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Next-generation plastic recycling: Breakthrough developments and the path toward a circular economy

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Abstract

The increasing amount of plastic garbage is a major global environmental problem that demands innovative and effective recycling strategies. It is evident that traditional mechanical recycling is not sufficient due to its being limited to certain types of garbage and limitation of material quality degradation over time. Thus, development in advanced plastic recycling technology is crucial for moving toward a sustainable circular economy. This detailed research gives an overview of these key advancements. The study investigates some of the newest technologies, such as chemical depolymerization, which breaks down polymers into high-quality monomers; catalytic pyrolysis, which turns mixed plastics into useful feedstocks; and innovative enzymatic treatments, providing gentle and selective degrading routes. This article also highlights some of the most important developments in process innovation and better feedstock preparation, as well as the important trade-offs between these methods' economic and environmental effects. Finally, it gives suggestions for how to move forward with future research, stresses the importance of integrated recycling processes, and lists the policy changes that need to be made to speed up the widespread use of these game-changing solutions. These initiatives will eventually lead to the creation of a truly circular economy for plastics.

Keywords: Plastic Recycling; Catalytic Techniques; Biological Techniques; Pyrolysis; Depolymerization

1. Introduction

There is little doubt that the huge rise in plastic production and consumption over the past years has been undeniably beneficial for modern society. Plastics are quite commonly used because they are light, strong, cheap, and used in a wide range of items for building, cars, electronics, textiles, and medicine. If current trends continue, worldwide plastic manufacturing is expected to reach up to 1,100 million tons by 2050, which is more than 390 million metric tons in 2021 [1]. Plastics have various uses, but their most useful and alarming quality of having resistance to degradation has led to a global environmental disaster. Approximate estimation states that over 9 billion tons of plastic were produced so far and almost 75% of these have ended up in landfills, oceans or the environment [2], [3], [4], [5], [6], [7]. Plastic waste that stays in both land and water habitats causes microplastic pollution, harms biodiversity, and may even be detrimental to people's health [8], [9], [10], [11].

Moreover, the "take-make-dispose" model suggests that people can't use any more plastic and recycling rates are unexpectedly too low right now. As per the UNEP 2023 report, only about 9–14% of the world's plastic trash gets

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effectively recycled, even though recycling is often considered as a key in achieving a plastics circular economy [12], [13]. After mechanical recycling, which involves sorting, shredding, cleaning, and remelting, thermoplastics are converted into new products. But there are significant limitations to this process. Downcycling is a common result of mechanical recycling. As the material is recycled, the polymer chains' mechanical performance and value degrades, Which is the drawbacks of the mechanical recycling [14], [15], [16]. Also, it doesn't work on composites with more than one layer, streams of mixed plastic, or polymers that have been contaminated with food, chemicals, or dyes [17], [18], [19].

Using better recycling technologies, which have lately come to light as a possible alternative, can get beyond the restrictions of mechanical methods. Pyrolysis, depolymerization, solvolysis, and gasification are all examples of chemical recycling methods. Biological recycling can also involve enzymes and microorganisms. To achieve material circularity, chemical recycling breaks down polymers into their individual monomers, hydrocarbons, or other byproducts that can be reused or re-polymerized [20], [21], [22]. Solvolysis breaks down PET into ethylene glycol and terephthalic acid. Pyrolysis can turn mixed polyolefins into fuels and waxes. Bio-based approaches that have been shown to enzymatically downgrade PET and related plastics in mild settings [23] are paving the way for greener and more effective recycling solutions.

Advanced plastic recycling has been a hotspot of new ideas in the past few years because of growing worries about the environment and new technologies. New methods like genetically engineered enzymes, ionic liquid-mediated solvolysis, microwave-assisted depolymerization, and catalytic hydrocracking have made recycling processes much more efficient and selective [24], [25]. Still, there are problems with scalability, cost-effectiveness, life-cycle effects, and how well it works with present waste management systems. To solve these difficulties, a lot of multidisciplinary collaboration consisting of materials science, biology, chemical engineering will be required and at the same time issues to be addressed through creating laws and policies.

Eventually, the goal of this review is to bring together the most recent discoveries in advanced plastic recycling by looking at the existing situation and making judgments about the potential, risks, and cutting-edge technology. The purpose of this plastic recycling project is to find solutions that are good for the environment and economically feasible that brings plastic into a real circular economy in the end.

2. Overview of Recycling Techniques

2.1. Mechanical Recycling and Its Limitations

Most people know about and use mechanical recycling to get rid of plastic waste. Plastic materials are collected, sorted, washed, shred, melted, and reshaped into new items as part of this process shown in Figure 1. This method is often used on thermoplastics like HDPE, PET, and PP because they can be recovered without changing their chemical structure. Mechanical or manual recycling are used in a great deal, but it has some critical limitations that make it less effective in dealing with the growing amount and complexity of plastic trash.

One of its biggest problems is that it needs clean input lines that don't have any other contaminants. There are many polymers, colours, fillers, and additives that make up plastic trash. It may also contain organic matter or other things that could make it dirty. When there are extra and incompatible pollutants or polymers that don't mix well together, recycled materials lose a lot of their quality end use implementation and application becomes impossible [26]. Lots of plastics that are recycled physically also go through a process called "downcycling," which makes them less strong and useful than new plastics. One main reason for the breakdown is that polymer chains break down due to heat and oxygen over several melt processing rounds. According to Al-Salem et al., this drops the molecular weight, makes the material more fragile, and tears down its structure [27].

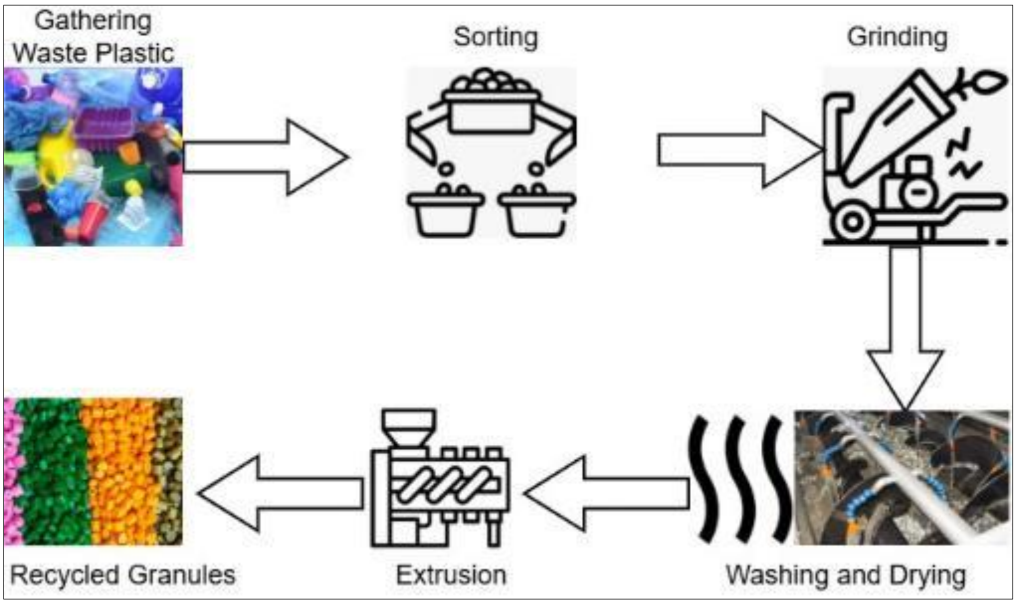

Figure 1 Overview of Mechanical Recycling Process

Plastics work better with the application of additives like plasticizers, flame retardants, dyes, and fillers etc. that tailor the performance and helps in posing the challenges in reprocessing and reuse. Even after the plastic has been reprocessed, these chemicals may still exist within the reprocessed materials causing the ambiguity in their effectiveness and usefulness. Again, these additives might contain toxic compounds built up in the recycled material, which would be detrimental for the environment and people's health [28]. Another notable limitation is the complexity in recycling multilayer or hybrid plastic packaging as these materials were designed and produced for the quality rather than recycle it simply. It's harder to recycle by hand because there are many layers made of different plastics, such as PET, polyamide, and polyethylene. Due to this, these things are often thrown away to the environment or burnt [29].

Because of these difficulties, more businesspeople and scholars are trying to introduce more advanced ways to recycle, such as chemical and enzymatic recycling. Plastics could be depolymerized into their basic parts with these methods. This would make it easy to recover higher quality materials. These initiatives are better for dealing with trash streams that are mixed and polluted. They help build a cycle economy by making new, high-quality plastics from just wastes [30], [31], [32].

2.2. Chemical Recycling of Plastics

Chemical recycling, often known as advanced recycling, encompasses a variety of innovative methods that decompose plastic waste into its basic molecular components, including monomers or other valuable chemical feedstocks. In contrast to mechanical recycling, which maintains the polymer backbone via physical reprocessing, chemical recycling modifies the molecular structure of polymers, facilitating the recovery of high-purity raw materials suitable to produce virgin-quality plastics [33], [34].

2.2.1. Chemical Recycling Process

Chemical recycling is to reverse the polymerization process by breaking down plastics into smaller molecules that can be reused according to fundamental concept. The process is accomplished using either thermochemical or solvolysis methods, which are made for different types of polymers and are discussed in forthcoming sections.

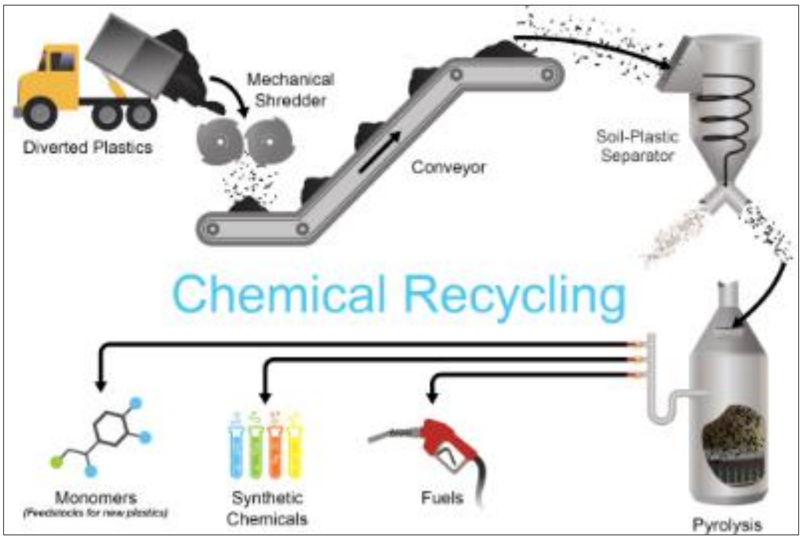

Figure 2 Chemical Recycling Pyrolysis Processes [35] (Open Access Journal)

- Pyrolysis: This is one of the most advanced and well-studied thermochemical reactions. The method involves breaking down plastic waste with heat in an oxygen-free atmosphere to make pyrolysis oil, gases, and char from polymer chains as shown in Figure 2 described by Sarpong K et al. [35]. Pyrolysis works best on mixed polyolefins like polyethylene (PE) and polypropylene (PP). The extracted oil can be refined into new plastic precursors or used as fuel. [36], [37].
- Gasification: Gasification as illustrated in Figure 3 transforms plastic waste into syngas—a combination of hydrogen and carbon monoxide—through its reaction with a restricted quantity of oxygen and/or steam at elevated temperatures. Syngas function as a multifaceted feedstock for the synthesis of chemicals, fuels, or novel polymers [38], [39].

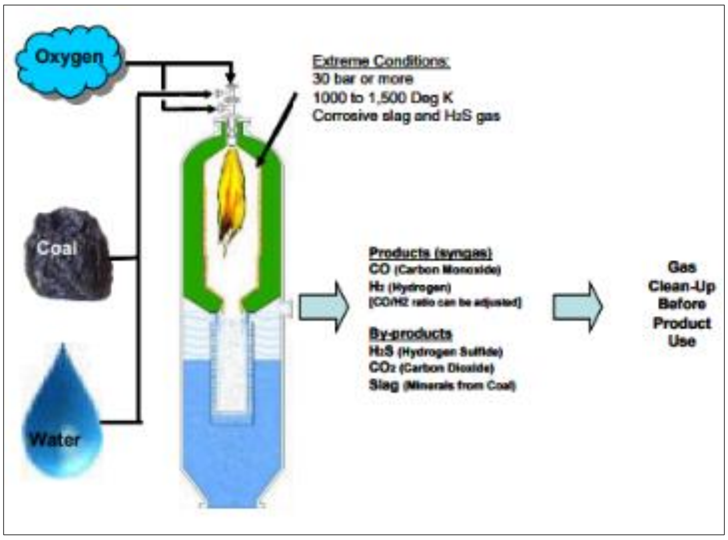

Figure 3 Fundamental Gasification Process [38] (Open Access Journal)

- Depolymerization: Depolymerization also known as solvolysis is performed for the utilization of solvents, catalysts, and occasionally heat to decompose polymers into their monomeric constituents. Glycolysis, metanalysis, and hydrolysis are frequently employed for polyesters such polyethylene terephthalate (PET) and polystyrene. The recovered monomers can subsequently be re-polymerized to produce new plastic materials with qualities which is comparable to those of virgin resins [40], [41].
- Dissolution: Dissolution-oriented Recycling, albeit fundamentally a physical process rather than a chemical one, is frequently categorized as advanced recycling due to its capacity to selectively remove specific polymers utilizing solvents. Additionally, this technique preserves the polymer's integrity while facilitating the

purification and recovery of certain resins, such as polystyrene or polypropylene, from heterogeneous or polluted waste streams [42], [43].

2.2.2. Benefits of Chemical Recycling

Chemical recycling is an important aspect of a circular plastics economy since it works better than other types of recycling [44], [45], [46]. Few advantages are mentioned below.

- Tolerant to Mixed and contaminated waste: Chemical recycling can deal with plastic waste streams that are complicated, mixed, and dirty, while mechanical recycling needs materials that are clean and in the appropriate order.
- Making Materials That Are Virgin-Equivalent: These methods turn polymers into monomers or molecular feedstocks. This creates materials that are the same as those created from oil, which makes them easier to utilize again.
- Widened Range: Chemical systems can recycle a larger spectrum of materials. These systems can recycle plastics that people don't generally think can be recycled mechanically, such brilliant polymers, composites, thermosets, and multilayer packaging.
- Decreased dependence on fossil fuel: Recycling chemicals might cut down on the demand for new petrochemicals and greenhouse gas emissions across the life cycle of a product, if it is driven by sustainable energy.

2.2.3. Limitations and Challenges of Chemical Recycling

Chemical recycling might make the environment and the economy a lot better, however there are a lot of problems that need to be overcome before it can be used as a viable option: Excessive energy requirement: lot of energy is needed for many chemical reactions, including pyrolysis and gasification. This makes concerns among people about bad impacts of fossil fuel to the environment. Quick commercialization: Most chemical recycling technologies are still being developed or tested, and only a few are being used on a large scale. It is still hard to scale these technologies from technical and economic point of view.

- High Cost: The high cost of chemicals, the complicated process, and competition from cheap virgin plastics have all made it hard for chemical recycling to become more common. The market for things made from recycled materials is still growing.
- Climate Challenges: Some chemical recycling processes involve technology and feed stock that might generate dangerous by-products or pollutants. To find out how much they affect the ecosystem, we need to do full life cycle assessments. The last thing to mention is that chemical recycling isn't a silver bullet, but it's highly essential since it solves the difficulties that mechanical recycling has. It is crucial for getting actual material circularity since it may make money from waste streams that are hard to deal with and unclean. Also, sufficient funding to be reimbursed for research and development, process optimization, integrating renewable energy, and supporting regulatory frameworks to attain its full potential. We need to look at the big picture when it comes to controlling plastic garbage and include chemical recycling as part of that plan.

2.3. Biological Recycling

Biological recycling, which employs enzymes or bacteria to break down plastic, is one of the emerging approaches that has showed a lot of promise as a low-energy, high-specificity way to break down and reuse plastic. The technique breaks down plastic trash into building blocks that may be utilized again and over again with the help of enzymes or microbes. It can be done in moderate weather and is in keeping with the ideals of a circular and bio-based economy[47].

2.3.1. Biological Methods for Recycling

There are two basic forms of biological regeneration: enzymatic depolymerization and microbial Degradation.

- Enzymatic Depolymerization: Biological catalysts, or enzymes, are used in enzymatic recycling to break down plastic polymers into their monomers. Enzymatic depolymerization operates at lower temperatures and pressures than thermochemical methods, with temperatures below 70°C and normal pressure. This implies that less energy is used, and fewer undesired by-products are generated [48], [49], [50], [51]. There has been a lot of research on cutinises, lipases, and carboxylesterases in connection to polyethylene terephthalate (PET). In 2016, scientists found a unique enzyme named PETase in the bacteria Ideonella sakaiensis. It turns PET into terephthalic acid (TPA) and ethylene glycol (EG), which may be utilized to create fresh PET [52]. This discovery made enzyme engineering more popular throughout the world, which led to improved versions like FAST-PETase, which can break down more than 90% of PET in 24 hours under typical settings [53].

Also, the usage in industry is growing better. Carbios, a French biotech company, has proven pilot-scale enzymatic recycling facilities that can turn PET into something else quite efficiently while preserving the monomer purity at the same level as fresh PET material [54].

- Microbial Degradation: Microbial degradation is when entire microorganisms, such bacteria or fungus, generate enzymes that break down polymers, either on the surface of the polymer or in the media around it. These bacteria use the oligomers and monomers that are left over as carbon sources to proliferate or manufacture other bio-based products, such as bioplastics like polyhydroxyalkanoates (PHAs) [55], [56].

The method is greatly affected by the kind of polymer. Polyesters employ hydrolytic enzymes, whereas polyolefins like polyethylene (PE) and polypropylene (PP) typically need to be oxidized first to work. Enzymes like laccases, peroxidases, or oxygenase add functional groups to the carbon backbone, which would otherwise be inert. Microbes may attack them more easily because of this [57]. Microbes including Pseudomonas spp., Bacillus subtilis, Rhodococcus rubber, and fungus like Aspergillus tubingensis have been demonstrated to grow on plastic surfaces, create biofilms, and help break down the plastic through enzyme activity outside of cells [58].

2.3.2. Advantages of Biological Recycling

Biological recycling is a nice concept because There are many good things about biological recycling of plastic, such as:

- Moderate Operating Conditions: Enzymatic and microbiological systems perform best at normal or moderate temperatures and pressures. They use a lot less energy than pyrolysis or gasification [49].
- Purity: Enzymes are highly adept at identifying certain chemical bonds, which makes them incredibly selective and pure. This implies that they have fewer side reactions and make more pure monomers that may be reused in a closed loop [53].
- Environment Friendliness: Being kind to the environment means using less chemicals and harmless biological agents, which means less waste and a smaller carbon footprint[54].
- Ability to handle complex Waste: Biological systems could be able to manage plastics that are blended, coloured, or layered that are challenging to recycle mechanically or chemically [55].
- Economic Benefit: Biological recycling collects molecules or metabolites that may be utilized to generate bio-based goods. This is another technique to help resources circularity.

2.3.3. Challenges and Future Prospects:

Biological regeneration may modify things; however, it has several issues:

- Reaction Rate and Throughput: New developments in enzyme engineering have sped up catalysis, but biological processes are still slower than chemical ones, which makes it harder to scale them up.
- Cost and Stability of Enzymes: It's still challenging to make enzymes for use in industry that are stable, repeatable, and cheap, especially when trying to break down strong polymers.
- Pre-treatment requirements: Some plastics need to be physically, thermally, or chemically pre-treated to make enzymes easier to get at by breaking up crystalline domains or adding things.
- Limited scope of application: Enzymes can't recycle some things. Polyesters, such as PET and PLA, have performed well for this procedure thus far. Researchers are trying to get biocatalytic approaches to work with polyolefins (such PE and PP), which don't have linkages that water can break down.

Finally, Proper initiatives to be taken for solving these challenges in the future by making advancements in protein engineering, synthetic biology, metabolic pathway optimization, and process improvement. Then sufficient fund is to be invested into biological recycling and individuals from other professions work together, to make a significant element of effort in dealing with plastic pollution throughout the world.

2.4. Integrated Approach

The complexity of pollution from plastic waste is increasing, characterized by the incorporation of new additives, polymers, and multiple layers of plastic. The effectiveness of recycling has suddenly become challenging. The integration of recycling solutions is increasingly favoured by researchers and industry professionals. Integrating mechanical, chemical, and biological processes in hybrid systems can enhance product quality, reduce healing time, and mitigate environmental impact [59]. An integrated recycling system aims to amalgamate the benefits of various recycling processes while reducing the limitations associated with each. Prior to recycling the plastics, they should be sorted, shredded, filtered and cleaned. This is very significant for high-value polymers of the same kind, including HDPE and PET. Recycling methods employ chemicals or living creatures to break down objects that are too unclean, broken, or hard to handle by hand. As an instance, one of the techniques to manufacture good materials is to fragment the molecules into simple parts called monomers[60][61]. The utilization of mixed systems facilitates the recovery of additional resources, as it allows for selective valuation of specific plastic streams. The processes of solvent-based dissolving, enzymatic or catalytic hydrolysis, and pyrolysis or gasification can be integrated into a unified system to extract PET from mixed plastic waste, eliminate polystyrene, and transform polyolefins into fuel or chemical feedstocks [59], [62]. These procedures are enhanced in less demanding environments through the incorporation of biological processes, specifically enzymatic depolymerization. Tournier et al. [63] and Wei and Zimmermann [64] indicate that these further decreases energy consumption and greenhouse gas emissions. Advanced sorting technologies, such as near-infrared spectroscopy [65]and machine learning-based visual identification [53], are being employed to improve pre-treatment processes. These prevalent technologies enable the automatic sorting of plastics by colour, grade, and type. Integrated systems that utilize renewable energy and aim for circularity demonstrate superior economic and environmental benefits compared to single-process recycling systems, as evidenced by techno-economic and life cycle assessment (LCA) studies [66]. These findings indicate that integrated recycling systems can significantly contribute to the development of a large-scale, cost-effective, and carbon-neutral plastics circular economy. Numerous questions remain unresolved, especially regarding the financing of essential infrastructure and system connections, the assurance of interdependent processes, and the management of diverse feedstock types. Addressing these gaps requires interdisciplinary teams, and regulations should promote their collaboration. Advancements in enzyme engineering, catalyst development, and modular system design are crucial.

3. Recent Research Trends and Key Developments

As the need to fight plastic pollution grows, research into recycling plastic is moving quickly. Important improvements include designing catalysts, engineering enzymes, assessing the effects on the environment, and creating policy frameworks. All these study areas are working together to build a circular economy for plastics that is better for the environment and uses more advanced technology.

3.1. Catalytic and Process Innovations

There are a lot of new ideas being made in the field of catalytic depolymerization, especially when it comes to pyrolysis, hydrocracking, and gasification. Traditional catalytic systems couldn't be as energy-efficient or scalable since they needed higher temperatures and pressures. There have been novel heterogeneous catalysts produced in the last several years. These include zeolite-based catalysts including ZSM-5, Beta, and Y zeolites[67] [68], as well as transition metal oxides [69]. These catalysts operate better when the conditions aren't as bad. These materials help you pick certain hydrocarbon ranges (such naphtha or diesel), minimize cooking, and make catalysts last longer. This makes processing cycles better for the environment.

Reactor engineering, on the other hand, has come a long way. Dielectric heating is used in microwave-assisted pyrolysis to swiftly and uniformly disseminate heat[70], [71]. This has cut down on response time and energy utilization by a lot. People are starting to understand that continuous-flow reactors, such as fluidized-bed and tubular reactors, may be employed in large factories and make products of consistent quality. These systems are more flexible and efficient than batch processes because they can better control dwell time, reaction kinetics, and heat transport. Machine learning and process simulation are becoming more and more crucial for designing and improving catalytic systems. This is to speed up the production of selective and effective catalytic platforms. These tools help you find out how well a catalyst works, what the ideal circumstances for a reaction are, and how to get rid of unwanted by-products.

3.2. Advances in Enzymatic Recycling

Enzymatic depolymerization of polyesters is a form of biocatalytic recycling which is also termed as a novel and captivating field of inquiry in sustainable materials science. The primary objective of this endeavour is to produce PET hydrolases, which are enzymes that disrupt ester bonds in polyethylene terephthalate (PET) polymers. Most of the research conducted on PETase from Ideonella sakaiensis since its discovery has focused on its stabilities at various temperatures [72], its ability to bind to other molecules, and its ability to catalyse reactions [73].

The development of synthetic enzymes such as DuraPETase, HotPETase, and FAST-PETase has facilitated progress. Being capable of maintaining the stability at elevated temperatures (approximately 60–70 °C), these enzymes function effectively in environments that are like those encountered in industry. In 24 hours, these enzymes can degrade PET by over 90%, even in the presence of numerous compounds, pigments, and other detrimental substances [72]. The frequent results in the amalgamation and degradation of waste feedstock makes this capability crucial for practical applications. The substrate is also more accessible and has a larger surface area due to the recycling process, which involves enzymes, chemical and mechanical pre-treatment processes, such as solvent-assisted enlargement or cryo-milling. A number of researchers did extra tests to see if adding enzyme components would help break down mixed polyester wastes like PLA and PBS [74] and expand the variety of substrates [75].

Carbios and other businesses that operate in industry have come a long way toward making their products available to the public by translating lab-scale results into pilot operations. These technologies have several good aspects, such designing products in circles, using materials in closed loops, and being less harmful to the environment.

3.3. Life Cycle Assessment and Sustainability Metrics

It's just as vital to think about how well-advanced recycling technologies work and how they will change the economy and the environment. One of the best ways to find out how recycling systems affect the ecosystem is through Life Cycle Assessment (LCA) [76]. This includes looking at their greenhouse gas (GHG) emissions, energy use, water use, and resource depletion [77].

According to life cycle assessments (LCAs), chemical and enzymatic recycling may need more energy from upstream sources than mechanical recycling does. But they usually require fewer new petrochemical feedstocks and make cleaner goods. Using renewable energy to break down PET chemically or polyolefins into monomers and fuels by pyrolysis might cut greenhouse gas emissions by a lot over the course of their whole lifecycle. Techno-economic assessment (TEA) [66]and life cycle assessment (LCA) are also becoming more and more popular to employ jointly. This integration lets researchers look examine the cost per ton of recycled materials, the return on investment, and how competitive the market is. More and more, these technologies are being utilized in the early stages of process design to detect problems and rank solutions that can be scaled up with little effect.

Also, more and more studies of sustainability are considering issues of social and environmental justice. Researchers are also looking into how different groups share the costs and benefits of the environment. This is especially true in communities that are poor or don't have a lot of resources, where the recycling system isn't very good.

3.4. Policy and Economic Drivers

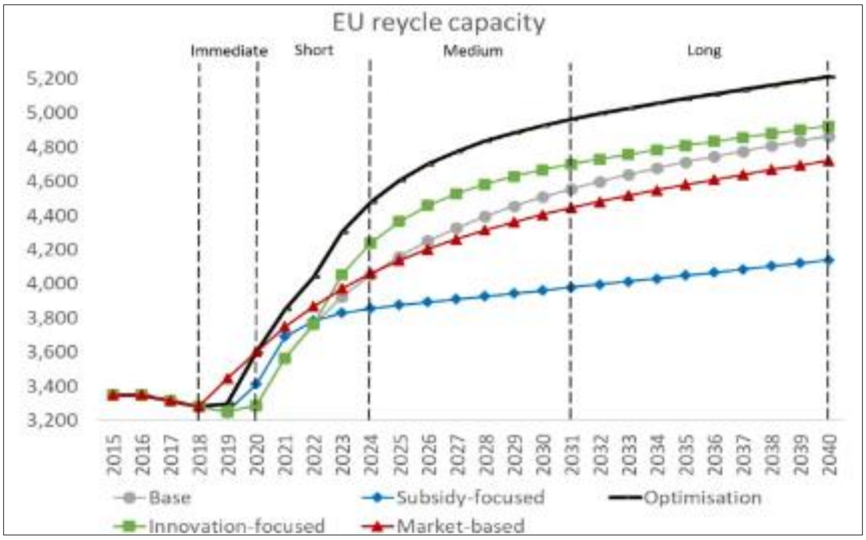

Figure 4 EU Recycle Capacity [78] (Open Access Journal)

Besides technological advancements being vital, the widespread implementation of advanced plastic recycling systems hinges on creating an environment with enabling policies and strong economic support. Research underscores the importance of regulations like Extended Producer Responsibility (EPR), which shift the burden of end-of-life product management to manufacturers, thereby stimulating markets for recycled materials and funding necessary infrastructure and innovation.

Some International examples those from the EU, Japan, and Canada show how governmental directives on plastic packaging and recycled content can accelerate private investment in cutting-edge recycling facilities. Figure 4 illustrates the EU recycle capacity as analysed by Nguyen et al. [78]. Similarly, in the United States, collaborative efforts between public and private sectors, along with government grants, have successfully supported the demonstration of these new technologies [79]. To make advanced recycling economically competitive with virgin plastics, particularly in fluctuating oil markets, economic incentives like tax breaks, subsidies, and carbon pricing are becoming increasingly important. Building consumer confidence and expanding markets for recycled products are also being achieved through standardized quality measures, certification, and eco-labelling. Ultimately, experts argue for a holistic approach that intertwines technological progress with robust economic support, infrastructure development, and global collaboration across the entire plastic value chain to forge a truly circular plastic economy.

4. Future Research

4.1. Improved Recycling Technologies

The basic goal of next-generation recycling is to make systems that are environmentally friendly, effective and efficient and economically viable for business. The future investigations should focus on:

- Catalytic Innovation in Chemical Recycling: Current catalytic processes, such as pyrolysis and solvolysis, frequently work best at high temperatures and don't pick and choose what they break down. Prospective works should focus on creating heterogeneous catalysts which are more active and selective for certain polymer bonds (such C–C or C–O), ideally in mild conditions. Zeolite-supported metal catalysts, acid-base bifunctional materials, and single-atom catalysts are all attractive options [25]. Research should also investigate how to deactivate, regenerate, and make catalysts work with mixed polymer streams.
- Energy Efficiency: The recycling process like pyrolysis and hydrocracking which consumes significant energy to be identified and worked out. The development of technologies that use microwaves, plasma, and solvents may help reduce heat loads. Recent research shows that microwave-assisted depolymerization can cut energy use by up to thirty percent compared to regular pyrolysis [80].
- Biological System Optimization: Crystalline polymers have limitations to enzymatic recycling due to slow kinetics although the latter has huge potential. Using protein engineering, directed evolution, and machine learning-assisted enzyme design, future research should focus on making enzymes more active, stable, and selective for their substrates [81], [82], [83]. Using synthetic biology, you can make groups of microbes that break down tough polymers like PVC and polyurethane. It is important to undertake research on scalability by optimizing bioreactors and using continuous fermentation methods.

4.2. Integration with Renewable Energy

The energy source for advanced recycling has a huge impact on the environment. Fossil fuels can be detrimental for the environment if they are used in recycling procedures that use a lot of energy. Using renewable energy sources like solar PV, wind, geothermal, or biofuel is very significant.

- Using renewable energy on-site at pyrolysis or depolymerization plants can greatly lower the amount of carbon they produce.
- In concentrated solar power (CSP) situations, thermal processes like gasification and pyrolysis could employ solar thermal energy.
- Photobioreactors can be used with living things to generate enzymes that use sunlight for energy. This makes the process eco-friendlier.

Moreover, adding equipment that recovers energy, such as steam turbines and heat exchangers, to the design of a process can also help it use a lot less energy.

4.3. Policy and Economic Support

Governments and international organizations need to give substantial legal and financial support to advanced plastic recycling to make up for the high costs of launching and operating the business. This assistance is aimed at making the world a better place for fresh ideas in the following way:

- Providing monetary incentives: This means giving money to help Public-Private Partnerships (PPPs) work together more easily and availing them of subsidies also refers to donating important funds (for example, through innovation funds or climate bonds) to minimize the financial risks of creating and testing these new technologies.

- Marketing policy: To increase the acceptance and competitiveness of recycled materials marketing techniques to be implemented. These include the imposition of plastic taxes, the imposition of additional fees on virgin polymers, and the provision of tradable recycling credits.
- Setting up standards that help: This entails making sure that items have a particular level of recycled content, that labeling are the same everywhere, and that product stewardship programs are in place. These kinds of frameworks make customers think about buying recycled polymers and make designers think about the environment when they develop things.

Additionally, setting up worldwide standards and certification techniques is vital for making sure that chemically and biologically recycled plastics are safe, of good quality, and will eventually build customer trust. The European Green Deal [84]and the U.S. Infrastructure Investment and Jobs Act (2021) [85]are two new laws that indicate how much people want to support new recycling technologies.

4.4. Public Awareness and Education

Advanced recycling won't work unless people use it properly and society accepts it positively despite technological advancement. There are still a lot of problems with recycled plastics, people throwing them out the wrong way, and not enough people taking part in collection schemes. A lot of action plans should be carried out, some of which are mentioned below:

- Educational Campaigns: Governments and NGOs should use public campaigns, school curriculum, and media outreach to teach people how to recycle. The EU and North America have the "Plastics Pact" as an example.
- Clear communication: Proper packaging labels that explain about the materials specification such as materials, uses, functionality and effectiveness duration, quality can help people make smart choices.
- Collaboration between business and academia: Universities and research institutions can work with businesses on citizen science projects, hackathons, and innovation challenges to get more people involved and teach them about the ideas of the circular economy.
- Digital Tools: Mobile apps and AI-based waste-sorting platforms can help homes and companies learn how to separate plastics correctly, which will improve the quality of the feedstock for advanced recycling.

Overall, the recommendations which are components of a broader strategy to enhance the technical readiness, environmental friendliness, and public acceptance of advanced recycling to be tailored properly. By investing in new catalysts and enzymes, utilizing renewable energy to power operations, establishing regulations that are beneficial, and engaging individuals, the world can move closer to a genuine circular plastics industry.

5. Conclusion

Plastic Waste approaches to a global potential with the new technologies introduced for recycling and ultimately for plastic waste management. Mechanical recycling is crucial; however, it is plagued by numerous challenges, including the inability to process polymers and the inability to function with combined or filthy plastics. There are two other techniques to extract good monomers and fuels from plastic: chemical recycling and biological recycling. Recycling is now a lot easier for the advent of better hybrid processing systems, enzymatic degradation, and catalysis.

There are still a lot of flaws that need to be solved. For example, it's hard to expand project due to technical problems, shortage of funds and high energy consumption. Cutting down the costs, making enzymes and catalysts better, and using renewable energy sources are all critical steps to getting the most out of these technologies. Moreover, a lot of potentials such as sorting by AI based model, design-for-recycling technology, and hybrid systems offer a better recycling process. At the same time, it is vital to make strong laws, give people money to do the right thing, and run campaigns to raise awareness to get people to adapt and make big changes.

Finally, synchronization is necessary among consumer attitudes and action plans, technology and politics to ensure a successful circular plastic economy. Advanced recycling might help close the loop on plastic production and have less of an effect on the environment by continuing to finance research, working together across industries, and committing to sustainable design and infrastructure

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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