

Review

Advances in Plastic Waste Recycling: Technologies, Environmental Impact, Research Trends, and Policy Perspectives

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Abstract: Plastic pollution is a global concern, necessitating innovative recycling strategies. This review presents an overview of recent technologies that recycle various types of plastics, including mechanical, chemical, and solvent-based methods. Applications in the production of secondary materials, fuels, and monomers are explored, and their contributions to reducing greenhouse gas emissions and resource depletion are compared. Based on the review results, future research directions are proposed to enhance recycling efficiency based on advanced catalysis, enzyme engineering, and polymer redesign. Policies and regulatory frameworks of the EU, USA, Japan, and South Korea are compared to identify their multi-faceted approaches that integrate technology, legislation, and sustainable design.

Keywords: Plastic, Recycling, Pollution, Environment, Mechanical method, Chemical method, Solvent-based method

1. Introduction

In modern daily life, plastics are ubiquitous, transforming from the packaging and construction industries to the healthcare and automotive industries. The versatility, durability, and cost-effectiveness of plastics have led to an exponential increase in their global production, which surpassed 400 million tons in 2021 and is projected to triple by 2060 [1,2]. Despite the benefits, the common use of plastics has inadvertently created an environmental crisis. However, less than 10% of global plastic waste is effectively recycled, while a significant portion of used plastics end up in landfills, incinerators, or natural environments, particularly oceans [1,3]. The accumulation of plastics in the environment causes ecological degradation, including habitat destruction, which harms wildlife through entanglement and ingestion, and the insidious proliferation of microplastics, which infiltrate into ecosystems, food chains, and even human bodies, posing long-term health risks [4].

The urgency of addressing plastic pollution has led to sustainable waste management practices, with recycling emerging as an important solution. Recycling used plastics requires a multifaceted approach. Recycling plastics reduces dependency on finite fossil resources, thereby conserving natural capital and lowering greenhouse gas emissions compared with the production of new plastics, contributing to climate change mitigation [5]. By diverting waste from landfills, land use for waste disposal can be minimized by recycling plastics, which prevents the release of harmful leachates into soil and water. Lastly, it reduces pollution by preventing plastic pollution into terrestrial and aquatic ecosystems, reducing the formation of persistent microplastics.

However, widespread and efficient plastic recycling has many challenges, including (1) the inherent diversity of plastic types, which leads to mixed and contaminated waste, (2) technical complexities associated with separating and reprocessing different polymers, (3) the economic feasibility of recycling processes versus virgin plastic production, and (4) the varying capacities and infrastructures across different regions. Despite these challenges, ongoing innovations in recycling technologies, coupled with evolving policy landscapes and growing public awareness, have been made for a circular economy for plastics.

Therefore, this review aims to provide a comprehensive and up-to-date elucidation of current and emerging technologies for plastic waste recycling, categorizing them by their mechanisms and exploring their diverse applications. The tangible environmental contributions of recycling methods are assessed on terms of their impact on greenhouse gas emissions, pollution mitigation, and resource conservation. Cutting-edge recycling methods are reviewed from the perspective of recycling efficiency enhancement, based on catalysis, enzyme engineering, artificial intelligence (AI) in sorting, and the innovative redesign of polymers for intrinsic recyclability. Policies and regulatory frameworks of the European Union, the United States, Japan, and South Korea are investigated to understand how governance structures affect plastic waste management and recycling. This review provides a basis for a sustainable and circular plastic economy.

2. Technologies and Applications

Plastic recycling technology is continuously evolving, driven by diverse plastic waste and the expectation for higher-value outputs. Current technologies are categorized into mechanical, chemical, solvent-based, and biotechnological methods.

2.1. Mechanical Recycling

Mechanical recycling, also known as primary or secondary recycling, is the most widely used method for processing plastic waste. It involves a series of physical processes to transform post-consumer or post-industrial plastic waste into new products without altering the polymer's chemical structure [6]. The process includes the following.

- Collection and sorting: Waste plastics are collected and then sorted, often manually or using automated systems, to classify different polymer types (e.g., polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS)) and remove contaminants.
- Washing and shredding: Sorted plastics are washed to remove dirt, labels, and residual contents, then shredded into flakes.
- Drying and pelletizing: The flakes are dried and then melted and extruded into pellets, which are used by manufacturers.

Mechanical recycling is effective for clean and single-polymer plastic waste, particularly for PET used for beverage bottles and HDPE for milk jugs and detergent bottles [6]. The recycled pellets are used in various applications as follows.

- PET: Recycled PET (rPET) is widely used to produce new beverage bottles (bottle-to-bottle recycling), food packaging, textile fibers for clothing and carpets (e.g., fleece), and strapping.
- HDPE: Recycled HDPE (rHDPE) is used to manufacture in non-food bottles, pipes, plastic lumber, playground equipment, and crates.
- LDPE and PP are used to produce trash bags, films, and non-food packaging, while recycled PP (rPP) is used for automotive parts, industrial fibers, and garden furniture [7].

Despite its widespread use, mechanical recycling has limitations. First, polymers are degraded in repeated reprocessing cycles. In each melting and reforming step, the polymer's molecular weight is reduced, leading to a decrease in mechanical properties, making the recycled material less durable or appropriate for high-performance applications. Contamination by other polymers, food residues, or non-plastic materials severely affects the quality of recyclate, often leading to lower-value applications, which is known as "downcycling". For example, plastics from bottles are recycled to park benches [8]. Mixed plastic waste, commonly found in municipal solid waste, is inappropriate for mechanical recycling without extensive and costly sorting.

2.2. Chemical Recycling

Chemical recycling, also known as advanced recycling or feedstock recycling, is performed to break down polymers into constituent monomers or other valuable chemical feedstocks, effectively leading to virgin-quality materials or fuels. Chemical recycling offers a solution for contaminated, mixed, or composite plastics that are difficult or impossible to mechanically recycle. The following techniques are used in chemical recycling.

- Pyrolysis: This process involves heating plastic waste at high temperatures (300–900 °C) in the absence of oxygen. The long polymer chains break down into smaller hydrocarbon molecules, producing a liquid oil (pyrolysis oil), a gas (syngas), and a solid char [9]. The pyrolysis oil is refined into diesel, gasoline, or naphtha or used as a chemical feedstock to produce new plastics, while the syngas are used for energy generation. Pyrolysis is effective for polyolefins (polyethylene or polypropylene) and polystyrene [10]. Through pyrolysis, mixed and contaminated plastic waste is recycled, which ensures high flexibility in product output.
- Gasification: In gasification, plastic waste is partially oxidized at high temperatures (>700 °C) to produce syngas, a mixture primarily of hydrogen (H₂) and carbon monoxide (CO) [11]. Syngas is a versatile chemical building block that is used to synthesize a range of chemicals (e.g., methanol, ammonia) or as a fuel source for power generation. Gasification presents high conversion efficiency, which enables a wide range of plastic waste and other difficult-to-recycle materials.
- Depolymerization (monomer recycling): This technique is used to recycle polymers formed through condensation polymerization, such as PET, PS, and polyurethanes (PU). Chemical reactions (e.g., hydrolysis, methanolysis, glycolysis for PET; pyrolysis or solvolysis for PS) are applied to revert the polymer to its original monomer building blocks [12]. The recovered monomers are purified and then repolymerized to create new, virgin-quality plastics, enabling a true closed-loop recycling system without quality degradation. This is a highly efficient method for high-value polymer (PET or nylon)

recycling [13]. Through depolymerization, high-quality, virgin-equivalent material is produced, and colored or slightly contaminated plastics are recycled.

- Hydrothermal liquefaction: In this process, plastic waste is converted into liquid fuels under high temperature and pressure in the presence of water. This is particularly appropriate for plastics containing oxygen or nitrogen.

Chemical recycling methods enable the reuse of plastics that would otherwise be incinerated or landfilled, offering recycling for difficult-to-recycle waste and generating high-value-added products for the chemical and fuel industries. However, these processes are energy-intensive and require considerable capital investment compared with mechanical recycling.

2.3. Solvent-Based Recycling

Solvent-based recycling is considered a technique of physical recycling. It has been developed based on the principle that different polymers dissolve in specific solvents at certain temperatures. This enables the selective dissolution, separation, and purification of target polymers from mixed plastic waste or multi-material composites without significant chemical degradation. In solvent-based recycling, waste plastic is mixed with a solvent to dissolve the target polymer and leave other plastics and contaminants undissolved. The dissolved polymer solution is filtered to remove impurities. Finally, the solvent is removed by precipitation, evaporation, or anti-solvent addition, leaving a pure and recovered polymer to be reprocessed [13].

The CreaSolv® process was developed by the Fraunhofer Institute. A selective solvent is used in the process to dissolve specific polymers from complex waste streams, for example, polystyrene from electronic waste or flexible multilayer packaging. The dissolved polymer is then precipitated as a high-quality material. Solvent-targeted recovery and precipitation (STRAP) is effective in recycling multilayer plastic packaging materials, which are typically unrecyclable due to the inseparable layers of different polymers. This process selectively dissolves one or more layers, allowing for their recovery and reuse [13].

Solvent-based recycling is ideal for high-value polymers from complex mixtures, such as separating specific polyolefins, polystyrene, or polyvinyl chloride (PVC) from mixed plastic waste, and for processing multilayer films (e.g., food packaging) where mechanical separation cannot be applied. The recovered polymers retain near-virgin properties. Solvent-based recycling enables the production of high-purity recycled polymers and the recycling of mixed and composite plastics. It is performed to operate at lower temperatures than chemical recycling, potentially reducing energy consumption. However, it requires specific solvent systems for different polymers, raising concerns about solvent recovery, toxicity, and overall process economics.

2.4. Biotechnological Approaches

Biotechnological approaches, specifically enzymatic degradation, are an emerging and highly promising method in plastic recycling. This method applies naturally occurring or engineered enzymes to break down polymers into monomers or oligomers under mild conditions, for example, at ambient temperature and pressure.

Certain microorganisms produce enzymes that can depolymerize plastics. Researchers are identifying, optimizing, and engineering these enzymes for industrial-scale application. Enzymes, such as PETase and MHETase, were discovered in bacteria capable of consuming PET [14]. These enzymes break down PET into its monomers, terephthalic acid (TPA) and ethylene glycol (EG). Through directed evolution and genetic engineering, the activity and stability of these enzymes are enhanced, enabling efficient degradation of PET at moderate temperatures [15,16]. Certain esterase enzymes and microbial consortia are promising in degrading polyurethanes, which are recycled to building blocks [17]. The enzymes lead to the production of virgin-quality monomers from specific plastic types, such as PET bottles and textiles, potentially enabling a truly circular economy for these materials. The advantages of biotechnological approaches include eco-friendliness, as water is used as a solvent and mild conditions are necessary for the process, which is related to low energy consumption. They also present high specificity for target polymers, which has the potential to recycle colored or contaminated plastics. Biotechnological approaches are limited to a few plastic types, as they have relatively slower reaction rates and lower scalability to industrial levels than chemical methods. The development and deployment of these technologies address the complex plastic recycling, offering specialized solutions for different types and qualities of plastic waste, and moving towards a more comprehensive circular economy model.

3. Environmental Contributions of Plastic Recycling

Plastic recycling offers substantial environmental benefits. It mitigates the adverse impacts of plastic production and waste, reduces greenhouse gas emissions (GHG), pollution, and conserves resources.

3.1. Reduction in Greenhouse Gas Emissions

The production of virgin plastics is energy-intensive and relies on fossil fuel use, leading to significant GHG emissions. These emissions occur from the extraction of raw materials (crude oil and natural gas), the energy-intensive polymerization processes, and transportation. Plastic recycling contributes to reducing these emissions and decreases the need for virgin material production.

- **Mechanical recycling:** For common plastics, such as PET and HDPE, mechanical recycling leads to immediate and substantial GHG reductions. For example, recycling one ton of PET saves approximately 1.5 to 3.0 tons of CO₂ equivalent emissions compared with producing virgin PET [5,18]. Similarly, recycling HDPE can reduce GHG emissions by 0.8 to 1.5 tons of CO₂ equivalent per ton of plastic [8]. These savings stem from reduced energy consumption in manufacturing processes and avoided emissions caused by raw material extraction.
- **Chemical recycling:** This is energy-intensive than mechanical recycling as it requires high-temperature processes. Chemical recycling emits less GHG than virgin plastic production, especially for hard-to-recycle or mixed plastic waste. By converting waste plastics into fuels or chemical feedstocks, it prevents them from being incinerated, which releases CO₂ and pollutants, from being landfilled, which generates methane, a potent GHG, or from anaerobic decomposition of organic matter often mixed with plastics. Life cycle assessments (LCAs) show that chemical recycling leads to substantial reductions in carbon footprint, particularly when the recovered products displace virgin fossil resources [8].

A report by Franklin Associates for the American Chemistry Council (ACC) indicates that plastic recycling, regardless of methodology, consistently lowers environmental impacts, including energy consumption, water use, and GHG emissions, regardless of plastic types [8].

3.2. Mitigation of Ocean and Land Pollution

Plastic waste accumulating in oceans and on land is caused by inadequate waste management and low recycling rates. Recycling plastic prevents plastic waste from accumulating and polluting the environment. By developing plastic collection methods, plastic waste is processed and reintroduced into the economy. Recycling reduces the volume of plastic waste that ends up in landfills, incinerators, or, most critically, in natural ecosystems. Recycling also prevents macro- and micro-plastic pollution, which harms marine life through entanglement and ingestion.

Macroplastics in the environment degrade over time due to ultraviolet (UV) radiation, abrasion, and biological activity, which break down into smaller fragments known as microplastics (<5 mm) and nanoplastics (<100 nm) [4]. These microscopic particles are a major concern because they are pervasive, difficult to remove, and can carry toxins, entering the food chain and impacting human health. By preventing the release of macro-plastics into the environment, recycling indirectly mitigates the formation of these insidious microplastics.

Efficient plastic recycling relies on effective sorting. Near-infrared (NIR) spectroscopy has been introduced for plastic waste sorting. NIR sensors identify different polymer types based on their unique spectral fingerprints, enabling rapid and accurate automated sorting of mixed plastic waste streams [19]. Its improved sorting efficiency increases the recovery rates of recyclable plastic, ensuring more plastic is diverted from landfills and oceans and processed into new products. Other technologies, such as X-ray fluorescence (XRF) for detecting chlorine (PVC) and sophisticated optical sensors, enhance the purity of sorted plastic for high-value recycling.

3.3. Resource Conservation

Plastic production is dependent on non-renewable fossil fuels, such as crude oil and natural gas. Recycling plastic enables resource conservation by substituting virgin materials with recycled content. Every ton of plastic recycled reduces the demand for virgin plastic production, thereby conserving millions of barrels of oil and cubic feet of natural gas annually. For example, recycling PET reduces fossil fuel consumption by approximately 60–80% compared with virgin production [5]. Plastic recycling contributes to energy security and reduces the environmental impacts associated with fossil fuel production, such as habitat disruption and potential spills. Beyond raw material conservation, the manufacturing process using recycled plastics requires significantly less energy than producing plastics from scratch. For instance, manufacturing products from recycled HDPE saves approximately 80% of the energy required for virgin HDPE production [18]. This energy saving translates into reduced emissions from power generation. Chemical recycling technologies, such as pyrolysis and depolymerization, contribute to resource conservation. They are applied to recover valuable chemical raw materials (monomers, naphtha, or syngas) from plastics that were previously considered "non-recyclable" due to contamination, mixed polymer composition, or complex structures (multilayer films). The recovered raw materials re-enter the petrochemical supply chain, displacing virgin fossil resources and fostering a truly circular economy where waste is transformed into valuable inputs [8]. Many plastic production processes are water-intensive. Recycling plastics requires less water than virgin plastic manufacturing, contributing to freshwater conservation, especially in water-stressed regions.

Plastic recycling is not only a waste management solution but also a sustainable resource management method. By revalorizing plastic waste, environmental burdens across the entire lifecycle of plastic products are reduced, contributing significantly to climate action, pollution control, and the preservation of finite natural resources.

4. Efficient Recycling

The challenges associated with plastic recycling range from material complexity and contamination to process efficiency and economic viability. To address the challenges, vigorous research efforts have been made by scientists and engineers. Innovative approaches have been to make recycling more effective, broader in scope, and more sustainable.

4.1. Catalyst Development

Catalysis plays an important role in enhancing the efficiency and selectivity of chemical recycling processes, particularly pyrolysis and depolymerization. Current research is focused on developing novel heterogeneous catalysts that operate under milder conditions, improve reaction rates, and selectively produce desired products (e.g., specific monomers or high-quality fuels) from mixed plastic waste. The following catalysts have been extensively researched recently.

- Zeolites and metal oxides: Modified zeolites (microporous aluminosilicate minerals) and various metal oxides (e.g., Al_2O_3 , TiO_2 , ZrO_2) have been researched as catalysts. These materials offer high surface areas, tunable acidity, and thermal stability, which promote the scission of polymer chains and direct the formation of specific products [20,21]. For instance, zeolites are applied to convert polyethylene waste into liquid fuels with high selectivity at lower temperatures compared to non-catalytic pyrolysis.
- Nanomaterials: The use of nanomaterials, such as graphene-based catalysts or metal nanoparticles, has been explored for their unique catalytic properties, including enhanced surface reactivity and improved dispersion, which ensures efficient depolymerization and valorization of plastic waste [22].
- Plastic-to-monomer catalysts: Catalysts that efficiently and selectively revert condensation polymers, such as PET, have been researched to recycle polymers, such as polyolefins, back to their monomers. This "monomer-to-monomer" approach enables closed-loop recycling, preserving material quality across cycles. Catalysts are designed to tolerate impurities often found in plastic waste, which traditionally hinder chemical recycling processes.

4.2. Enzyme Engineering

Based on the development in biotechnological recycling, enzyme engineering has been studied to significantly improve their performance for plastic degradation.

- Directed evolution: This powerful technique mimics natural selection in a laboratory setting. Scientists introduce random mutations into enzyme genes and then screen for variants with improved properties, such as higher activity (faster degradation), increased thermal stability (allowing operation at higher temperatures without denaturation), or enhanced specificity for different plastic types [15,16]. A 300% enhancement in PETase activity was reported through directed evolution, making it viable for industrial applications [15].
- Computational design: Alongside experimental methods, computational tools (e.g., molecular docking, molecular dynamics simulations) are used to predict the changes in an enzyme's structure. This enables rational design of enzymes with optimized catalytic sites for specific plastic substrates [23].
- New enzyme discovery: New microbial strains from diverse environments (e.g., landfills, compost sites) have been identified to find novel enzymes capable of degrading a wider range of plastics, including polyurethanes, polyamides, and even polyolefins, which are notoriously resistant to enzymatic breakdown [24].
- Enzyme production and immobilization: Scaling up enzymatic recycling requires efficient and cost-effective enzyme production methods. Microbial fermentation is optimized for enzyme synthesis and robust enzyme immobilization to improve their reusability and stability in industrial reactors.

4.3. AI in Recycling

Efficient sorting is the bottleneck for many recycling processes, especially mechanical recycling. AI and robotic automation are revolutionizing recycling processes to enhance speed, accuracy, and the ability to differentiate complex materials.

AI-integrated optical sorting facilities use advanced cameras and deep learning algorithms to analyze visual information (color, shape, and texture) and spectral data from NIR spectroscopy of plastic waste. These algorithms identify different polymer types, distinguish between opaque and transparent plastics, and detect contamination levels with unprecedented accuracy [25,26]. This

enables the precise separation of mixed plastic streams into high-purity fractions. AI algorithms guide robotic arms equipped with specialized grippers to rapidly and accurately pick out specific plastic types or remove contaminants from the waste stream. These robots reduce human exposure to hazardous waste and achieve higher throughput than manual sorting. AI can also be used for real-time quality assessment of recycled pellets, ensuring that the processed material meets specific purity and property standards required by manufacturers. AI models predict equipment failures in recycling plants, optimizing maintenance schedules and reducing downtime, thereby improving overall operational efficiency.

Recently, AI, particularly models such as AlphaFold, has played an important role in plastic recycling by identifying or predicting molecular structures and their degradation. While AlphaFold is designed for protein folding, its deep learning principles for predicting complex 3D structures from sequences are relevant to material science related to plastic recycling. In plastic recycling, AI engines can be used to analyze the intricate molecular architectures of various plastics and their depolymerized products. This includes chemical bonds of a polymer under various recycling conditions. By simulating these interactions at an atomic level, AI can be used to optimize depolymerization by identifying appropriate catalysts, temperatures, and pressures to efficiently break down plastics into high-purity monomers, minimizing the production of unwanted byproducts [27]. It is also used to characterize recycled products by predicting the molecular structure and purity of recovered monomers or oligomers to ensure their quality. AI can predict the recyclability of novel polymers even before production, accelerating the development of inherently circular plastics. Machine learning, including generative models, has already been used to design chemically recyclable polymers by predicting their properties from monomer structures [28].

This AI-driven approach significantly reduces the time and cost associated with traditional trial-and-error experimentation, moving plastic recycling towards a more efficient, sustainable, and truly circular economy

4.4. Polymer Redesign for Recyclability

Advancement in plastic recycling involves "design for recyclability" to create polymers that are easier to recycle or even "circular by design." This forward-looking research contributes to developing new materials or modifying existing ones to enable efficient reprocessing without degradation. New polymers include the following.

- Covalent adaptable networks (CANs) and dynamic covalent bonds: These are innovative polymer architectures that incorporate reversible bonds within their structure. Different from traditional thermosets, which form permanent, irreversible cross-links and are notoriously difficult to recycle, CANs reprocess the breaking and reforming of dynamic bonds under specific conditions [29]. This allows them to be reshaped and reused without significant loss of mechanical properties, bridging the gap between thermoplastics and thermosets.
- Self-healing and reversible polymers: While still largely in the research phase, self-healing polymers can extend product lifespan, and polymers with reversible characteristics simplify deconstruction for recycling.
- Sustainable additives and fillers: Additives and fillers that are compatible with recycling processes or are biodegradable have been developed to reduce the contamination issues in recycling.
- Chemically recyclable polymers: New polymers that can be easily depolymerized back into their monomers are designed for mild chemical treatments. Examples include polymers with specific cleavable linkages or those designed to "unzip" when triggered by a specific stimulus. Promising chemically recyclable polymers include the following.

Especially, chemically recyclable polymers are regarded promising solution for recycling plastics. Polydiketoenamine (PDK) is broken down into its original monomers using strong acid. This process separates the monomers from additives from dyes, or fillers. The recovered monomers are reused to create new PDK with no loss in performance or quality. PDK polymers are redesigned to optimize the breakdown process of PDK. By tweaking the chemical structure, the temperature and rate of depolymerization can be controlled for efficient recycling [30]. Polylactic acid (PLA) is made from renewable resources, including corn starch or sugarcane. While PLA is compostable, chemical recycling offers a method to address its slow natural decomposition by depolymerizing PLA back into its original monomers (lactic acid or lactide) [31], which can then be repolymerized into virgin-quality PLA without performance loss. This closed-loop approach is crucial for establishing a truly circular economy for PLA. Chemical recycling of PLA typically involves depolymerization through various methods, including hydrolysis (acidic, alkaline, or neutral), alcoholysis, or glycolysis. These processes break down the polymer chains into lactic acid or lactide monomers. The recovered monomers can be purified and then polymerized again to produce new PLA. Microwave-assisted depolymerization is also being explored to reduce reaction times and energy consumption. Chemical recycling of polyhydroxyalkanoates (PHAs) involves solvolysis (hydrolysis, alcoholysis) to break down the polymer chains. Hydrolysis can regenerate the corresponding hydroxyacid monomers. Hydrolysis of PHAs regenerates hydroxyacid monomers. As PHAs are mainly recycled through pyrolysis, catalyst systems and reaction conditions are extensively researched for high-purity monomer recovery through chemical methods

[31]. Polyethylene furanoate (PEF) is a next-generation bio-based polyester, replacing conventional PET. PEF is derived from renewable plant sugars, and importantly, is designed for chemical recyclability. PEF is chemically recycled through hydrolysis, methanolysis, or glycolysis. These processes break down the polyester linkages, yielding the original monomers. The recovered 2,5-furandicarboxylic acid (FDCA), the key building block of PEF, and ethylene glycol are purified and repolymerized to produce new PEF, completing the circular loop. It also involves enzymatic depolymerization for efficient monomer recovery under mild conditions.

Research on new polymer design represents a concerted effort to overcome the technical barriers to plastic recycling to recycle plastic waste into a valuable resource in a circular economy.

5. National Policies and Regulatory Frameworks

In plastic recycling, technological advancements, robust policy frameworks, and regulatory measures are necessary. Recycling needs to be incentivized to promote circularity. Different countries and regions have adopted diverse approaches to tackle this challenge, reflecting their economic, social, and political contexts.

5.1. European Union (EU)

The EU has established circular economy policies, especially for plastics. The related strategy is driven by the EU Circular Economy Action Plan (CEAP), adopted in 2020. This plan decouples economic growth from resource depletion and includes several pivotal measures for plastics. CEAP sets legally binding targets, mandating a 55% recycling rate for plastic packaging by 2030 across member states [32]. This drives investment in collection, sorting, and recycling infrastructure. The extended producer responsibility (EPR) scheme is mandatory across the EU. It transforms the financial and/or operational responsibility for the end-of-life management of products from municipalities to the producers. Producers are required to finance or organize the collection, sorting, and recycling of their products, incentivizing them to design for recyclability.

Adopted in 2019, the Single-Use Plastics (SUP) Directive aims to prevent and reduce the impact of certain plastic products on the environment. It bans single-use plastic items for which alternatives are readily available, including plastic plates, cutlery, straws, and cotton bud sticks, and sets ambitious collection targets for plastic bottles (90% by 2029) [33,34]. Several EU member states, including Italy, Spain, and the UK, have introduced taxes on non-recycled plastic packaging, providing a financial incentive for the use of recycled content and driving demand for recyclates. Under EPR, fees paid by producers can be "eco-modulated," meaning lower fees for easily recyclable packaging and higher fees for packaging that is difficult to recycle or contains hazardous substances. This incentivizes design for recyclability. The EU is formulating harmonized standards for recycled plastic content and labeling, and certifying recycling processes, to build trust in recycled materials. The EU's approach integrates legislative bans, economic incentives, and producer responsibility to create a powerful impetus for a circular plastics economy.

5.2. United States (US)

The US approach to plastic recycling is more fragmented than the EU, due to a decentralized regulatory system where state and local governments hold significant authority. The Environmental Protection Agency (EPA) launched the National Recycling Strategy in 2021 to create a stronger, more resilient, and more cost-effective recycling system than before [35]. While not setting binding national recycling rates, it focuses on improving markets for recycled commodities, increasing collection and materials management, reducing contamination, enhancing recycling infrastructure, and reducing waste. Significant policies include the following.

- Recycled content mandates: States, including California, have mandated recycling plastic packaging and beverage bottles that contain a certain percentage of recycled content and increase this percentage over time (e.g., California SB 54, the Plastic Pollution Producer Responsibility Act of 2022) [36,37]. These mandates create market demand for recycled plastics.
- Single-use plastic bans: Numerous states and cities have enacted bans or fees on single-use plastic bags, straws, and polystyrene foam products.
- EPR: While not as widespread as in the EU, a growing number of states are adopting EPR legislation for packaging, shifting the financial burden of recycling to producers.
- Bottle Bills (Container Deposit Laws): Ten states enact "bottle bills" to establish a deposit-refund system for beverage containers, significantly increasing collection and recycling rates for PET and aluminum [38].

- Industry-led initiatives: Given the less prescriptive federal framework, industry initiatives and voluntary commitments play a significant role in the U.S., with major brands establishing their recycled content targets and investing in recycling infrastructure.

The U.S. landscape is characterized by such policies, with progressive states leading innovation, but a lack of national uniformity creates complexities for businesses operating across state lines.

5.3. Japan

Japan has been recognized for its strong emphasis on waste management, particularly through the "3Rs" (Reduce, Reuse, Recycle) principle, enshrined in its legislative framework. The Container and Packaging Recycling Law (1995) is the cornerstone of Japan's recycling policy. It obligates producers and retailers to recycle containers and packaging waste. This law has contributed to high collection rates for plastics, with a focus on specific categories, such as PET bottles. Japan boasts impressive collection rates for plastic containers and packaging, exceeding 80% [39]. This high rate is largely attributed to well-established municipal collection systems and public cooperation in rigorous waste segregation at the household level. While mechanical recycling of specific plastics is proliferating, Japan utilizes "thermal recycling" (energy recovery from waste incineration) due to limited landfill space and energy security concerns. Japan has invested in advanced incineration technologies that generate energy with relatively lower emissions. Japan has articulated a vision for a circular economy, promoting the efficient use of resources and minimizing waste across all sectors. Recent policy efforts focus on promoting innovation in chemical recycling and reducing reliance on virgin plastics [39]. Japan's approach combines strong producer responsibility with robust public engagement in reducing waste, resulting in high collection rates, although its reliance on thermal recycling differentiates it from the EU's material-first approach.

5.4. South Korea

South Korea, facing similar pressures from rapid industrialization and urbanization, has implemented stringent policies to manage plastic waste and promote a circular economy. Its Resource Circulation Act (2018) enforces waste segregation at source, promotes recycling, and limits landfill disposal and incineration [40]. It includes provisions for EPR schemes for various products, including packaging. Similar to bottle bills, South Korea operates a deposit-refund system for certain beverage containers, enhancing collection rates. In South Korea, households are required to rigorously separate waste into categories (food waste, recyclables, and general waste), with specific bins for different plastic types. Public participation is fundamental to the recycling system's effectiveness. The Korean government recognizes the limitations of mechanical recycling and provides subsidies and policy support for developing and deploying chemical recycling infrastructure for managing difficult-to-recycle plastics and fostering a high-value circular economy. While not as explicit across all plastic types as in the EU or California, the government mandates recycled content in new products and packaging. South Korea has also increased fees for waste disposal and introduced bans on certain single-use plastics in the retail and food service sectors to discourage their consumption. South Korea's policy is characterized by strong government intervention, mandatory waste segregation, and a proactive stance on investing in advanced recycling technologies, aiming for a high resource circulation rate [41].

In summary, while the EU leads with a harmonized legislative framework driving high recycling targets and EPR, the U.S. relies on state-level innovation and industry commitments. Japan has more public participation and collection rates than other countries, integrating thermal recycling, while South Korea focuses on strict segregation, government subsidies for advanced recycling, and broader resource circulation.

6. Conclusion

A circular economy for plastics is characterized by the integration of technological innovation, environmental imperatives, and evolving policy landscapes. While traditional mechanical recycling remains foundational for readily separable, clean plastic streams, the advent of advanced chemical, solvent-based, and biotechnological methods is transforming the processing of complex, contaminated, and mixed plastic waste. These cutting-edge technologies convert previously non-recyclable materials into valuable secondary resources, monomers, or fuels, significantly displacing virgin plastic production and its associated high energy consumption and fossil fuel dependency. Such technological advancement contributes to mitigating greenhouse gas emissions and reducing land and ocean pollution, minimizing waste from landfills and natural ecosystems, and reducing the proliferation of harmful microplastics and conserving finite fossil fuel resources.

Despite these significant advancements, challenges persist, demanding a concerted, collaborative effort from researchers, policymakers, industries, and consumers. The most pressing challenge is to scale up promising chemical and enzymatic recycling technologies to industrial viability, addressing high capital investment requirements, fluctuating virgin plastic prices, and the inherent variability in feedstock quality. The cost of enzyme production and the relatively slow kinetics of enzymatic processes necessitate extensive research and development focused on enhancing technical efficacy, cost-efficiency, and energy consumption. Furthermore, the purity of plastic waste feedstock is important. Therefore, continuous innovation in technologies for "design for recyclability" is essential to simplify end-of-life processing. Harmonized global standards for material identification, labeling, and consistent extended producer responsibility (EPR) frameworks are necessary to navigate the complexities of international trade and foster truly global circular supply chains, transcending current regional disparities in policy.

Future of plastic recycling demands a multi-faceted approach centered on key technological developments: the seamless integration of AI and advanced robotics for superior waste sorting and material recovery; intensive research into enzyme engineering for cost-effective and efficient enzymatic recycling, particularly for challenging polyolefins; and, most profoundly, the development of "circular by design" plastics that are inherently easy to depolymerize or possess dynamic bonds for infinite reprocessing. The widespread adoption and refinement of chemical and enzymatic recycling are mandated to maximize the potential of technology advancement. Depolymerizing plastics back into their original monomers or other valuable chemical feedstocks enables a circular economy where plastics are recycled infinitely without quality degradation. More energy-efficient, cost-effective, and capable of handling mixed or contaminated plastic waste streams must be adopted based on the depolymerization of various polymers via pyrolysis, solvolysis, and enzymatic routes. It is also vital to integrate AI technology and robotics. AI-powered sorting systems, using machine learning and computer vision, are becoming increasingly sophisticated. These systems can accurately identify and separate different plastic types, including complex multi-layer packaging, significantly reducing contamination and improving the purity of recycled materials. AI is also playing a significant role in optimizing recycling processes, predicting equipment failures, and even designing new, inherently recyclable polymer structures. Recently, AI models have been applied in plastic recycling to research molecular structures. AI models analyze the complex molecular structure of various plastics and their depolymerized products. AI models are used to optimize depolymerization by simulating molecular interactions at an atomic level to predict the molecular structure and develop purification processes. Such AI-driven methods make plastic recycling contribute to the efficient and sustainable circular economy.

In plastic recycling, "design for recycling" and "closed-loop systems" are emphasized. By focusing on mono-materials, easily separable components, and reduced harmful additives, collaboration among manufacturers, designers, and recyclers ensures effective recovery and reintegration of used plastics, building a "take-make-dispose" model to a regenerative circular economy. A standardized and transparent approach to life cycle assessments (LCAs) is necessary for various recycling technologies for future policy and investment decisions. For future policy formulation and investment decisions, a standardized and transparent framework for life cycle assessments (LCAs) is imperative across diverse recycling technologies. A robust circular economy of plastics requires sustained investment in advanced recycling methods to improve material recoverability along with the reinforcement and harmonization of global policies to enhance stakeholders' engagement, including academia, industry, government, and consumers.

To achieve a truly circular economy, more than technological innovation or policy adoption is necessary. System-wide transformation from production to consumption and end-of-life management is required. Incremental improvements in materials or processes must be achieved to address the entire lifecycle of plastics. One essential enabler of this transformation is the Digital Product Passport, a lifecycle management system that must be broadly implemented. By providing transparent information regarding product composition, recyclability, and environmental impact, it empowers consumers and producers to make informed, responsible decisions. The development and widespread adoption of AI-powered circular economy platforms is also critical. Such platforms enable the quantitative evaluation of formulated policies and technological advancement, which is vital for resource consumption, carbon emissions, and economic viability—thus supporting evidence-based policymaking. The "Circular Design", a paradigm that integrates considerations of disassembly, reuse, and recycling at the initial stages of product development, must be introduced, too. This cultural movement requires integrated efforts across technology, regulatory frameworks, and public consciousness. Such a multidimensional approach, combining technological innovation, systemic policy integration, and public engagement, is essential for realizing a truly sustainable plastic economy.

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