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Review Article

Hydrolysis of Plastic Waste as a Sustainable Pathway for Polymer Recovery and Material Regeneration

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Abstract: Plastic waste has become an issue of serious concern because it is persistent, not biodegradable, and greatly inefficient to recycle. The traditional mechanical type of recycling is restrained by the degradation and contamination of plastics, whereas the thermochemical process typically requires large energy inputs and yields complicated by-products. Hydrolysis also presents a scientifically viable alternative, which will allow chemical depolymerization of condensation-type plastics (polyethylene terephthalate (PET), polyamides (PA), polyurethanes (PU)). The reaction works through cleavage of the ester, amide, or urethane bonds in the presence of water, acids, or bases as reactants to generate high-purity monomers that can be repolymerized or used in industry. In this paper, the performance of hydrolysis-based plastic waste recycling has been reviewed, including the mechanisms, catalyst development, process parameters, and relative environmental performance. According to life-cycle and techno-economic analysis, hydrolysis will prove to be capable of generating significant carbon reductions and energy savings compared to pyrolysis and incineration with the optimization of reaction conditions and solvent recovery systems. Although scaling, reactivity, and purification of monomers are still problematic, heterogeneous catalysis, solvent engineering, and integration of renewable heat development all increase the promise of using heterogeneous catalysis as an effective tool in ensuring sustainable polymer recycling and material recycling.

Keywords: Hydrolysis, Plastic Waste Recycling, Chemical Depolymerization, Polymer Recovery, PET Degradation, Sustainable Materials, Monomer Regeneration.

1. INTRODUCTION

The rapid increase in plastic production and consumption rates in the last seventy years has become one of the strongest environmental problems of modern civilization. By 2022, the production of plastics worldwide had exceeded 400 million metric tons per year, and it is estimated that by 2050 the amount will have doubled in case of persistence of the present consumption trends persist (Huang, 2022). Sadly, the proportion of post-consumer plastic waste that is successfully recycled is low, and the rest is burnt, deposited into waste fills, or discarded carelessly into the environment (Schwarz *et al*., 2021). Plastic debris has been found in almost every system of the ecosystem, including ocean gyres and even freshwater systems, as well as agricultural soils and even the air, and this presents dire ecological and health hazards. Microplastics and nanoplastics are formed as a result of degradation, and they may find their way into food chains, disrupt aquatic life, and get trapped in the tissues of people, which is a global concern because of their long-term toxicity and stability (Zhao *et al*., 2022). This crisis is growing, and this calls the necessity of new waste management techniques and closed-loop recycling technologies, which are beyond the old-fashioned mechanical techniques.

The traditional form of recycling, which is a mechanical recycling that includes physical rework that involves sorting, shredding, melting, and remolding, is an old path that has been used to process plastic waste. Yet, this process has its internal limitations. Every round of mechanical recycling causes polymer chain scission, oxidation, and contamination,

and it leads to a certain tendency of a reduction in mechanical properties and quality of color of the recycled material (Hahladakis *et al*., 2018). Mixed and multilayer plastics, which find application in food packaging, textiles, and consumer goods, are of great concern as they are hard to separate and, in most cases, cannot be processed in the melt process. Furthermore, mechanical recycling does not reform the Moly structure of the polymer; it just increases the life of the polymer a bit before it can also be discarded. This way, it makes a lot of the plastic waste on the planet go into either a landfill or the environment, continuing a linear take-make-dispose cycle that is unsustainable over time (Schyns and Shaver, 2021).

As a solution to these systemic failures, chemical recycling has become a change agent that seeks to reclaim monomers or useful intermediates of plastic wastes by means of depolymerization. Chemical recycling has the benefit of potentially being recycled indefinitely since polymers can be broken down chemically to their building blocks, Monomers, and the properties and functions of the polymer do not suffer. Numerous chemical pathways have been considered, including pyrolysis, glycolysis, methanolysis, ammonolysis, and hydrolysis, and focus on individual polymer types and bonding structures (Liu *et al*., 2021). Hydrolysis is one of them and has attracted more interest because of its selectivity, relatively mild conditions of operation, and the capacity to produce high-purity monomers. It is especially applicable to condensation polymers (polyethylene terephthalate (PET), polyamides (PA6, PA66), polyurethanes (PU)) that have hydrolysing ester, amide, or urethane bonds (Al-Sabagh *et al*., 2016). This process not only allows recovery of important monomers like terephthalic acid (TPA) and ethylene glycol (EG), but also helps in their reintegration into the polymer production processes, which leads to sustainable regeneration of materials.

The hydrolysis mechanism is based on the breaking of the covalent bonds- most of the so-called ester bonds in PET- with the help of water, acid, or base at controlled temperature and pressure. Depending on the catalyst or reagent that has been employed, it can be carried out in a variety of modes, including neutral hydrolysis, acid hydrolysis, and alkaline hydrolysis (Paci & La Mantia, 2019). Neutral hydrolysis uses pressurized hot water or steam to depolymerize polymers into monomers or oligomers, whereas acid hydrolysis uses proton sources like sulfuric or phosphoric acid to allow the cleavage of bonds through the protonation of the carbonyl oxygen atom in the backbone structure. The alkaline hydrolysis, in its turn, entails the hydroxide ions attacking electrophilic carbonyl carbons, resulting in salts of the respective acids (e.g., sodium terephthalate) and glycoses as products (Liu *et al*., 2021).

Hydrolysis can work at relatively low temperatures (200 °C to 250 °C) and does not use as much energy as thermochemical procedures such as pyrolysis or gasification that reach temperatures above 500 °C. In addition, it yields fewer gaseous by-products and is more selective in monomer recovery, hence it is a more preferred route in environmental preservation. Hydrolysis is an efficient chemical recycling path with empirical evidence. It has been indicated that with optimal reaction conditions, PET hydrolysis can produce up to 90-95 percent monomer recovery of terephthalic acid and ethylene glycol with only a few side-products (Zhu *et al*., 2020; Pereira *et al*., 2024). The monomers recovered can be used directly in polymer synthesis in their purified form and without much modification, as they are as pure as virgin feedstocks. As an example, even colored or contaminated waste of PET that could not be processed by mechanical recycling has so far been shown to be treated by high-pressure hydrolysis with subcritical or supercritical water (Abedsoltan *et al*., 2023). Equally, heterogeneous and enzymatic catalysis has also shown recent improvements through the application of engineered enzymes, including PETase and cutinase, which have been shown to depolymerize efficiently under mild conditions, minimizing the amount of energy and environmental impact (Wei *et al*., 2022). New developments of this kind highlight the versatility and applicability of hydrolysis in the next-generation systems of waste management.

In addition to technical performance, hydrolysis fits with other objectives of sustainable materials regeneration, whereby waste products are constantly transformed into useful materials. Compared to the thermochemical conversion processes, in which the ultimate product is usually fuels or low-value hydrocarbons, hydrolysis aims at maintaining the complexity of the molecules, which can be re-polymerized as monomers. This will lower reliance on virgin petrochemical feed and lessen the environmental impact of extracting raw materials and burning of plastics (Jeswani *et al*., 2021). Hydrolysis can be made a low-carbon process with a significantly reduced environmental impact when combined with renewable energy sources to provide heating and solvent recovery. Therefore, hydrolysis is not simply a treatment procedure, but a tactical component of regenerative polymer recovery solutions that will enable the global material economies to become more resilient, as a result of converting the plastic life cycle into a regenerative rather than a linear system.

2. Mechanism and Process Parameters

The ability to selectively cleave ester, amide, or urethane bond-type links in the polymer backbone by the influence of water molecules (neutral hydrolysis), acid catalysts (acid hydrolysis), or base catalysts (alkaline hydrolysis) is the basis of the hydrolysis of condensation-type plastics like Polyethylene Terephthalate (PET). During neutral hydrolysis, the polymer chain is broken down into smaller oligomers and finally, monomers, including terephthalic acid (TPA) and ethylene glycol (EG), through water under high temperature and pressure, attacking the ester bond (Anuar *et al*., 2022).

Acid hydrolysis increases the rate of bond-scission by protonating the carbonyl oxygen, thereby raising the electrophilicity of the carbonyl carbon and enhancing nucleophilic attack by water (Paci & La Mantia, 2019). Hydroxide ions are also direct nucleophiles in an alkaline hydrolysis, which breaks the ester bond to produce carboxylate salts (e.g., sodium terephthalate) and glycoses (Spaseska and Civkaroska, 2010). It is also important to understand these various mechanistic pathways, as the direction of hydrolysis used affects the kinetics of a reaction, the formation of by-products, the compatibility of catalysts, the downstream purification needs, as well as energy usage.

In addition to the mechanistic background, a number of process parameters have a major influence on the conversion efficiency, yield of monomers, and the formation of impurities. One of the most important is temperature: the neutral hydrolysis experiments indicate that the optimal performance is frequently reached in the range between 220 and 300 °C, with the residence time being 30-90 minutes, with an autogenous pressure of 25-90 bar (Thulasiraman *et al*., 2025). Equally, a neutral hydrolysis experiment found that a weight ratio of water-PET of about 10:1 gave the best TPA production without undue dilution and energy cost (Thulasiraman *et al*., 2025). The other parameters, including the stirring speed (when using solid polymer feedstocks), particle size (smaller particle sizes increase the surface area and minimise diffusion barriers), and feed pretreatment (e.g., elimination of contaminants), are also important (Pereira *et al*., 2023). In the case of catalyst-assisted hydrolysis, the type of catalyst, its loading, and lifespan under corrosive conditions should also be optimised. Machine-learning studies have recently started to correlate all these parameters to process output, providing data-driven routes to parameter optimisation (Li *et al*., 2025).

The interaction of the pressure and solvent environment is also a key factor. Water can be in either the subcritical or supercritical state in a neutral hydrolysis, which improves the diffusivity and contact of the polymer with the water but also increases the cost and safety requirements of some equipment. According to Pereira *et al*., (2023), successful hydrolysis may occur at pressures between 1-35 MPA at temperatures above 190 °C. High pressure often leads to a greater dissolution rate in oligomer and a greater yield of monomer, but also introduces increased capital and operational costs. During alkaline hydrolysis, scission is greatly affected by the concentration of the hydroxide (or other base): low concentrations of the base increase the rate of the reaction, but can produce salt wastes and necessitate further purification. As an illustration, time-course alkaline hydrolysis of PET studies indicate that reaction time decreased 5 h to 3 h, at the same time, an increase in hydroxide concentration of 0.1 mol per mol PET to 2.0 mol per mol PET caused an increase in TPA yield in alkaline hydrolysis of PET, which increased to values nearer than 90 percent (Spaseska and Civkaroska, 2010).

Another parameter optimization dimension is the system of catalysts and solvents. Recent studies have now considered heterogeneous catalysts rather than just acid or base catalysts (e.g., metal oxides, polyoxometalates), ionic liquids, and even enzyme-based systems (Wei *et al*., 2022). An example of this is the catalytic neutral hydrolysis of PET reviewed by Umdagas *et al*., (2025), which identifies the use of catalysts that facilitate the breaking up of the outer layer, as well as inner layers, to maximize overall yield and minimize the amount of residence time required. The solvent environment (usually water, although it may also be combined with co-solvents or catalysts) must be such that it can adequately give the polymer sufficient swelling, penetration, and heat transfer to allow effective reaction. The size of the plastic feed used is also crucial: smaller particles (e.g., smaller than 10 mm) higher surface-to-volume ratio, lower thermal gradients, and fully depolymerize. Further contribution is through mechanical pretreatment (shredding, washing, drying), which eliminates contamination and makes feeding the reactor easier.

Lastly, it is necessary to pay attention to process integration and downstream purification. Even though high-purity monomers can be obtained through hydrolysis in ideal conditions, dyes, additives, remaining catalyst, oligomers, and salt by-products may impair quality unless purified after (Zhu *et al*., 2020). The severity of the reaction should be moderate: too harsh conditions (high temperature, duration) can cause secondary side-reaction, cause degradation of the monomers, or produce colored products that may complicate the purification process and lower the payback (Pereira *et al*., 2024). This therefore means that mechanism and process parameter optimisation that include feedstock pretreatment, reaction kinetics (temperature, pressure, residence time, reagent ratios), catalyst or enzyme systems, and downstream monomer purification are important aspects that should be seen in holistic terms to realise hydrolysis as a commercially viable polymer-recovery technology.

3. Environmental and Energy Perspectives

Through complete life-cycle assessments (LCAs), it has been found that hydrolysis, as a chemical recycling process of plastics, especially polyethylene terephthalate (PET), has significant environmental benefits over traditional end-of-life disposal schemes, such as landfill and incineration. Since hydrolysis is performed under the conditions of moderate thermal and pressure (usually 200-250 °C, 1-3 MPa) and allows direct recovery of monomers, the process has few greenhouse gas (GHG) emissions and low energy intensity, in comparison with virgin polymer production or thermal degradation. According to LCAs, it has been shown that hydrolysis would decrease total carbon emissions by up to 60-70% compared to incineration with energy recovery and reduce almost 40% of total carbon emissions compared to virgin

polymer production under the assumption of efficient solvent recycling and renewable electricity inputs (Jeswani *et al*., 2021; Alhazmi *et al*., 2021). The environmental advantages are due to the fact that not only is the extraction of fossil feedstocks avoided, but the virgin monomer is also replaced with a regenerated one. Besides, hydrolysis produces low levels of toxic air pollutants because it does not involve combustion or high-temperature cracking, unlike pyrolysis or gasification pathways that release volatile organic compounds (VOC) and polycyclic aromatic hydrocarbons (PAH) (Costa *et al*., 2022).

The heating and pressurization are the main sources of energy requirement during hydrolysis, especially in continuous reactor systems. Research shows that overall energy consumption can be reduced by 25-35 percent through optimization of the exchanger of heat recovery, insulation, and integration of reactors with renewable or waste-heat (Arena *et al*., 2003). Solvency recovery units and incorporation of hydrolysis with renewable steam production (solar, geothermal, or biomass) also increase the sustainability of the process. This is because the closed-loop recovery of aqueous and alkaline solvents not only reduces the amount of waste being released but also, to a large extent, the process water requirement and chemical losses. Moreover, the substitution of acids with solid catalysts or enzyme-based systems might decrease the toxicity of the effluents and the need for neutralization downstream, which causes an environmental footprint (Wei *et al*., 2022).

Economically, Techno-economic-assessments (TEA) indicate that hydrolysis plants would have good cost distributions when scaled in excess of 30-50 tons per day, in particular when the purity of monomers would allow direct recycling in polymerization units. It is demonstrated that life-cycle costing indicates that recovery and third-use of terephthalic acid (TPA) and ethylene glycol (EG) can save up to 60 percent of the costs of raw materials, as compared to purchasing virgin monomers (Arena *et al*., 2003; Pereira *et al*., 2024). The economic viability is enhanced even more when the solvent recycling efficiencies are above 90% and hence dramatically reduces the reagent costs and the wastewater treatment burdens. Hydrolysis yields high-purity and predictable chemical products that can be easily incorporated into the existing polymer production lines, as compared to pyrolysis, which produces mixed hydrocarbons of varying market value.

Nonetheless, the reliance on environmental and energy benefits is on the process structure and local energy structures. The carbon saving is reduced drastically when the hydrolysis is driven by electricity generated by fossil fuel or when solvent recovery is not efficiently achieved. It is, therefore, important to couple hydrolysis to low-carbon sources of power to achieve a maximum environmental benefit. The other critical consideration is the transport logistics; local processing centers of PET waste will be able to reduce the feedstock transportation emissions and enhance the sustainability of the entire system. Moreover, conversion rates can be stabilized by means of adopting new and more sophisticated monitoring and control systems, i.e., real-time temperature and pH optimization, which minimizes the use of energy and minimizes operational costs.

Accordingly, hydrolysis of plastic waste is a better and more promising chemical recycling path compared to other methods in terms of environmentally friendlier and viable economic prospects in case it is carried out in integration with renewable energy, recovery of solvents, and effective downstream purification. The process helps to reduce the global GHG emissions, reduce reliance on virgin petrochemicals, and enhance the energy efficiency of polymer supply chains. Further optimization of the plant, feedstock logistics and catalyst innovation will be necessary to retain ecological and financial sustainability in large-scale hydrolysis processes.

4. Challenges and Future Perspectives

Although incredible achievements have been made in recycling plastics through hydrolysis, there are several technical and economic, as well as infrastructural challenges that are preventing the extensive industrial implementation of this technology. The major challenges include the heterogeneity of feedstocks- post-consumer plastics are not pure and can generally consist of multilayered composites, additives, and colorants, which disrupt uniformity of reactions and purity of monomers. The fillers, stabilizers, and adhesives are considered impurities, making it difficult to do downstream purification, which is costly to process. In addition, hydrolysis reactions have lower kinetics than pyrolysis or gasification, and thus either longer residence times or larger catalyst loadings are needed to fully depolymerize the material. This is more energy-consuming and less efficient in throughput. The application of aggressive reagents like strong acids and bases comes with other issues of corrosion in the reactor, catalyst deactivation, and neutralization of wastes that, in turn, increase operational and maintenance expenses.

Hydrolysis on a large scale also has engineering and economic limitations. Making corrosion-resistant reactors that can maintain high pressures and reduce fatigue of their materials is one of the greatest challenges. Heating, pressurization, and solvent recovery costs are added costs to the overall operating costs. Though experiments at lab scale claim recovery yields of well over 90, it is necessary to control feedstock composition, temperature versus time profiles, and fluid mechanics to maintain these recovery yields at an industrial level. There should also be high efficiency of the solvent recovery and effluent treatment systems in order to ensure that not only the environmental impact but also the cost

of operation is minimized. The absence of closed-loop solvent management means that the hydrolysis plants will have the risk of producing high volumes of alkalinity or acid waste streams, which may jeopardize the sustainability goals.

Catalytically, the ongoing studies are directed to substitute the traditional homogeneous catalysts with heterogeneous ones or recyclable ones to be able to retain high selectivity and activity at mild conditions. Catalysts that are supported on zeolites, metal oxides, and polymers have the potential to enhance the reaction rates and minimise the possibility of corrosion. Simultaneously, new research is being proposed on the possibilities of biocatalytic and enzymatic hydrolysis through the use of engineered enzymes like PETase and MHETase, which can depolymerize polyesters at near-ambient or ambient temperatures. This is an eco-friendly method of recycling plastic that significantly reduces the amount of energy required and gets rid of toxic effluents, thus making it a viable alternative to other forms of plastic recycling in the future. Nevertheless, there are still difficulties in the stability of enzymes, scalability, and cost-effective production that will need additional biotechnological innovation (Wei *et al*., 2022).

Another area of advancement of the efficiency and predictability of processes is the integration of digital technologies, such as computational modeling, machine learning (ML), and artificial intelligence (AI). Such tools can optimize the conditions in reactors, forecast kinetic paths, and minimize the costs of trials in experiments. One of the most enduring barriers to industrial adoption that AI-based catalyst and reaction networks design may provide is dynamic control of processes using mixed-plastic feeds. Also, techno-economic assumptions and process parameters need pilot-scale demonstration projects to validate these elements before commercialization. These programs can help obtain essential information regarding the stability of reactors, throughput, regeneration of catalysts, and energy efficiency of the lifecycle (Vanapalli *et al*., 2021; Khan *et al*., 2022).

In the future, it is possible to say that the policy, infrastructure, and collaboration of industries will be the key to the success of hydrolysis as a sustainable route to polymer recovery. Governments should develop favorable regulatory conditions and financial incentives to use chemical recycling technologies, and industries should invest in value chains of waste collection, preprocessing, and chemical conversion. The international cooperation, especially in those areas where industrial chemical recycling is developing, like in Iraq, may be a strategic step in constructing pilot plants and relocating the technological experience. The interplay between material science, green chemistry, and industrial engineering can change hydrolysis from an instrument of laboratory method to a polymer recovery and material regeneration tool of sustainable resource use.

5. CONCLUSION

Hydrolysis is a scientifically verified and greener approach to addressing the increasing plastic waste problem using specified chemical depolymerization. In contrast to other conventional forms of mechanical or thermochemical recycling, hydrolysis provides the opportunity to recover polymer feedstocks in high-caliber chemical purity and low degradation, which restores the original worth of monomers. The approach will not only reduce landfill waste since discarded plastics can be converted not only into reusable molecular building blocks, but it will also help reduce reliance on virgin petrochemical resources. The flexibility of the process to various types of polymers, including mainly condensation polymers like PET, PA, and PU, contributes to its versatility in the quest for implementations of sustainable material recovery all over the world.

By optimisation in terms of operational efficiency, hydrolysis may bring about some impressive environmental benefits. Refined catalysts, temperature, pressure, and solvent recovery systems can tremendously reduce the usage of energy and emissions through process intensification. The resulting monomers can be directly recycled back into the current polymer production flow, which is a closed material cycle that greatly reduces extraneous production of waste. The characteristics make hydrolysis one of the prospective unlocking factors to a transformation of plastic waste, constituting a liability to the environment into a renewable chemical resource. Moreover, the inclusion of the process with renewable energy to supply heat or electricity can significantly reduce its carbon footprint and make its contribution to the low-emission industrial systems.

However, to achieve the maximum hydrolysis development, it is necessary to overcome a number of existing challenges. The variability of feedstock, contamination, and additives remains a problem, complicating reaction kinetics and further purification. The competitiveness in the scale of the process, maintained at cost-effective levels and environmental protection, is an imperative challenge to both engineers and policymakers. The corrosion-resistant reactor design, creating recyclable heterogeneous catalysts, and the strong solvent recovery units are all that are needed to transfer the hydrolysis success in the laboratory to the industry. The future interdisciplinary research involving chemical engineering, materials science, and environmental management will be unavoidable in overcoming these obstacles.

In the case of developing countries like Iraq, in which the rapid increase in urbanization and industries has increased the rate of plastic waste accumulation, hydrolysis is a viable and proactive solution. Pilot-scale plants would

allow building local capacity to develop advanced recycling processes and would open new economic opportunities based on the manufacture of high-quality recycled monomers. These would enhance the national systems of waste management and foster sustainable industrial practices. Through proper investment, policy facilitation, and adjustment of technology, hydrolysis can have a radical role to play in facilitating a resource and circular materials economy in Iraq and other parts of the world.

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