of sustainable development.

Table 1:

Pyrolyzer Type	**Operational Complexity**	**Bio-Oil Yield (%)**		**Particle Size**	**Biomass Flexibility**	**Scale-Up Feasibility**	**Gas Flow Rate**
Fixed Bed	Medium	75		Larger	High	Hard	Low
Fluidized Bed	Medium	75		Smaller	Low	Easy	High
Recirculating Bed	High	75		Medium	Low	Hard	Low
Rotating Cone	Medium	70		Medium	High	Medium	Low
Ablative	High	75		Larger	High	Hard	Low
Screw/Auger Reactor	Low	70		Medium	High	Easy	Low
Vacuum	High	60		Larger	Medium	Hard	Low

Conclusion

Pyrolysis is an innovative technology offering a unique and environmentally friendly approach to tackling the rising problem of plastic waste. By converting non-recyclable plastics into bio-oil, syngas, and char, pyrolysis minimizes environmental pollution, recycles valuable resources, boosts energy security, and supports industrial sustainability. Its ability to manage different types of plastic waste, including contaminated and mixed plastics, renders it a practical choice in comparison to traditional recycling and disposal techniques. Moreover, its integration into a circular economy framework highlights its capacity to create a closed-loop system that reduces waste and enhances resource efficiency. Even with difficulties such as energy consumption and variations in feedstock, advancements in catalytic methods and process enhancement can improve its financial feasibility and ecological sustainability. Global case studies emphasize the scalability and effectiveness of pyrolysis, underscoring its significance in achieving sustainable waste management and contributing to a cleaner future.

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