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Recycling and Upcycling chemical Plastic Waste Using the Heterogeneous catalysis

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Abstract

This research proposes to utilized heterogeneous catalysis in the process of chemical recycling of the plastic so as to produce high value-added products which will go a long way in making the environment very sustainable by converting the waste plastics into useful chemicals and materials in an economic and environment friendly manner. A comprehensive methodology was implemented that included literature review to evaluate performance, in addition to environmental and economic impact analysis and industrial feasibility study. The outcomes proved that heterogeneous catalysis is a suitable strategy for the management of plastic wastes since it enables the transformation of plastics into valuable products under mild conditions for conversion, aligning with the circular economy principles, minimizing the harm of plastics on the environment and providing feasible techniques that are suitable on an industrial level.

Keywords: *Heterogeneous, Recycling, Upcycling, Plastic Waste, catalysis*

1. Introduction

Upcycling and recycling are two waste reduction and support the environment techniques; nevertheless, their technique and outcome are not the same (Podara et al., 2024). Where the upcycling involves of transform old and useless objects and processing fresh challenges into objects of higher value and other useful products, thus creating something useful out of waste without throwing them away. In contrast, Recycling involves collection of waste paper, glass and metals among others and processing these basic commodity stocks into new consumer goods hence protracting the life of some crucial raw materials. While recycling involves the reuse of basic components, upcycling or what experts call recycling of optimization reinvents garbage and gives it another useful form (Pereyra et al., 2024; Gnatiuk et al., 2022).

Looking at the global challenge of plastic waste there is no doubt that environmental sustainability and health are at threat where the plastic generation and consumption continue to rise, while waste management facilities are still inadequate in developed and developing countries, so plastics keep ending up in landfills, water bodies and the sea. Hence, this global pollution presents several threats to the living environment, the wild life and human kind via pathways such as ingestion of microplastics and leaching of toxic substances (Manal et al., 2024; Tan et al., 2022). Mechanical recycling is a handy way of reducing the issue of plastic waste but has some drawbacks in that it is difficult to sort different types of plastics out and that the quality of the polymer keeps declining with every cycle of recycling. This in turn calls for new plastic waste end-of-pipe treatment solutions which focus more towards sustainable resource recovery than merely disposal (Manal et al., 2024; de Assis et al., 2021).

Subsequently, chemical recycling and upcycling by heterogeneous catalysis has the potential to solve the ecological problem of plastic waste management and promote a circular economy (Chu et al., 2022; Mark et al., 2020). The catalyst and reagents are in different phases in heterogeneous catalysis, usually a solid phase for catalysts and gaseous phase reagents or reactant products and homogeneous catalysis, where the catalyst and reagents can be in the same phase, can be solid liquid or gaseous phase, or even in two immiscible liquid phases such as oil and water (Butera, 2024). In heterogeneous catalysis, both adsorption and reaction as well as desorption take place at the catalyst surface, and the typical reaction parameters such as thermodynamics, mass transfer, as well as heat transfer effects are involved in the reaction kinetics (Hu et al., 2024).

The heterogeneous catalytic process has shown many advantages over other thermal techniques, such as high selectivity in the formation of the required products, moderate conditions, and the high conversion of waste plastics into valuable materials (Peng et al., 2022; Chu et al., 2022; Tan et al., 2022). It also breaks down a variety of plastics into more useful classifications as liquid hydrocarbons for fuel, arene compounds for synthetic purposes, carbon materials with a myriad of uses, and atomic hydrogen for energy (Knauer et al., 2024; Liu et al., 2023). It is therefore imperative that the effective and sustainable heterogeneous catalytic transformations are to be carried out for reducing the environmental and health impact of plastics and the plastic waste and to support the concept of circular economy on plastics.

1.1 Research problem and question

Plastic waste has accumulated rapidly to an enormous extent that exceeds the capabilities of many areas to properly address using the current avenues for global recycling and upcycling. Where traditional methods of recycling and upcycling inevitably result in downcycled goods of inferior quality, this serves as one motivation behind numerous consumers seeking alternative remedies (Jung et al., 2023; Chen et al., 2021). Consequently, heterogeneous catalysis plays such a significant role for the recycling and upcycling of plastic waste into high value chemicals through the implementation of the most suitable catalysts supported in the feasibility study of diverse types of plastics. Such research seeks to answer to question; how can utilize heterogeneous catalysis effectively to improve and promote the recycling and upcycling of plastic waste.

1.2 Objective

The conversion of plastic waste is a complex challenge due to variations in material properties and composition. The research aims to identify of the role and potential that heterogeneous catalysis for the recycling and upcycling of plastic waste into valuable chemicals through determine the most adequate catalysts to be used in the wide analysis of various types of plastics and their effectiveness.

1.3 Significant

The research provides great importance in offering the essential knowledge for responding to the threat of plastic waste in international environment. Where the plastic waste is one of the commonplaces because plastics are ubiquitous in the environment and get hazardous to living forms troubles. Therefore, the significance research pertains to advancing the understanding of heterogeneous catalysis in recycling and upcycling as follows:

1. Combating environmental pollution as generated by plastics waste.
2. Recycling as an approach of encouraging the circular economy where waste is transformed to useful resources.
3. Improving the effectiveness and eco-effectiveness of materials recycling technologies.
4. To present a guide to industries and policymakers to embrace innovative solutions regarding anything to do with waste management.

2. Methodology

This research implements a theoretical approach to investigate the role of using heterogeneous catalysis in plastic waste recycling and upcycling based on conducting a comprehensive review of existing studies on catalytic processes for plastic waste managing.

3. Literature Review

3.1 Challenges of Categorizing Plastics for Catalytic Recycling and Upcycling

The differences in the characteristics of the polymer backbones and the functional groups suggested that the catalysts must be versatile and efficient in achieving high conversion and selectivity for the depolymerization and conversion into valuable products. Where the polyolefins which are polyethylene (PE), polypropylene (PP) and polystyrene (PS) form a bulk of plastic waste. It also easily recovers and re-use their recalcitrant nature, largely due to the abundance of robust C-C and C-H bonds that are chemically inert (Lv et al., 2024). Conventional chemical recycling strategies like pyrolysis and catalytic cracking demand significant energy consumption, high temperatures and partial selectivity for desired chemicals as by-products (Lv et al., 2024; Locaspi et al., 2023). It is therefore the design of heterogeneous catalysts that can target C-C as well as C-H bonds selectively at milder conditions is therefore an essential step towards the efficient upcycling of polyolefins (Wang et al., 2024; Lv et al., 2024; Chu et al., 2022). To increase the rate of depolymerization reaction and to increase the selectivity of this process, several approaches of which the use of small-molecule co reactants. Therefore, coreactants can be used to cleave C-C bonds in polymer chains to yield smaller and more valuable molecules; for instance, hydrogen used in hydroprocessing encourages C-C bond cleavage and generates liquid hydrocarbons (Lv et al., 2024; Tan et al., 2022).

Besides, the polyesters are one of another giant categories of plastics as polyethylene terephthalate (PET) and polylactic acid (PLA), where polyesters have ether bonds (C–O), which are more susceptible to chemical cleavage compared to polyolefins (Bohre et al., 2023; Payne & Jones, 2021). As a result, these materials are relatively good targets for chemical recycling when compared to polyolefins. The presence of heterogeneous catalysts can promote depolymerization via several routes, such as glycolysis, pyrolysis, alcoholysis and reductive depolymerization. Whereas glycolysis uses glycols to cleave the ester bonds forming smaller oligomers or monomers. Depolymerization can also be carried out by alcoholysis using alcohols such as methanol. On the other hand, reduction depolymerization utilizes reducing agents with catalysts to cleave the ester bonds, yielding useful chemicals (Bohre et al., 2023). Nonetheless, the obstacles persist in achieving high selectivity towards target monomers, and the deactivation of catalysts by contaminants found in real plastic waste feeds. Contaminants may poison the active sites of catalyst and not only decrease its activity but also influence product selectivity. Hence, it is necessary to develop effective chemical recycling processes for polyesters by developing heterogeneous catalysts with good tolerance to impurities and selectivity (Zhang et al., 2022).

In addition, the catalytic upcycling of other polymers such as polyamides, polycarbonates and polyvinyl chloride (PVC) represent specific challenges for catalytic upcycling (Lv et al., 2024, Liguori et al., 2021; Hong et al., 2017). Polyamides including nylon have amide linkages prone to hydrolysis. Nevertheless, breaking these bonds is challenging due to the requirement of dedicated catalysts and reaction conditions. Polycarbonates as well have carbonate linkages in their polymeric structure, are suitable for chemical recycling; however, they need specific catalysts to cleave these types of bonds without generating too many undesired by-products (Liguori et al., 2021). One of the best-known examples is polyvinyl chloride (PVC)which has chlorine atoms in the backbone and was known to produce dangerous chlorinated species during normal biodegradation or during processing (Liguori et al., 2021; Zhu et al., 2018). It is therefore important to design heterogeneous catalysts which allow for the efficient and selective depolymerization of these polymers with reduced formation of unwanted secondary products, Also, for purposes of enhancing the sustainability of these recycling systems, much emphasis has to be placed on the efficiency of the recycle of such polymers alongside the impact it has on the environment in its overall production.

3.2 Heterogeneous Catalyst Design and Structure-Activity Relationships

The rational design of heterogeneous catalysts plays an important role in developing highly endowed and selective polymer recycling with minimal environmental consequences. In the design process, a fundamental understanding of catalyst structure activity relationships enable performance to be tuned with respect to a few controllable parameters (Shah et al., 2023). These are the properties of a metal that forms the catalyst where varying in different metals will have significant effects of their capability to activate specific chemical bonds and the selectivity of the catalyst for preferential products (Tan et al., 2022). Some metallic based catalysts such as the nickel-based catalysts have been shown to be very effective in the recycling of the PET (Kang et al.,2024) while platinum and rhenium among other metals are being tested on the polymer polyolefin degradation (Ellis et al., 2021). Importantly, the electronic properties of the metal, its oxidation state and its complexation with polymers are the key for catalyst activity and selectivity.

On the other side, support material is also part of state-of-the-art catalyst in regard to stability improvement and active site accessibility as well as plastic substrate access. zeolites, metal oxides and activated carbons (Cho et al., 2023; Chu et al., 2022). The texture of the catalyst in terms of surface area and pore size distribution, which correlate with catalytic activity towards plastic degradation, varies with the choice of support material. In addition, the electronic characteristics of the metal are transformed by the support material, which increases catalytic performance and selectivity (Wang et al., 2024; Cho et al., 2023). The change of active site also is a key process for enhancing catalytic activity (Wang et al., 2024). Where it be realized by means of doping with metals or non-metallic species, surface functionalization by attaching specific functional groups or tailoring morphological structures. Furthermore, catalytic pathways have showed a significant impact on the reaction processes by application of extra catalysts such as copper with nickel-based catalysts in PET recycling. As such, things change to enable new polymer catalyst interaction and opens up new design options in catalysts (Kang et al., 2024).

Finally, the features of the catalyst including size, shape and porosity significantly affects the surface area in contact with anode plastic substrate. Where the hierarchical porous structures have been beneficial to enhance the mass transfer as well as to augment the catalytic efficiency (Wan et al., 2023, Chu et al., 2022). It also provides a more uniform placement of active sites accompanied by increased accessibility, which improves the catalytic efficiency on average (Wan et al., 2023). On this basis, the heterogeneous catalysts are designed based on more of the above factors, which makes the catalytic processes in the recycling of plastic more efficient and sustainable.

3.3 Catalytic routes for Plastic Depolymerization, Upcycling and Recycling

Different catalytic routes have been pursued so every route has its own advantages and disadvantages, thus the final route depends on the type of plastics being targeted, nature of products whether chemicals or fuels to be achieved as pure or mixed stream and sustainability of the process (Weng et al., 2023). One of these routes is hydrotreating, using hydrogen to cleave the carbon-carbon (C–C) and carbon-oxygen (C–O) linkages that are present in plastic and typically yield liquid hydrocarbons that may serve as fuels (Lv et al., 2024; Tan et al., 2022). Where the transition metal-based materials can function as part of a heterogeneous catalyst, such as nickel, palladium, or platinum, speed the hydrogenation and bond-scission processes, these process demands high selectivity to liquid hydrocarbons needs not just for the performance with hydrogenation-active and cracking insertive catalysts be selected, but also requires optimal reaction conditions as temperature, pressure, partial of hydrogen, because methane is more active than they are; thus, quickly lead to a large amount of low molecular weight unwanted products (Tan et al., 2022). In glycolase and alcoholase routes, alcohols (methanol or ethylene glycol) cleave the ester bonds in polyesters, yielding smaller molecules such as monomers or oligomers. When employing heterogeneous catalysts, metal oxides and mineral zeolites, the reaction will happen under lower temperatures than non-catalytic methods, providing a pathway as such. The kinetics and thermodynamics of the reaction are influenced depending on which type of alcohol and catalyst is used, determining both the rate and the efficiency for this process by means of methanol yields methyl esters and ethylene glycol give the corresponding glycol esters, as the reaction mechanism and its products are largely determined by the acidity or basicity of the catalyst (Bohre et al., 2023).

Pyrolysis is also a widely adopted route comprising thermolysis of plastics in anaerobic condition. This creates around a thousand products in gaseous, liquid as pyrolysis oil, and solid states as coal. On the other hand, conventional pyrolysis that a well-established process, but approaches often yield a complex product mixture (Abbas et al., 2023; Kusenberg et al., 2022; Uthpalani et al., 2023). Due to this reason, catalytic pyrolysis is employed for better selectivity and higher yield of useful products due to conversion in preferred pathways while suppressing the formation of unwanted by products (Abbas et al., 2023). Furthermore, oxidative pyrolysis involves the use of oxygen or oxidizing agents to cleave the polymer chains and thus gives rise to valuable oxygen compounds, where the designer heterogeneous catalysts metal oxides and supported nanoparticles can act to provide differential control over reaction selectivity and limit undesired products. In order to realize this, the reaction conditions temperature and pressure, including partial pressure of oxygen must be finely tuned in such a way that complete oxidation of the polymer is prevented while promoting target compounds, wherever the choice of catalyst is crucial to channel the reaction toward targeted value-added product routes (Wan et al., 2023).

3.4 Interfacial Reactions and Interactions of Catalyst-Plastic

The processes of heterogeneous catalytic plastic recycling and upcycling are basically dependent on the micro interaction between catalyst and plastic at the interface governing the observable reaction kinetics, mechanism and the product composition of ultimate products (Ong et al., 2024). However, the limitation in contact between the catalyst with plastic is quite a challenge where contact area is low under condition lower than melting temperature of polymer which leads to low reaction rates (Bai et al., 2023). To overcome this, methods like direct catalyst layer deposition on the plastic surface, swelling of polymer in solvents and supercritical fluid are employed to increase the interfacial area or even mechanical methods like grinding are used. These are bidirectionally based upon the enhanced dynamic environment where physical contact of plastic with catalyst raises performance and efficacy. However, the diffusion of reactants & products through the catalyst-plastic interface is one of the key factors that determine the rate and effectiveness of a reaction (Ong et al., 2024).

The composition of the polymer is important as well with crystalline areas being not very reactive because it would be impeded for catalyst coming to that area due to low mobility. Furthermore, the presence of impurities or additives in the plastic may have a harmful impact on catalyst performance through poisoning active sites and modifying reaction pathways. Consequently, the impact of the structure of polymers on the interaction with the catalyst has been investigated through microscopy and spectroscopy and these have been employed to decipher these effects to enhance catalytic work (Kolganov et al., 2023). Improving the catalytic process of plastic recycling involves these aspects which can greatly enhance the functionality and aid in establishing sustainable technologies. Improving these processes will help to enhance catalytic performance, but also mitigate plastic waste and the environmental impact by addressing true sustainability targets in the long run.

4. Conclusion

Heterogeneous catalysis presents a paradigm shift for the recycling and upcycling of plastics with specific reference to the environmental and economic implications of the traditional techniques. Because it also facilitates transformation of plastic into useful chemicals, this approach is consistent with sustainability, and the circular economy. Additionally, heterogeneous catalysis is expected to have significant applications in the transition from the current “take-make-dispose” system of managing plastics waste to a circular economy. Since the current and future catalytic processes are under continuous study for designing more efficient catalysts, optimizing the process and discovering new catalytic processes, there are chances of efficient and sustainable systems for recycling as well as upcycling of plastics.

The key factors contributing to the management of the heterogeneous catalytic process for the treatment of plastic waste include the stability of the catalyst, its selectivity, as well as its cost. The critical path toward cost-effective, highly efficient catalysts for the practical application of this technology involve of multifunctional and recyclable catalysts; light-driven and electro-catalytic processes; and, efficient recycling of catalysts. The combination of biocatalysis with chemical catalysis is also anticipated to deliver highly selective and greener plastic upcycling strategies to support a more sustainable world. Therefore, future researches should focus on addressed the current limitations and seeks to advancement of catalytic recycling technologies in future studies by establishing new exciting strategies through special catalyst design, process improvement, as well as the application of interprofessional studies to realize the full potential of catalytic recycling and upcycling technologies. Additionally, using scientific development alongside policy backing and raising people’s awareness, we can harness heterogeneous catalysis to tackle the urgent issue of plastic waste and shift to a more sustainable utilization of plastics.

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