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TOWARDS CIRCULAR ECONOMY THROUGH NOWEL WASTE RECYCLING TECHNOLOGIES

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Abstract. The shift towards a circular economy is gaining momentum as a crucial strategy to address environmental sustainability challenges, particularly the growing concerns related to waste management and resource depletion. In this context, novel waste recycling technologies are emerging as vital components in transforming waste into valuable resources, closing the loop in production and consumption cycles. Traditional linear 'take, make, dispose' systems are being replaced by innovative technologies that aim to reduce waste generation, extend product life, and recover resources from end-of-life products. This paper explores the role of new waste recycling technologies in advancing the circular economy. Key technologies such as pyrolysis, hydrothermal liquefaction, chemical recycling, and biotechnological approaches are discussed for their potential to handle diverse waste streams, including plastics, electronics, and organic. Each technology is evaluated in terms of its ability to convert waste into valuable secondary raw materials like fuels, chemicals, and bioplastics, and its contributions to reducing environmental footprints. Furthermore, the paper highlights integrating these technologies within the circular economy framework, focusing on how they contribute to reducing reliance on virgin resources, minimising waste sent to landfills, and decreasing carbon emissions. Case studies are presented to demonstrate successful applications of novel recycling methods in industry, showing their scalability, economic viability, and environmental benefits. In conclusion, novel waste recycling technologies are essential for achieving the objectives of a circular economy, offering pathways to a more sustainable and resource-efficient future. However, further research, policy support, and technological development are needed to overcome challenges such as economic feasibility, regulatory barriers, and technological scalability, ensuring that these innovations can be effectively integrated into global waste management systems.

Keywords: circular economy; renewable energy; decarbonisation; pyrolysis oil technology; plastic waste recycling

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1. Introduction

The circular economy is a sustainable economic model that contrasts with the traditional linear economy, which follows a "take, make, dispose" pattern. Instead, the circular economy focuses on keeping products, materials, and resources in use for as long as possible, maximising their value, and minimising waste. When applied to plastic waste, the circular economy emphasises reducing the environmental impact of plastic production and consumption, improving recycling processes, and reusing materials rather than discarding them after a single use. Decarbonisation using synthetic fuels derived from plastic waste is an emerging approach that could help mitigate the environmental impact of both plastic pollution and fossil fuel consumption. This method focuses on converting waste plastics into synthetic fuels (such as diesel, gasoline, or jet fuel) through various processes, contributing to reducing carbon emissions. Plastic waste has emerged as a pressing environmental concern globally, with significant implications for ecosystems, public health, and resource management. The escalating volume of plastic waste generated each year exacerbates challenges associated with conventional disposal methods and underscores the urgent need for innovative waste management solutions. Among these solutions, converting waste plastics into fuel energy through pyrolysis represents a promising avenue for mitigating the environmental burden of plastic pollution and the growing demand for sustainable energy sources. The conversion of waste plastics into fuel energy via pyrolysis offers a promising solution that not only diverts plastic waste from landfills but also generates valuable energy products, including liquid fuels, gases, and char. This approach aligns with the principles of the circular economy by transforming waste into resources, thereby reducing reliance on fossil fuels and contributing to the transition towards a more sustainable energy system.

2. Literature Review

Plastic waste, which is largely made from petrochemicals, can be transformed into synthetic fuels through several key technologies: pyrolysis and gasification. Pyrolysis converts plastic into various products, including synthetic crude oil, which can be refined into fuels. This process involves heating plastic waste without oxygen to break it into smaller molecules. Pyrolysis is a thermochemical process that can convert waste plastic into valuable products such as gas, liquid, and solid residue. It involves the decomposition of plastics at high temperatures in the absence or with little oxygen supply (Kabeyi & Olanrewaju, 2023). The process can be carried out using different types of plastics, including polypropylene (PP), polystyrene (PS), and polyethene (PE) (Pharande & Bagwan, 2023**)**. The plastic waste is first sorted and crushed before being fed into a reactor maintained at about 500°C. Nitrogen gas is used to create an inert environment and aid in fluidisation (Aisien, & Aisien, 2023). The cracked gas produced is then condensed and separated using cyclone separators and electrostatic precipitators. The resulting products include gaseous fuel, liquid, and residue. The yield of these products can vary depending on the temperature used in the process (Kafle et al., 2023).

Plastic waste originates from the degradation or disposal of polymeric materials. When plastic products degrade or are discarded, they contribute to the accumulation of plastic waste. Plastic waste generation occurs when plastic materials are rendered obsolete or unusable (Pharande & Bagwan, 2023). The production and consumption of plastics are key contributors to the formation of plastic waste. Their versatility and affordability drive the widespread adoption of plastics. Approximately 4% of the global oil and gas output is allocated for plastics manufacturing. Pyrolysis offers a method to convert plastic waste into oil. (Kabeyi & Olanrewaju, 2023). The different manufacturing processes of plastic products generate plastic waste (Pannucharoenwong et al., 2023). The plastic waste is produced by solar panels, which are necessary for transitioning towards renewable energy (Tvaronavičienė, 2024). The growth of industrial development and a vast population increased the use of plastics enormously (Evode et al., 2021). Plastic waste comprises a mixture of various plastic polymers. Projections suggest that by the year 2050, global plastic waste is estimated to reach 12 billion tons (Aisien & Aisien, 2023).

Plastics are manufactured substances derived from polymers, which consist of extensive chains of repeating units. There are several types of plastics (Figure 1), each characterised by its unique chemical composition and properties.

The circular economy for waste recycling is a sustainable approach aimed at minimising waste and maximising resource efficiency. It contrasts with the traditional linear model (take, make, dispose) by keeping materials in use for as long as possible through recycling, reuse, and upcycling. Below are key principles, strategies, and examples of circular economy applications in waste management. Products should be designed to be easily dismantled, repaired, or upgraded, allowing their components to be recycled or reused. Plastic waste can be converted into pellets to produce new plastic products, while organic waste can be transformed into compost or bioenergy.

Figure 1. Six common types of plastics.
Source: Chang (2023)

Recent literature highlights advancements in the circular economy and the remaining challenges in scaling up plastic recycling and reducing plastic consumption. Key studies and reports have provided significant insights into plastic waste management and strategies for transitioning toward a circular economy. Khandelwal et al. (2019) evaluate the potential for chemical recycling and its role in reducing carbon emissions compared to mechanical recycling. They conclude that chemical recycling offers a more sustainable solution for difficult-to-recycle plastics but remains economically challenging and requires further technological advancements (Khandelwal et al., 2019). Geyer et al. (2020) discuss the widespread inefficiencies in the global recycling system and the need for improved infrastructure and systems to ensure that plastic waste is adequately processed and reused. It suggests that a more integrated approach to recycling, including supporting circular supply chains, is necessary for achieving sustainability goals (Geyer et al., 2020). Effective recycling depends on technological advancements, consumer participation, and proper waste management practices. Research highlights that changing consumer behaviour and raising awareness about the importance of recycling is crucial for circularity (Bocken et al., 2016). Fahim et al. (2021) analysed the prospects of using pyrolysis to convert plastic to liquid oil. The authors stated that produced liquid oil had a higher calorific value than fossil fuel. This novel waste recycling could be used to develop more circular business models. Entrepreneurship has to be integrated into chemistry and engineering education (Ead et al., 2023).

There are multiple ways of producing energy or useful products from waste plastics. The methods and ways are developing each day. Innovation in polymerisation projects is developing very quickly. There are several types of energy production from waste plastics. One method is plasma gasification, which converts plastic waste into fuel oil using a plasma reactor (Galaly & Dawood, 2023). Another method is pyrolysis, which involves heating plastic waste in a low-oxygen environment to produce synthesis gas, which can be used to generate electricity, create transportation fuels, or produce chemicals (Moroliya et al., 2023). Mechanochemical methods can also be used, where polymer wastes are converted to fuel gases through ball-milling with oxidants. (Nguyen & Tuan, 2022). Catalysis-pyrolysis is another approach, where waste plastics are converted to gasoline, syngas, and carbon nanotubes using catalysts. (Chow et al., 2021). These methods offer alternatives to fossil fuels and contribute to waste management by converting plastic waste into valuable energy resources.

Pyrolysis is a process where waste plastics are heated in an environment devoid of oxygen, forming synthesis gas. This gas can serve various purposes, including electricity generation, the production of transportation fuels, and the synthesis of chemicals. (Moroliya et al., 2023). Pyrolysis continues to gain traction as a promising technology for multiple applications beyond waste management. Here are some notable areas where pyrolysis is being utilised or explored:

Plastic recycling pyrolysis can break down plastic waste into valuable products like liquid fuels, waxes, and chemicals. This offers a promising solution for plastic recycling, particularly for plastics that are difficult to recycle through traditional mechanical methods due to contamination or complex composition.

Carbon capture and utilisation pyrolysis can play a role in carbon capture and utilisation (CCU) strategies by converting carbon-rich feedstocks into valuable products like biochar or activated carbon. These products can be used for applications such as soil amendment, water purification, and carbon sequestration. (Pandey et al, 2020).

Pyrolysis represents a pivotal anaerobic thermochemical process that breaks down lengthy carbonaceous materials within an inert gas environment, often at heightened temperatures. This process can occur either with or without the assistance of a catalyst. When no catalyst is utilised, it's termed thermal pyrolysis, while the involvement of a catalyst results in catalytic pyrolysis. Plastic waste undergoes pyrolysis and typically yields three primary products: plastic oil (which can exist in liquid or waxy form), non-condensable gases encompassing CH4, H2, CO, and CO2, and a carbon-rich solid char residue. The liquid plastic oil primarily comprises aliphatic compounds along with mono- and polyaromatics. This oil finds utility across various applications, such as direct usage in steam boilers for power generation or as a foundational compound for processes like monomer recovery, carbon nanotube production, and the fabrication of transportation fuels.
Conversely, the waxy plastic oil comprises long-chain alkanes and alkenes exceeding C20, possessing notably high boiling points (>500 °C). This type of oil necessitates additional processing, often through techniques like fluid catalytic cracking, to transform it into liquid fuels or other valuable petrochemical products. (Chang, 2023). These reactors have the properties of breaking down the carbon chain of different plastics. Each reactor's efficiency of burning plastics and processing time will be changed. The fixed bed reactors are the ones that are easy to operate, simple to operate, and easy to manufacture; it doesn’t need any special skill to work on it. It takes longer to settle down the carbon black ash residue inside it. (Luo et al., 2010). Semi-batch reactors are used mainly in small-scale industries; they require pretty much space, and setup has a lot of consideration. Special equipment and a monitoring system are needed to control the unit. (López et al., 2011).

By addressing these research objectives, this study aims to contribute to developing sustainable solutions for plastic waste management while advancing the utilisation of waste-derived fuels as a renewable energy source.

Pyrolysis is a key technology in the transition to a circular economy, as it enables the recycling of waste materials into valuable products, reduces environmental impact, and promotes sustainability. Innovations in pyrolysis technology are making it more efficient, scalable, and cost-effective. As global demand for recycled materials and renewable energy sources continues to rise, pyrolysis will likely play a central role in waste management and resource recovery.

Considering the urgent need to address the plastic waste crisis, research into alternative waste management approaches has gained increasing attention from policymakers, industries, and academia.

The study aims to investigate the feasibility and potential benefits of converting waste plastics into fuel energy through pyrolysis according to circular economy principles. By examining the pyrolysis process's technical, environmental, and economic aspects, this study seeks to evaluate its effectiveness as a waste management strategy and energy recovery technology. Specifically, the research aims to:
- explore plastic waste pyrolysis within the context of a circular economy to evaluate its potential as a sustainable, resource-efficient technology for managing plastic waste and promoting the recovery of valuable materials;
- evaluate the environmental impact of waste plastic pyrolysis, including energy consumption, greenhouse gas emissions, and waste reduction potential.

By addressing these research objectives, this study aims to contribute to the development of sustainable solutions for plastic waste management while advancing the utilisation of waste-derived fuels as a renewable energy source.

3. Methodology of Research

The heat transfer is significant in the reactor for better breaking down of the plastics and for the height yield of the plastic oil from the plastic vapour forming inside the reactor. The heating of the reactor can be done in multiple ways (Fig. 2). The heating of the burner can be given through a burner where we can use gases like LPG, CNG, biogases, and sometimes solid fuels like wood and coal are also being used mostly in the fixed bed reactors. The reactor can also be made for electricity as a heating medium using windings created around it, and the electricity is passed to heat it. Sometimes, solar energy can also be used to heat. The main disadvantage of this type of reactor using electricity as a medium is that it won't get the efficiency to produce enough temperature supply for producing gases from plastics. The microwave reactor is also used sometimes, but not very commonly, to produce it. Its main disadvantages are longer heating times, loss of energy, and the need for unique materials to create the special reactor. These classifications can be further broken down (see Figure 2).

A condenser is a device where steam condenses, and the latent heat of evaporation released by the steam is absorbed by cooling water. (Kapooria et al., 2008). The main parameters that determine the operating mode of the condenser are cooling water flow rate, cooling water temperature, heat exchange area, and steam flow into the condenser (Vodeniktov et al., 2021).

First, based on the number of Passes, that is, Single pass - As the name suggests, a one-pass condenser system only allows the fluids to pass through one another once. This setup is perfect for uses with abundant cooling water, such as cooling marine engines and Multipass systems - the fluids pass through each other more than once using U tubes or baffles. A multi-pass condenser enhances the contact duration between the steam and the cooling medium (often water or air) by using numerous passes for the steam, improving heat transfer efficiency. Cross-flow condensers -fluids flow perpendicular to each other. Cooling water flows through the tubes, and steam flows around these tubes at an angle of 90° (Kapooria et al., 2008). The fluid flowing inside the tubes is called the tube side fluid, and the fluid flowing outside the tubes is the shell side fluid. The hot and cold fluids alternate between each of the plates. It is known for high heat exchange efficiency (Wang et al. 2024).

The whole process has been mentioned and how the pollutants can be captured and used in multiple ways as because it's already the process in waste management. Also, the whole process can be maintained by very little CO2 emission, which can be nearly zero. Multiple steps need to be taken to attain zero carbon emissions. The carbon emissions and other unwanted emissions can be monitored by using multiple techniques, and equipment can be used. In this modern technical world, everything can be monitored clearly without errors. The project's main goal is to reduce emissions and recover energy from plastic waste products. Based on the multiple end products from this process, they are monitored for treatment.

Sustainability in the process of converting waste plastics The waste plastics are converted into alternative carbon-rich fuels for substitution for heating and producing electricity purposes in multiple ways. It can directly replace heavy combustion diesel engines, where a large amount of liquid fuel is combusted using air. On the other hand, this whole production process starts from collecting the waste plastics to delivering the final products connected in terms of sustainability.

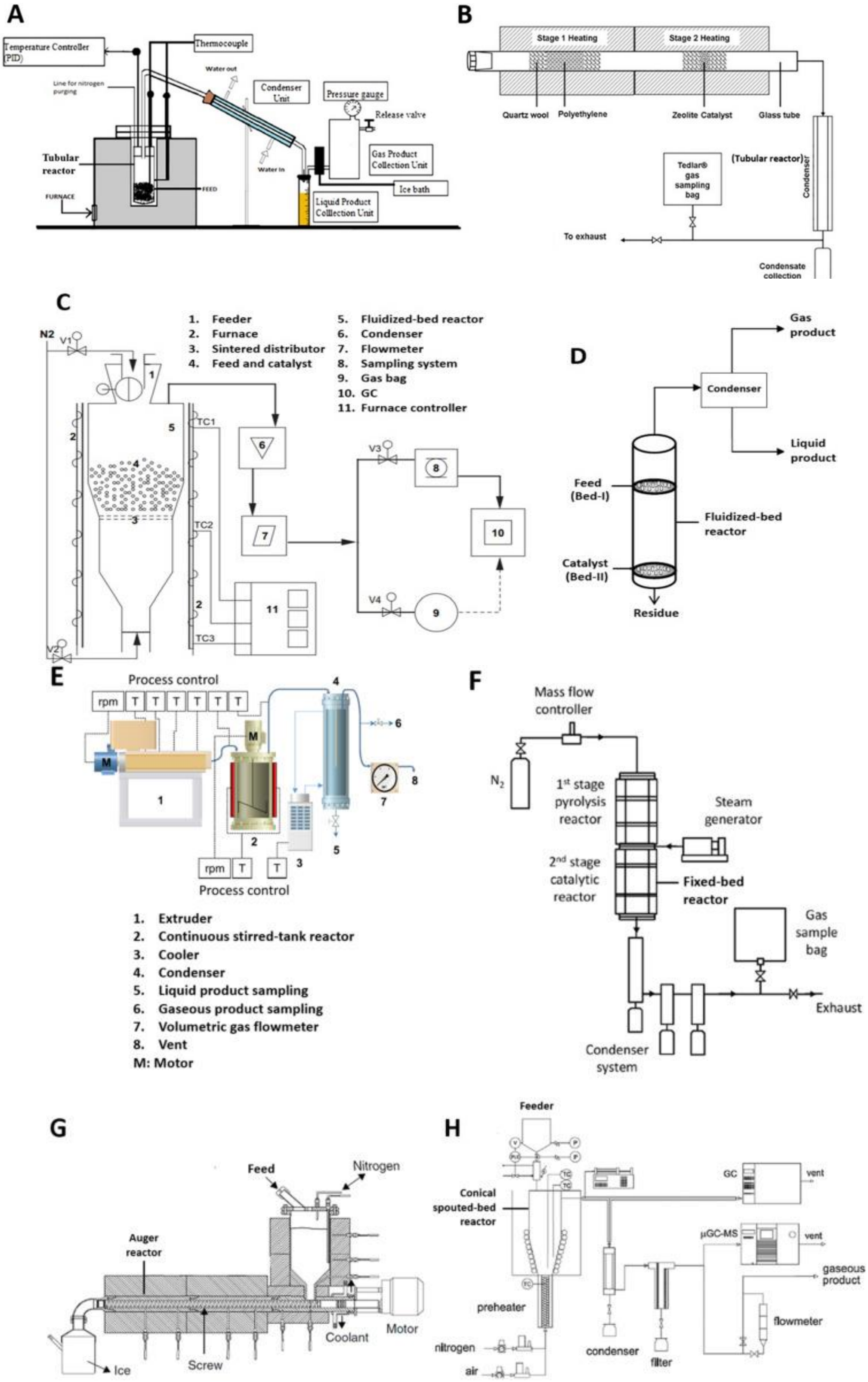

Figure 2. Types of heating based on the reactor type. A) One-stage tubular reactor, (B) two-stage tubular reactor, (C) one-stage fluidised-bed reactor, (D) two-stage fluidised-bed reactor, (E) one-stage continuous stirred-tank reactor, (F) two-stage fixed-bed reactor, (G) one-stage auger reactor and (H) one-stage conical spouted-bed reactor

Source: Chang (2023)

4. Experimental Results and Discussion

The fixed bed reactor is utilised in experimental settings to produce pyro-oil from various plastics (Vilas et al., 2023). For the construction of the reactor, stainless steel 1.4044 hot rolled pipes are employed due to their superior heat retention properties during heating processes. Additionally, a cyclone reactor is incorporated into the system to separate heavier pyro-gas particles from lighter ones. This separation is crucial for producing fuel without wax, although the extracted wax can serve other lubricating purposes.

Figure 3 is from the exact size of the reactor, which is planned to be used for the real-time experiment. The pictures above clearly state that it can be used for experimental purposes without any problems.

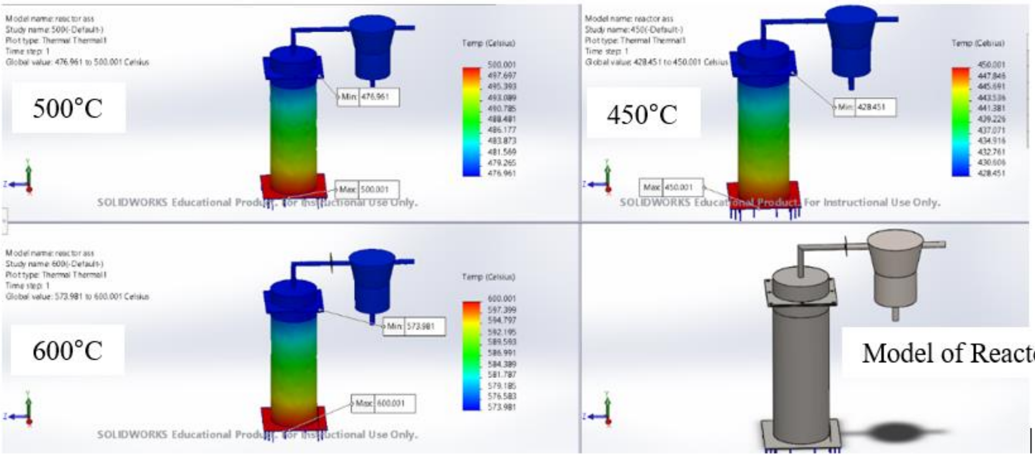

Figure 3. shows the model and simulation of the fixed bed reactors at three different temperatures of 450°C, 500°C and 600°C.
Source: own processing

Condenser design Figure 4 shows the flow control system used in the parallel flow regime where hot steam flows in the inner pipe while the cooling fluid flows on the annular side (Novarini et al., 2018). Tube and coil condenser system is a commonly used hybrid design that requires less space but still has a large heat transfer surface.

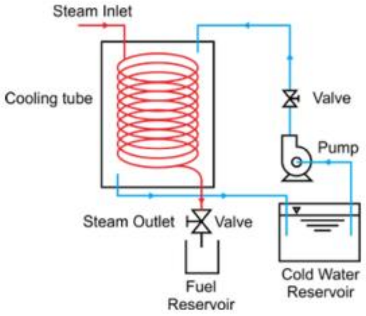

Figure 4. Condenser system design
Source: Novarini et al. (2020)

The plastics are being sorted based on the characteristics and the applications. After the segregation, the plastics are shredded into 5-10mm sizes for volume. The plastics shrink nearly 40% of their volume when heated inside the reactor. The vapour gets produced by heating the plastics in an oxygen-free environment. The burner device is connected to the gas controller to monitor the supply of the LPG, which was used as the heating medium for producing heat. The reactor is connected with copper tubes to transfer the gas from the reactor to the cyclone rector, where the gas and impurities get separated based on the use of gravity and the mass of the particles. Based on this, the calculation determines the heat required to produce the pyro-vapour from the plastics. The plastic feed supplied is 5 Kg. Polypropylene (PP) was chosen for the experiment. The characteristics of plastic are shown in Table 1.

Table 1. Characteristics of Polypropylene (PP) and Polyethylene (PE)

Characteristics	Polyethylene (PE)	Polypropylene (PP)
Specific Heat of solid PE	2.2 kJ/kg-K	2.2 kJ/kg-K
Melting Point of PE	125°C	165°C
Latent heat of fusion of PE	500 kJ/kg	800 kJ/kg
Specific Heat of liquid PE	2.78 kJ/kg	2.79 kJ/kg
Cleavage temperature of PE	350°C	350°C
Activation energy for PE	280 MJ/kmol	135 MJ/kmol
Molecular weight of PE	90000 kg/kmol	220000 kg/kmol

Source: Vilas et al. (2023)

According calculations, provided by Vilas et al. (2023) there is a needed energy amound:

Assuming that 50% plastic feed is polypropylene i.e. mass of PP = 2.5 kg. Therefore, Heat energy required by PP = 1602.7636 × 2.5 = 4006.909 kJ. Heat energy required by PP = 4006.909 kJ.

Assuming that 50%plastic feed is polyethylene i.e., mass of PE = 2.5 kg Therefore, Heat energy required by PE = 1326.61 × 2.5 =3316.5 kJ. Heat energy required by PE = 3316.5 kJ

Table 2. Heat exchange calculations

Properties	Inner pipe	Annulus
Inlet temperature (T_{in})	300^{o}c	30 ^{o}C
Outlet temperature (T_{out})	35 ^{o}c	20 ^{o}C
Mass Flow	0.01 kg/s	0.38kg/s

Source: own processing

As per the calculation above (Table 2), it's used for theoretical reference only.

So, the heat required for this will be somewhere near this. Also, the heat loss needs to be calculated. Through careful theoretical calculations, the experimental work is prepared for setup. The flow of the vapour from the reactor needs to be maintained by the proper constant heat supplied for the reactor.

For the lab experians the reactor is created from the 0.5mm of stainless steel used for ventilation. The total length of the pipe is 250mm. The diameter of the pipe is 120mm. The cover used for the reactor is also made from stainless steel, but a plate of 3mm carbon steel with bolt holes connects the reactor and the reactor cover. A 6mm base plate is welded in the bottom to withhold the heat from the torch. The total heat is supplied through propane gas with high heating energy. The reactor is connected to a stand to make the height from the floor. The torch is kept from the bottom to heat the reactor. The reactor is kept in an outdoor safe environment to prevent any damage caused by the reactor.

The steel shell of the condenser is 400 mm in height and 150 mm in diameter. The tube is made of copper tubing with a 0.5-inch diameter that has been spirally wound to a 1000 mm length. The product exits the condenser as liquid tar. The condenser's cold fluid is stored to cool and eventually be used again. The cooling fluid is maintained at a constant temperature between 15 and 20 degrees Celsius, while the condenser's intake temperature is 300 degrees Celsius.

The decarbonisation potential of converting plastic waste into synthetic fuels offers a unique opportunity to address two critical environmental challenges: plastic waste pollution and fossil fuel dependence. By transforming waste plastics into valuable fuels, it can help reduce carbon emissions while offering a sustainable pathway for plastic recycling. Plastic waste contributes significantly to pollution, with millions of tons entering landfills and oceans each year. Converting plastic waste into synthetic fuels can help mitigate plastic's environmental impact while reducing CO_2 emissions associated with plastic disposal.

A study by Geyer et al. (2020) reported that around 8 million tons of plastic enter the oceans annually, causing severe environmental damage, which can be reduced through plastic recycling technologies such as pyrolysis (Geyer et al., 2020). The carbon footprint of plastic waste treatment can be reduced by up to 30% through conversion to synthetic fuels compared to landfilling or incineration. Liu et al. (2019) found that using pyrolysis for plastic waste conversion could reduce CO_2 emissions significantly by avoiding open burning or landfilling (Liu et al., 2019). By converting plastic waste into synthetic fuels, this technology could displace some of the need for fossil fuels, reducing the carbon emissions associated with fossil fuel extraction, refining, and consumption. Müller et al. (2021) estimated that converting 1 ton of plastic waste into synthetic fuels could displace up to 2.3 tons of CO_2 emissions typically produced by extracting and refining crude oil (Müller et al., 2021). 2023 lifecycle analysis by Sundaram et al. revealed that synthetic fuels from plastic waste, mainly when produced using renewable energy, could result in 30-50% lower carbon emissions compared to conventional fossil fuels (Sundaram et al., 2023).

Although converting plastic waste into synthetic fuels helps reduce plastic waste and displaces fossil fuels, the conversion processes still produce emissions, mainly depending on the energy source used for conversion. Singh et al. (2022) reported that pyrolysis, one of the primary conversion methods for plastic waste, produces a carbon intensity of about 500-700 g CO_2 per kWh. This is lower than fossil fuel-based energy but still generates emissions that must be addressed through technological advancements (Singh et al., 2022).

The conversion of plastic waste into synthetic fuels fits into a circular economy model where waste is continuously recycled and reused, reducing the need for new raw materials and minimising emissions. Kumar and Gupta (2023) explored how a circular plastic-to-fuel model could help recycle plastic waste back into usable energy, thus reducing the need for petroleum extraction and reducing emissions in the process (Kumar & Gupta, 2023). Wang et al. (2022) highlighted that plastic waste often contains mixed plastics and contaminants, which can reduce the quality and yield of the synthetic fuels produced, leading to increased emissions in some cases (Wang et al., 2022). Economic, technical, and infrastructural barriers still limit the widespread adoption of plastic-to-fuel technologies.

Conclusions

Adopting a circular economy for managing and recycling plastic waste is a crucial step toward mitigating plastic pollution's environmental, social, and economic impacts. Unlike the traditional linear economy that emphasises consumption and disposal, the circular model prioritises resource efficiency, waste minimisation, and material recovery. Through innovative recycling technologies, material design, and policy frameworks, the circular economy offers sustainable solutions for closing the loop on plastic waste.

The idea would be to capture and reuse the CO2 emitted during pyrolysis as a feedstock for other reactions (e.g., to produce chemicals or fuels), creating a closed-loop system. This could allow for a more sustainable approach, minimising or neutralising carbon emissions, contributing to a circular carbon economy.

Pyrolysis is emerging as a promising technology in the circular economy for managing plastic waste, with ongoing research focused on improving the process and expanding its industrial application. By converting plastic waste into valuable products like fuels and chemicals, pyrolysis can significantly reduce plastic waste and promote sustainability. However, challenges remain, including the need for economic feasibility and addressing the environmental impact of the process, which are the subject of ongoing research efforts.

Transitioning to a circular economy for plastic waste is challenging, including high costs, technical limitations, and a lack of consumer awareness. However, by fostering collaboration between governments, industries, and consumers and leveraging technological and policy advances, societies can build a more sustainable and resource-efficient future. This shift is essential to addressing the global plastic waste crisis and creating a regenerative economy that benefits both people and the planet.

Scientific Novelty and Practical Value of the Findings

The scientific novelty of converting plastic waste to pyrolysis oil with minimal decarbonisation lies in improving the efficiency of the process while reducing emissions, integrating carbon capture, and using cleaner energy sources. Innovations in catalyst design, reactor technology, carbon capture, and process control could transform the waste-to-energy industry into a much more sustainable and carbon-neutral process. A novel reactor design could incorporate heat recovery systems or alternative fuels (like biochar) to power the pyrolysis process. This could drastically reduce the need for fossil fuel-based energy inputs, lowering the carbon emissions associated with plastic-to-oil conversion. A novel preprocessing technique could involve cleaning and sorting plastic waste to reduce these impurities, improving the efficiency of the pyrolysis process and reducing toxic emissions. This would enhance the quality of pyrolysis oil and lower the environmental impact.

The practice value of converting plastic to pyrolysis oil with low decarbonisation is significant, both environmentally and economically. Still, careful attention to energy sources, technological improvements, and waste management practices is required to minimise the carbon footprint. As decarbonisation technologies evolve and renewable energy integration becomes more common, the process can become increasingly sustainable and profitable.

References

Aisien, F. A., & Aisien, E. T. (2023). Production and characterisation of liquid oil from the pyrolysis of waste high-density polyethylene plastics using spent fluid catalytic cracking catalyst. *Sustainable Chemistry for Climate Action*, 2, 100020. https://doi.org/10.1016/j.scca.2023.100020

Bocken, N.M.P., de Pauw, I., Bakker, E., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, 33(5), 308-320. https://doi.org/10.1080/21681015.2016.1172124

Chang, S. H. (2023). Plastic waste as pyrolysis feedstock for plastic oil production: A review. *Science of The Total Environment*, 877, 162719. https://doi.org/10.1016/j.scitotenv.2023.162719

Chow, C.-F., Lam, C.-S., Lau, K.-C., & Gong, C.-B. (2021). Waste-to-Energy: Production of Fuel Gases from Plastic Wastes. *Polymers*, *13*(21), Article 21. https://doi.org/10.3390/polym13213672

Ead, H., Rezk, M., Piccinetti, L., Santoro, D., Elbadry, A., & Sakr, M. (2023). Integrating entrepreneurship into chemistry education - Cairo University post-graduate students' case study. *Insights into Regional Development*, 5(2), 72-82. https://doi.org/10.9770/ird.2023.5.2(5)

Evode, N., Qamar, S. A., Bilal, M., Barceló, D., & Iqbal, H. M. N. (2021). Plastic waste and its management strategies for environmental sustainability. *Case Studies in Chemical and Environmental Engineering*, 4, 100142. https://doi.org/10.1016/j.cscee.2021.100142

European Union's Circular Economy Action Plan (2019).

Fahim, I., Mohsen, O., & ElKayaly, D. (2021). Production of Fuel from Plastic Waste: A Feasible Business. *Polymer*, 13(6), Article Number 915 https://doi.org/10.3390/polym13060915

Galaly, A. R., & Dawood, N. (2023). Energy Recovery and Economic Evaluation for Industrial Fuel from Plastic Waste. *Polymers*, 15(11), 2433. https://doi.org/10.3390/polym15112433

Geyer, R., Jambeck, J. R., & Law, K. L. (2020). Production, use, and fate of all plastics ever made. *Science Advances*, 6(12), eaax5273. https://doi.org/10.1126/sciadv.1700782

Kabeyi, M. J. B., & Olanrewaju, O. A. (2023). Review and Design Overview of Plastic Waste-to-Pyrolysis Oil Conversion with Implications on the Energy Transition. *Journal of Energy*, e1821129. https://doi.org/10.1155/2023/1821129

Kafle, S., Gaire, P., & Tuladhar, N. (2023). Production of fuels by pyrolysis of waste plastics: Technical notes. *IOP Conference Series: Materials Science and Engineering*, 1279, 012008. https://doi.org/10.1088/1757-899X/1279/1/012008

Khandelwal, H., Dhar, H., Thalla, A. K., & Kumar, S. (2019) Application of life cycle assessment in municipal solid waste management: a worldwide critical review. *Journal of Cleaner Production*, 209 (2019), 630-654. https://doi.org/10.1016/j.jclepro.2018.10.233

Kumar, S., & Gupta, V. (2023). Circular plastic-to-fuel models and their decarbonisation impact. *Journal of Cleaner Production*, 296, 126491. https://doi.org/10.1016/j.jclepro.2021.126491

Liu, G., Zhang, J., & Zhang, H. (2019). Environmental and economic impacts of pyrolysis of plastic waste into synthetic fuels: A review. *Waste Management*, 87, 205-217. https://doi.org/10.1016/j.wasman.2019.02.027

López, A., de Marco, I., Caballero, B. M., Laresgoiti, M. F., & Adrados, A. (2011). Influence of time and temperature on pyrolysis of plastic wastes in a semi-batch reactor. *Chemical Engineering Journal*, 173(1), 62-71. https://doi.org/10.1016/j.cej.2011.07.037

Luo, S., Xiao, B., Hu, Z., & Liu, S. (2010). Effect of particle size on pyrolysis of single-component municipal solid waste in fixed bed reactor. *International Journal of Hydrogen Energy*, 35(1), 93-97. https://doi.org/10.1016/j.ijhydene.2009.10.048

Müller, J., Albrecht, F., & Tiedje, N. (2021). Feasibility of converting plastic waste to synthetic fuels. *Energy Conversion and Management*, 243, 114309. https://doi.org/10.1016/j.enconman.2021.114309

Moroliya, D. M. R., Borkar, M. S., Thaware, M. K., Nandanwar, M. A., & Chandel, M. S. (2023). Design & Fabrication of Extract Bio-Diesel from Waste Plastic Material. *Journal of Energy Engineering and Thermodynamics (JEET)*, 3(04), Article 04. https://doi.org/10.55529/jeet.34.22.27

Nguyen, R. K. G., Tuan Anh (Ed.). (2022). *Energy from Waste: Production and Storage*. CRC Press. https://doi.org/10.1201/9781003178354

Novarini, N., Kurniawa, S., Rusdianasari, R., Bow, Y., & Rifa, A. I. 2020. Conderser Design on Plastic Oil Distillation Equipment. 2020: Proceeding ISETH (International Summit on Science, Technology, and Humanity) / International Conference on Community Empowerment and Engagement (ICCEE) e-ISSN 2615-1588 https://proceedings.ums.ac.id/iseth/article/view/1285

Pandey, U., Stormyr, J. A., Hassani, A., Jaiswal, R., Haugen, H. H., & Moldestad, B. M. E. (2020). Pyrolysis of plastic waste to environmentally friendly products. *WIT Transactions on Ecology and the Environment*, 246, 61-74. https://doi.org/10.2495/EPM200071

Pannucharoenwong, N., Duanguppama, K., Echaroj, S., Turakarn, C., Chaiphet, K., & Rattanadecho, P. (2023). Improving fuel quality from plastic bag waste pyrolysis by controlling condensation temperature. *Energy Reports*, 9, 125-138. https://doi.org/10.1016/j.egyr.2023.05.231

Pharande, V. A., & Bagwan, S. Sh. (2023). A Review Conversation of Waste Plastics into Fuel. *Indian Scientific Journal Of Research In Engineering And Management*, 07(04). https://doi.org/10.55041/ijsrem18705

Singh, R., Garg, S., & Sharma, P. (2022). Pyrolysis of plastic waste for synthetic fuel production: Current status and future perspectives. *Renewable and Sustainable Energy Reviews*, 155, 111819. https://doi.org/10.1016/j.rser.2021.111819

Tvaronavičienė, M. (2024). The Transition towards Renewable Energy: The Challenge of Sustainable Resource Management for a Circular Economy. *Energies*, 17, 4242. https://doi.org/10.3390/en17174242

Vodeniktov, A., Chichirova, N., & Melnikova, V. (2021). Experimental Assessment of the Condenser at Off-Design Modes. *Case Studies in Thermal Engineering*, 28, 101457. https://doi.org/10.1016/j.csite.2021.101457

Wang, D., Wu, Q., Wang, G., Zhang, H., & Yuan, H. (2024). Experimental and Numerical Study of Plate Heat Exchanger Based on Topology Optimization. *International Journal of Thermal Sciences*, 195, 108659. https://doi.org/10.1016/j.ijthermalsci.2023.108659

Wang, F., Zhao, X., & Yang, H. (2022). Impact of feedstock contamination on plastic-to-fuel efficiency. *Waste Management & Research*, 40(7), 757-764. https://doi.org/10.1177/0734242X221086529

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