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Review Article

Advances and Approaches for Chemical Recycling of Plastic Waste

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Abstract: There is the ever-increasing plastics waste leading to serious environmental and economic challenges, which need to be addressed through sustainable recycling solutions. The quality of the recycled plastics is limited due to the degradation of the polymer and contamination in traditional mechanical recycling approaches. New chemical recycling technology is an alternative which allows the depolymerization of plastic down to the practical monomer, recovering it in high purity and offering closed loop recycling. The focus of this review is on the integration of pyrolysis methods in the area of chemical recycling which mainly provides means of enhancing the management of plastic waste. Furthermore, the environmental and economic impacts of chemical recycling are evaluated based on a Life Cycle Assessment (LCA) study and compared to the mechanical recycling as well as landfill disposal. However, its promise is yet to be widely adopted due to many challenges including high energy consumption, process scalability, economic feasibility, etc. Future research should aim towards finding ways to optimise catalyst efficiency, reduce operational costs and also integration of chemical recycling within the framework of the circular economy. Chemical recycling technologies should play a strategic role in reducing the global plastic waste crisis and their large-scale implementation will be crucial and need to be facilitated by strategic policy interventions and industrial collaborations.

Keywords: Chemical Recycling, Plastic Waste Management, Pyrolysis, Gasification, Hydrolysis, Depolymerization, Life Cycle Assessment, Circular Economy, Sustainability.

1. INTRODUCTION

Owing to its lightweight, durability and versatility, plastics have become indispensable in a modern society. Nevertheless, overutilization of them has set off a growing plastic waste crisis where four hundred million metric tonnes of plastic are produced every year (Davidson *et al*., 2020). The land and marine pollution caused by plastic waste disposal results from the improper disposal as plastic waste affects the ecosystem and human health. The drawbacks of the currently practiced waste management strategies of landfilling and incineration are greenhouse gas emissions and toxic byproducts (Thiounn *and* Smith, 2020). Currently, mechanical recycling (most used for plastic waste management) includes grinding, melting and reprocessing plastics. As it is still limited by polymer degradation and contamination, the quality and the usability of recycled plastics is reduced in their useability (Kijo Kleczkowska, 2022). This has resulted in increasing interest in other kinds of recycling, and chemicals recycling offers a promising option to overcome the challenges.

Demonstrated methods of chemical recycling commonly known as advanced recycling are the break down of polymer plastics into their monomeric or oligomeric constituents. Unlike mechanical recycling, chemical recycling returns the plastics to their original building blocks, and allows for high purity material to be recovered and thereby facilitates closed loop recycling (Huang *et al.,* 2022). This technique proves to be most useful for dealing with difficult and contaminated plastic waste streams that are not suitable for mechanical recycling. Advancements in the catalysts, reaction conditions, and process efficiencies in the past have improved the possibility of chemical recycling which can now be implemented on a large scale (Singh *et al.,* 2017). There exist several chemical recycling methods, pyrolysis, gasification, hydrolysis, and depolymerization, which have their own advantages and challenges.

Conversion of plastic waste into liquid fuels, syngas, and char under oxygen-free condition is one of the most widely studied chemical recycling methods, named pyrolysis (Jha *and* Kannan, 2021). To do this, this process presents a sustainable option to producing fossil fuel in such a way which reduces dependence upon nonrenewable resources. Another thermal decomposition technique, gasification, heats plastics to high temperatures in the absence of oxygen until they are decomposed and rendered as synthesis gas that can be used to generate energy and as chemical feedstocks (Davidson, *et al.,* 2021). In contrast, hydrolysis and depolymerization allow the controlled breaking down of condensation polymers, e.g. PET or polyamides, into their monomeric form so they can be used in polymer manufacture (Pivnenko *et al*., 2016). In addition, the methods of obtaining these compounds in an efficient and environmentally friendly way have been continuously improved using the development of new efficient catalyst, the use of green solvents and process optimization techniques.

However, chemical recycling still has several limitations due to high energy consumption, economic feasibility and technological scalability. (Faraca and Astrup, 2019) In order to successfully integrate chemical recycling into existing waste management systems, reactor design, efficiency of energy, and rates of material recovery need to be improved. Moreover, policy frameworks and regulatory incentives will help to promote investment and industrial adoption of chemical recycling technologies (Thiounn *and* Smith, 2020). Using chemical recycling and comparing them to mechanical recycling and landfilling, the LCA studies have revealed that it greatly reduces the impacts on the climate as well as environmental impact. This, however, needs to be further researched to increase process sustainability and reduce its costs (Singh *et al.,* 2017)

With the ever-increasing demand for sustainable waste management solutions worldwide, chemical recycling presents itself as a viable solution to a reduction of plastic waste volumes, and to the progression of circular economy principles. Novel recycling technologies which are under development, collaborations with industry and intervention from policy makers will be key to achieving the potential of chemical recycling. Chemical recycling techniques, what this implies for their environmental and economic performance, and further research directions were reviewed in this review with an effort to address the challenges in plastic waste management.

2. Chemical Recycling by Pyrolysis

Pyrolysis is a method of thermochemical degradation of plastic waste to liquid fuels, gaseous products and char under conditions of absence of oxygen (Huang *et al.,* 2022). The pyrolysis efficiency is highly dependent on temperature, heating rate, and residence time. It has also been shown that catalysts of zeolites and metal oxides can enhance product selectivity and yield (Singh *et al.,* 2017). Catalytic pyrolysis of advanced plastics like polyethylene and polypropylene using catalytic pyrolysis can significantly improve the conversion efficiency and can be considered an alternate resource to fossil based resources (Jha *and* Kannan, 2021). Yet, the process still needs to be scaled up, the feedstock is not yet consistent, and the operational efficiency is not optimized (Qureshi *et al.,* 2020). The pyrolysis efficiency and product yield depend a great deal on the composition of plastic waste. An example being studies have shown polyolefins including polyethylene (PE) and polypropylene (PP) yield higher amount of liquid oil whereas polystyrene (PS) yields aromatic that can be useful for petrochemical industry (Sharuddin *et al.,* 2016). An additional issue surrounding PVC and PET was presented as the chlorine and oxygen present in both polymers form corrosive byproducts which necessitate additional purification steps (Miandad *et al.,* 2016). Advancements in selective pyrolysis technologies have been recent in an attempt to maximize feedstock sorting and achieving better quality products (Miandad *et al.,* 2017).

Catalytic pyrolysis is considered an avenue to improve the reaction selectivity and suppress the formation of undesired byproducts. Catalysts like zeolites, mesoporous silica and metal oxides help in the breakdown of the polymer chain at low temperatures hence promoting the yield of valuable liquid fuels (Kiran *et al*., 2000). However, the studies have demonstrated that catalytic pyrolysis is also beneficial for improving the stability of pyrolysis oils, allowing them to be used in downstream applications (Chang, 2023). However, the problems of loading the catalyst, the catalyst deactivation and regeneration need to be further studied (Dai *et al.,* 2022).An efficient design of the reactor to carry out pyrolysis is crucial. Commongly such reactors configured as fluidized bed reactors, fixed bed reactors, and rotary kilns and having their own advantages and limitations are used. Thus, large scale operation can be accomplished in fluidized bed reactors due to their uniform heat distribution and efficient transfer of mass (Pinto *et al.,* 1999). On the other hand, fixed bed reactors are simpler to operate, lower capital investment is needed however uneven heating and lack of scalability may be suffered (Cunliffe *et al.,* 2003). Actually, microwave assisted pyrolysis has recently been shown as a promising method, whose rapid and energy efficient heating mechanisms (Kusenberg *et al.,* 2022).

Pyrolysis environmental impact will depend on feedstock composition, process conditions, as well as waste management strategies. In this regard, according to life cycle assessments (LCA), pyrolysis is associated with a lower carbon footprint than incineration, as well as landfilling (Faraca *and* Astrup, 2019). However, essential measures are needed to control emissions of volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) (Qureshi *et al.,* 2020). To minimize these environmental risks, researches are underway to further advance in gas cleaning technologies through adsorption with activated carbon, catalytic oxidation, etc. (Sharuddin *et al.,* 2016). Despite its advantages, there are several economical and logistical hurdles to the spread of pyrolysis. However, the cost of pyrolysis plants construction and maintenance is high, moreover, the oil prices change may affect the economical viability of pyrolysis fuels (Miandad *et al.,* 2017). In addition, there is nothing standard externally to regulate and model policies that cause barriers to market integration (Chang, 2023). Therefore, it will be important for policymakers, researchers and industry stakeholders to collaborate to develop a sustainable pyrolysis infrastructure and further promote plastic waste management (Dai *et al.,* 2022).

Pyrolysis is a promising chemical recycling method to convert plastic waste to useful products. Significant progress has been made in the development of feedstock selection, catalyst, reactor and emission control. Nevertheless, scalability, economic feasibility, and regulatory issues need to be overcome before widespread implementation of such a technology is possible. In future research, the reaction conditions should be optimized, cost-effective catalysts should be developed, and the pyrolysis should be integrated with concepts of circular economy in order to make the most of its potential towards the sustainable waste management (Pinto *et al.,* 1999; Cunliffe *et al.,* 2003; Kusenberg *et al.,* 2022).

3. Life Cycle Assessment of Chemical Recycling

The environmental impacts of the chemical recycling technologies and their comparison to mechanical recycling, incineration, landfill disposal, etc., can be comprehensively evaluated by life cycle assessment (LCA) (Davidson *et al.,* 2021). According to Zhao and You (2021), the LCA methodology takes into account multiple parameters, i.e., energy consumption, greenhouse gas emissions, resource depletion and waste generation, through which they present a systematic assessment of the sustainability of different recycling pathways. Chemical recycling has strong potential to decrease the carbon footprint of plastic waste management and allows for circular material recovery (Jeswani *et al.,* 2021). Nevertheless, the recycling efficiency, energy requirements and composition of feedstock vary, which needs to be investigated further to enhance the sustainability metrics (Singh *et al.,* 2017).

However, chemical recycling technologies including pyrolysis and gasification usually involve high heat and energy supply, which may result in significant deterioration on their overall environmental performance (Costa *et al.,* 2022). Yet, when combined with renewable energy sources, their life cycle effects can be minimized (Gandhi *et al.,* 2021). For example, pyrolysis based chemical recycling has been shown to have lower emission compared to incineration under the conditions optimized for energy recovery (Jeswani *et al.,* 2021). In addition, gasification can supply further benefit to the plastic waste because it enables the conversion of the plastic waste into syngas as a feedstock in chemical synthesis or for energy production (Saebea *et al.,* 2020). Nevertheless, residual impurities including chlorine and sulfur compounds may cause emissions, which must be controlled strictly (Ciuffi *et al.,* 2020).

The main advantage of chemical over mechanical recycling is the capacity of chemical recycling to respond contaminated, multi layered and degraded plastics that would otherwise be destined for landfills (Perugini *et al.,* 2005). In order to solve the polymers degradation and contamination problem, mechanical recycling is widely utilized; however, the quality of the recycled materials degrades as a function of the recycled number (Alhazmi *et al.,* 2021). On the other hand, chemical recycling supports high-purity monomer recovery which allows for the recovery into new plastics with no mechanical properties loss (Gu *et al.,* 2017). This emphasizes the importance of carrying out the LCA studies to identify the best strategies for treatment of plastic waste considering the composition of the waste and the recycling goal (Antelava *et al.,* 2019). One of the recent LCA analyses of chemical recycling processes indicates areas where improvements are needed. For example, Costa *et al*., (2022) showed that feedstock purity is crucial for the pyrolysis of energy efficiency and the product yield. Furthermore, designing chemical recycling pathways involving optimized reactor design, catalyst formulative and solvent recovery system can also improve the overall sustainability of them (Jeswani *et al.,* 2021). Machine learning and computational modeling are also emerging as a tool to applying machine learning, and computational modeling in LCA studies for predictions with environmental impacts and to identify potential efficiency gains (Zhao *and* You, 2021).

While chemical recycling has the potential to address some of the problems with traditional recycling, economic and regulatory barriers remain significant hurdles should they hope to achieve a large scale implementation. Chemical recycling plants are characterized by high capital and operation costs, as well as uncertain market demand for recycled monomers (Arena *et al.,* 2003). Furthermore, many regions have current policies and regulatory framew or k s that encourage mechanism recycling and waste-to-energy solutions instead of chemical recycling, therefore additional policy incentives and incentives are required to promote the development of the technology of this area (Alhazmi *et al.,* 2021). Furthermore, incorporating LCA findings into policymaking can help enable more conscious decision making through recycling strategies as it guarantees that the strategies are with respect to sustainability (Pires Costa *et al.,* 2022).Additional future research should be done on improving LCA models, integrating renewable energy source, and promoting policy support for a widespread adoption of chemical recycling as an effective method for sustainable plastic waste management (Davidson *et al.,* 2021; Zhao *and* You, 2021; Jeswani *et al.,* 2021).

4. Challenges and Future Perspectives

Although chemical recycling technologies have made substantial progress, there exist multiple inhibitors that prevent their widespread uptake. However, the businesses suffer from large capital costs due to construction and operation of chemical recycling plants (Davidson *et al.,* 2021). Furthermore, several chemical recycling processes, such as pyrolysis or gasification, demand large amounts of energy input and therefore are considered as being environmentally unsustainable (Wong *et al.,* 2015). However, to make these technologies more viable, the process is optimized to improve the efficiency and lower the energy that is consumed ((Mohammed *et al.,* 2019 *and* Kibria *et al.,* 2023). Future developments must include reducing operational costs and emissions by increasing efficiency in the process, integrating renewable energy sources and improving reactor designs (Thiounn *and* Smith, 2020). The second challenge is that plastic waste streams are very complex. Chemical recycling differs from mechanical recycling which processes primarily relatively pure polymer types, but must handle mixed, multi layered and contaminated plastics making the recycling process more difficult (Vanapalli *et al.,* 2021). Additives, dyes, coatings, that are abundant in many consumer plastic products, hinder chemical recycling reactions leading to low yield of monomer and lack of bundle monomer purification at low cost (Khan *et al.,* 2022). To tackle these issues, advanced sorting and pre-treatment techniques including automated waste segregation systems and chemical additives will facilitate easier polymer breakdown need to be developed (Ali *et al.,* 2021).

The concern surrounding the environmental impact of chemical recycling process is still there. Although these technologies alleviate the challenge of plastic waste ending up in landfills, they can still lead to the formation of emissions and noxious byproducts to a notable extent when plastic contains chlorine, such as PVC (Sharma *et al.,* 2020). Moreover, some of the chemical recycling methods have production of toxic gases and char residues which requires stringent environmental control measures (Chang *et al.,* 2011). In order to minimize the formation of harmful byproducts and maximize recovery of the feedstocks to value products, advanced catalyst design and improved reaction kinetics are required (Qassim and Mohammed, 2019 *and*Singh *et al.,* 2014). Furthermore, incorporating the integration with carbon capture technologies can reduce greenhouse gas emissions in the high temperature recycling process (Hossain *et al.,* 2022).

Further aggravating the expansion of chemical recycling is the issue of regulatory and policy challenges. Currently, many countries do not have clear guidelines on how chemically recycled plastics should be classified and whether they fulfill the requirements of food grade, and high-performance applications (Ali *et al*., 2021). Furthermore, existing policies for waste management in most countries appear to prefer mechanical reprocessing and waste to energy to chemical reprocessing, which consequently results in unfavourable incentive for the companies to invest in establishing new reprocessing facilities (Hossain *et al.,* 2022). Policymakers have to create regulations to enable use of chemical recycling innovations, including subsidies for constructing plants, tax incentives for use of chemically recycled materials, and high restrictions, like banning landfilling of non-recyclable plastics (Thiounn *and* Smith, 2020).

In the future, chemical recycling in pursuit of depolymerization aims at developing ecofriendly catalysts for achieving higher depolymerization efficiency coupled with minimal environmental impact (Kibria *et al.,* 2023). Such metal oxides and zeolites are expensive and tend to slowly degrade over time lowering overall performance. The researchers are looking into bio-catalysts, enzyme-based degradation techniques, and deep eutectic solvents as an alternative to their sustainable use in making chemical recycling a more economical and environmentally friendly process (Ali *et al.,* 2021). Furthermore, further development of artificial intelligence (AI) and machine learning approaches could find reaction conditions in which the process can be optimized, controlled, and predict the long-term sustainability metrics of different chemical recycling pathways (Qassim *et al.,* 2021*and*Chang *et al.,* 2011).

Scaling up of chemical recycling will also rely on industrial collaboration. Chemically recycled plastics need to be created and built through partnerships between petrochemical companies, waste management companies, and policymakers, creating an integrated supply chain (Vanapalli *et al.,* 2021). Moreover, chemically recycled monomers should always be able to be recycled to produce new plastic products with no loss of quality (Sharma *et al.,* 2020). Investment in chemical recycling infrastructure can be further driven by raising the public awareness as well as consumer demand for materials that can be sustainably produced (Khan *et al.,* 2022; Abbas *et al.,* 2020).

Although chemical recycling shows exciting potential for resolving the plastic waste management problem, it is essential to address its economic, technical, and regulatory limitations on a wide front. To improve the feasibility of chemical recycling on a large scale and all of these innovations in catalyst design, waste sorting technologies, and process efficiency need to be prioritized. In order to facilitate such transition towards sustainable circular economy of plastic, policy support, financial incentives and industry collaboration will be essential. In that future research should concentrate on reducing use of energy, optimizing reaction networks and applying chemical recycling within the broader framework of other waste management regimes in order to extract full potential for environmental and economic sustainability in the long run (Davidson *et al.,* 2021; Thiounn and Smith, 2020; Hossain *et al.,* 2022).

6. CONCLUSION

There is a perfect solution for our plastic waste problem — Chemical Recycling. If plastics are broken down into their monomeric building blocks, chemical recycling will not only permit collection of high-quality material back but also support circularity in the plastics industry. The overcoming many limitations of mechanical recycling, this method enables processing of plastics, contaminated, mixed or degraded which otherwise would contribute to environmental pollution. Chemical recycling for widespread adoption has much to offer from the societal perspective, its adoption may lead to positive economic, environmental and health benefits. This technology prevents plastic pollution which otherwise leads to plastic waste diverted to the landfills and ocean, protects the marine ecosystems and mitigates the harmful impacts of microplastics on the human health. Moreover, chemical recycling can cut greenhouse gas emissions for plastic production from fossil fuels by as much as 91% compared with the fossil fuels industry, a major step toward helping to combat the effects of climate change worldwide.

Chemical recycling can provide a new opportunity for both waste management and manufacturing fields economically. The implementation of chemical recycling plants may result in job creation, the investment in sustainable industries and the value chain of plastic materials. Additionally, chemical recycling manufactures high quality recycled feed stocks which help take the dependency of virgin fossil – based plastics for raw material sourcing and make it more sustainable, and cost effective. As a result, this will help produce consumer products that are more affordable and environmentally responsible. Socially, chemical recycling has the potential to contribute to integrating chemical recycling into the municipal waste collection systems by improving the urban cleanliness, preventing accumulation of waste, and sustaining the local economies. A few more campaigns can be done to spread public awareness and education in the responsibility of using and disposing plastic and thereby encouraging a culture of sustainability. Furthermore, government backing in terms of forming policies, subsidies and regulatory structures can aid in advancing the transition towards a plastic economy that is more efficient and circular and so, in turn, benefit society as a whole.

However, further evolution will be required before chemical recycling can become widespread. Additional research and technological development of catalyst efficiency, energy maximization, and waste subset are needed to bring these processes from technologically novel to being economically viable and environmentally friendly. Scaling up chemical recycling infrastructure, regulating chemical recycling in a way that is compatible with law and policy, and its capacity to incorporate plastic waste sustainably will require collaboration between industries, governments and the research institutions. To sum up, chemical recycling produces an appealing solution to one of our world's most existent environmental problems. It has the potential to make a sustainable and resilient society through enhancement of resource recovery and reduction of pollution, and through fostering of economic growth. This then, paves the way for future efforts that should work on minimizing the aforementioned limitations, enhancing infrastructure, and resolving to achieving chemical recycling as a part of a comprehensive waste management scenario to unleash the ultimate societal benefits and environmental impacts.

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