

Review

An Overview of Circular Economy Approaches for Plastics

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Abstract

Plastic pollution has received worldwide attention due to its extensive environmental and health implications. The circular economy has emerged as a potential solution to plastic pollution. This overview comprehensively presents different plastic circular economy approaches and discusses their advantages, disadvantages, and implementation challenges. It highlights that the current plastic circular economy approaches primarily comprise mechanical recycling, chemical recycling, bio-based and biodegradable plastics, extended producer responsibility, deposit-refund schemes and take-back systems, design for circularity, and digital and smart waste management. Mechanical recycling is more well-established than chemical recycling but could downcycle plastic waste. Chemical recycling may facilitate the achievement of the closed-loop circular economy. Bio-based plastics can compete with food production and the biodegradable ones may require controlled composting conditions, though they come from renewable feedstocks. Extended producer responsibility promotes recycling and a shift toward sustainable materials but faces inadequate regulations and enforcement. Deposit-refund schemes and take-back systems are tied to extended producer responsibilities and depend on consumer awareness, infrastructure development, and regulatory enforcement. Design for circularity facilitates plastic reuse, recycling, and



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repurposing but is constrained by technology and cost. The digital and smart waste management approach improves the traceability and segregation of plastic waste but is limited by cost and digital infrastructure gap. In developing economies, the barriers to plastic circular economy implementation include economic constraints, technological challenges, expertise shortages, regulatory discrepancies, consumer habits, and a lack of infrastructural development. To overcome these barriers, the recommendations include supporting informal waste collection and its integration into the formal waste management system, public-private partnerships for investment, developing industrial composting facilities, enforcing clear labeling and disposal instructions, mandating extended producer responsibility, expanding collection points and accessibility, banning non-recyclable multi-layer plastics and developing artificial intelligence and blockchain for waste tracking.

Keywords

Circular economy; extended producer responsibility; plastic pollution; recycling; smart technology; waste management

1. Introduction

Plastics have become an integral part of modern society, revolutionizing industries ranging from packaging and healthcare to construction and electronics. Their versatility, durability, and cost-effectiveness have driven exponential production growth, reaching approximately 460 million metric tons annually [1]. However, this widespread use has resulted in severe environmental consequences, including plastic pollution, resource depletion, and greenhouse gas emissions [2]. Currently, the costs linked to the external effects (on the economy, environment, and society) of plastics after their use are estimated conservatively at \$3.7 trillion. This amount surpasses the entire profit margin of the plastic packaging industry [3]. If no measures are implemented, the lifetime cost associated with plastics is projected to increase twofold by 2040, reaching US \$7.1 trillion. This amount represents 85% of the total global health expenditure in 2018 and exceeds the combined GDP of Germany, Canada, and Australia in 2019 [3].

Linear economic approaches, which follow a "take-make-dispose" strategy, have exacerbated these challenges by generating vast amounts of plastic waste with limited recycling or recovery. In response, the concept of a circular economy (CE) for plastics has gained traction as a sustainable alternative, emphasizing resource efficiency, waste minimization, and closed-loop material cycles [4]. Thus, there is a significant opportunity for the industry to embrace this new plastics economy [5]. This shift could improve socioeconomic outcomes throughout the supply chain while significantly minimizing plastic waste and reducing its harmful impact on the environment [6].

The CE is an economic model designed to decouple growth from resource consumption by promoting strategies such as reuse, repair, recycling, and remanufacturing [7]. In the context of plastics, CE aims to reduce environmental footprints while retaining material value within the economy [8]. Transitioning from a linear to a circular system necessitates innovative business models, policy interventions, technological advancements, and behavioral shifts [9]. Several CE approaches have been proposed to achieve these goals, including recycling-based approaches, bio-

based plastics, extended producer responsibility (EPR), and digital solutions such as blockchain-enabled traceability [10-12].

Despite the increasing focus on CE principles, the implementation of CE for plastics remains inconsistent across regions and industries. Several challenges hinder the widespread adoption, including economic barriers, technological limitations, regulatory gaps, and consumer behavior [13]. Current global plastic recycling rates remain low, with only about 9% of plastic waste being recycled, while the rest is incinerated, landfilled, or leaked into the environment [14]. Additionally, the complexity of plastic compositions, contamination in waste streams, and inadequate infrastructure further complicate the transition to a fully circular system. Addressing these barriers requires an interdisciplinary approach that integrates policy, industry, and scientific advancements [15].

Given the immense scale and complexity of the plastic pollution crisis, an overview that spans the breadth of CE approaches offers a more holistic and impactful contribution than narrowly focusing on a single strategy. Understanding the full landscape of CE strategies is critical to identifying synergies, gaps, and scalable solutions [16, 17]. While deep dives into individual approaches can yield valuable technical insights, they often fail to capture the interconnected nature of the systems involved. In contrast, a broad overview enables cross-comparison of methods such as recycling, bio-based alternatives, extended producer responsibility, and digital tools, while highlighting how combinations of these strategies may be more effective across varying contexts [18]. This comprehensive lens is especially vital given the fragmented and uneven implementation of CE principles globally, and it allows for a more inclusive discussion of best practices, implementation barriers, and enabling conditions.

As such, this overview provides a comprehensive account of CE approaches for plastics, evaluating their effectiveness, challenges, and future potential. In contrast to existing reviews of the plastic CE that focus on limited approaches [19] or on practices specific to certain regions, like European countries [20], it explores a broader array of approaches globally, supported by cases of their implementation. Although existing reviews often emphasize particular enablers of the CE for plastic waste, such as consumer behavior and digitalization [21] or specific aspects like the value chain [22], this overview adopts a broader perspective by examining various plastic CE approaches without delving into specific components. By analyzing current research and emerging trends, this review aims to contribute to the discourse on sustainable plastic management and inform policymakers, businesses, and researchers on viable pathways toward a CE.

2. Literature Review Methods

A systematic approach was employed in this comprehensive overview to identify, evaluate, and analyze relevant academic research on CE approaches for plastics. The methodology involved the following steps:

1. **Search Strategy:** A structured search was performed using academic databases comprising Scopus, Web of Science, and ScienceDirect. Key terms included "circular economy plastics," "plastic recycling," "sustainable plastic management," "waste-to-resource strategies," and "policy interventions in plastic waste management."
2. **Inclusion and Exclusion Criteria:** Studies included in this study must be 1) academic articles, technical reports, and official publications from authorities and governments, 2) peer-reviewed, 2) published within the last decade, 3) related to the CE approaches for plastics, 4)

related to the implementation of the plastic CE; and 5) linked to the barriers, challenges, advantages and disadvantages of the CE approaches. Articles that are constrained to specific technological, material, and engineering advances were excluded from the overview since the focus is on the overarching CE approaches. Similarly, articles that propose regulatory frameworks and policies are excluded, as this review concentrates on the implementation of plastic CE approaches.

3. Data Extraction and Categorization: Key themes were identified. The key themes here were the various plastic CE approaches. Studies were categorized to align with the article's thematic structure.
4. Critical Analysis and Synthesis: The selected literature was critically analyzed to identify trends, knowledge gaps, and conflicting perspectives. Particular attention was given to studies that provided efficiencies of the CE approaches and real-world case studies.

A flowchart summarizing the review process is shown in Figure 1.

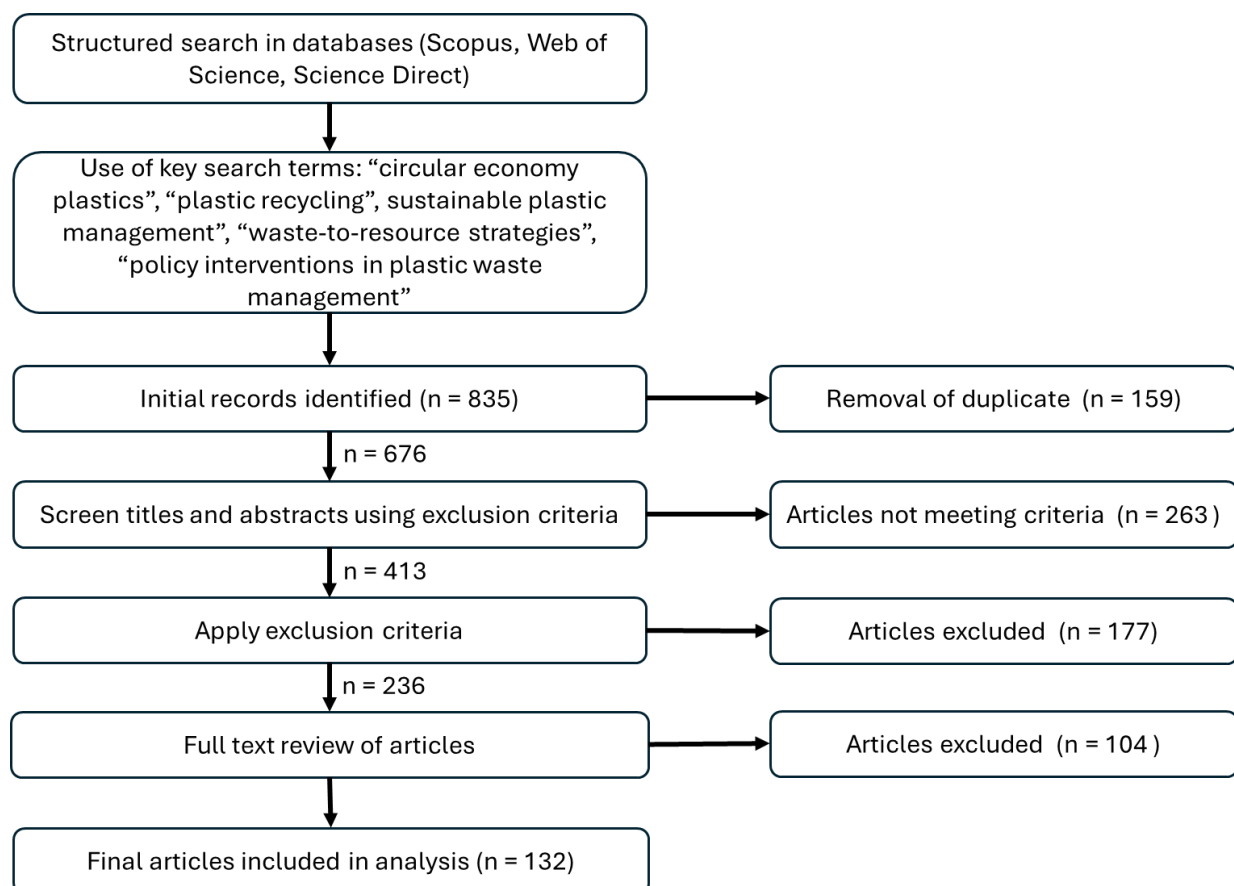


Figure 1 Flowchart illustrating the methodology of the literature review.

3. Approaches of Plastic CE

The CE for plastics is a sustainable model aimed at eliminating plastic waste and pollution by designing materials for reuse, recycling, and regeneration. Unlike the traditional linear economy, which follows a "take-make-dispose" approach, the CE focuses on keeping plastics in circulation for as long as possible, reducing environmental impacts while maximizing resource efficiency [4]. This

system relies on three key principles: eliminating unnecessary plastic waste, innovating for sustainable materials, and ensuring plastics are reused or recycled effectively [23].

The literature indicates that the main plastic CE approaches comprises 1) mechanical recycling approach that focuses on the collection, sorting, and reprocessing of plastic waste into new products [24, 25]; 2) chemical recycling approach, which involves breaking down plastics into their molecular components through processes like pyrolysis, depolymerization, and gasification [26, 27], 3) bio-based and biodegradable plastics approach, which promotes the development and use of plastics derived from renewable resources (e.g., plant-based polymers) and biodegradable alternatives to reduce environmental persistence [28, 29], 4) EPR approach, mandating manufacturers to take responsibility for the end-of-life management of their plastic products, encouraging sustainable design, and improving waste management systems [30, 31], 5) deposit-refund schemes and take-back systems, which incentivize consumers to return plastic products for proper recycling or reuse through financial incentives [32], 6) design for circularity approach, focusing on redesigning plastic products for longevity, reparability, and recyclability to minimize waste generation [33, 34], and 7) digital and smart waste management approach, which utilizes digital technologies such as blockchain, artificial intelligence (AI)-driven waste sorting, and Internet of Things (IoT) tracking systems to enhance traceability and efficiency in plastic waste management [35]. These approaches are discussed in further detail below.

3.1 Mechanical Recycling Approach

Mechanical recycling is one of the most widely used methods for processing plastic waste, allowing it to be reintroduced into the production cycle without significant chemical changes. This process involves sorting, cleaning, shredding, melting, and reprocessing plastics into new products [24]. Mechanical recycling can be closed-loop, where recycled plastics are turned into products of similar quality. It can also be an open-loop system if the plastic degrades and is repurposed into lower-value items [25]. A closed-loop recycling system refers to a process where a material is continuously recycled into the same or similar product without significant loss of quality. This system minimizes waste and reduces the need for virgin materials, making it a key component of a CE. For instance, polyethylene terephthalate (PET) bottles collected through recycling programs are cleaned, shredded, and reprocessed into new PET bottles [36]. An open-loop recycling system is a type of recycling process where waste materials are converted into new raw materials or products, but not necessarily into the same type of product they originated from. In this system, the recycled material may degrade in quality over time (downcycling) or be used in a different industry. For instance, in an open-loop system, plastic bottles are converted into polyester fibers used in textiles or carpets instead of being reprocessed into new bottles [37, 38].

Mechanical recycling typically involves collection and sorting, during which waste materials collected from households, industries, or businesses are sorted manually or using automated systems, such as near-infrared sensors, air classifiers, or magnetic separators [39] (Figure 2). Materials are separated by type, color, and polymer composition to improve recyclability. Subsequently, the materials are cleaned to remove contaminants like food residues, adhesives, labels, or other impurities that can affect quality. They are then shredded into smaller pieces to facilitate processing [39] (Figure 2). The cleaned and shredded materials are melted at high temperatures to form pellets, flakes, or granules [24, 40] (Figure 2). Additives like stabilizers or

colorants may be introduced to enhance their properties. The molten materials are then molded, extruded, or pressed into new products [41]. In a closed-loop system, the materials are used to manufacture similar items from which they are derived. In an open-loop system, the materials are processed into new products [24].

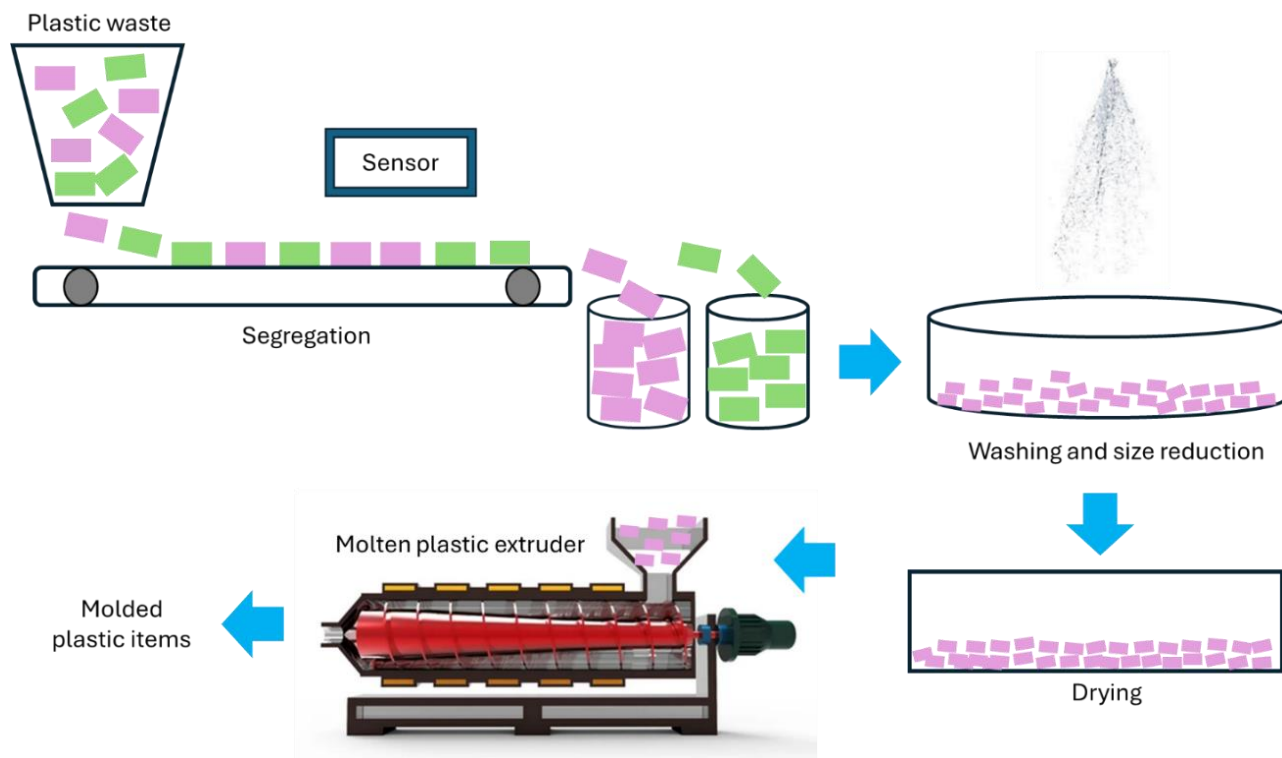


Figure 2 Processes of mechanically recycling plastic waste.

The mechanical recycling approach has the advantage of energy efficiency. Compared to chemical recycling, which is discussed in the subsequent section, this approach consumes less energy since it does not involve breaking down polymers into monomers. It also helps reduce carbon emissions associated with virgin plastic production [42]. Mechanical recycling is cheaper than chemical recycling since it does not require complex chemical processes. The process is well-established, making it more economically viable in many regions [43]. Additionally, it reduces the plastic waste bound for incineration or landfilling, thus reducing the greenhouse gas emissions associated with these disposal means [42]. However, many plastics, especially multi-layered and composite plastics, are difficult to recycle mechanically [44]. Certain thermoset plastics, such as epoxy resins, cannot be melted and reshaped. Recycled plastics also lose mechanical properties after each cycle due to polymer degradation. This limits their applications and often requires blending with virgin plastics to maintain quality [45]. Mechanical recycling requires clean and well-sorted plastic waste. The presence of contaminants in plastic waste, like food residues and additives, could reduce recyclability and product quality [46]. Unlike chemical recycling, mechanical recycling often leads to downcycling, where plastic is converted into lower-value products, e.g., from PET bottles into textiles rather than new bottles [41]. Efficient mechanical recycling requires a well-developed waste collection and sorting system, which is lacking in many regions. As mechanical recycling requires the diminution of plastic waste, it potentially generates and releases microplastics into the environment [47].

3.2 Chemical Recycling Approach

The chemical recycling approach is an advanced method for managing plastic waste, breaking down plastic polymers into their basic molecular building blocks. These molecules can then be repurposed into new plastics, fuels, or chemicals, contributing to a closed-loop CE for plastics [48]. Unlike mechanical recycling, which retains the polymer structure, chemical recycling decomposes plastics at the molecular level, allowing for higher quality and more versatile outputs. The major types of chemical recycling comprise pyrolysis, gasification, hydrolysis and solvolysis, and depolymerization [26] (Figure 3). Pyrolysis, otherwise called thermal depolymerization, involves heating plastics in the absence of oxygen to break them down into liquid fuels, monomers, or chemical feedstocks (Figure 3). It is suitable for polyolefins, like polyethylene and polypropylene, which are difficult to recycle mechanically [49]. Gasification is essentially a high-temperature process (approx. 1000°C) in low-oxygen conditions that converts plastics into syngas ($\text{CO}_2 + \text{H}_2$). Syngas can be used to produce methanol, ammonia, or fuels [50].

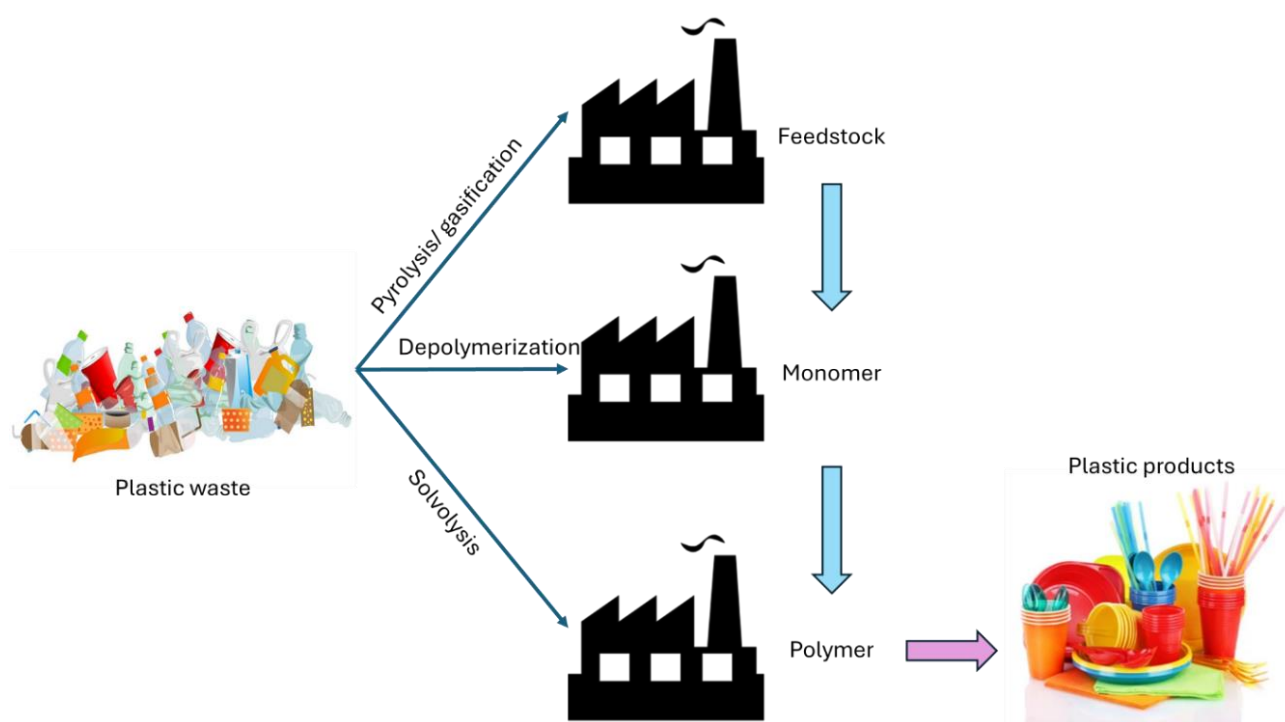


Figure 3 Chemical recycling of plastic waste.

Hydrolysis and solvolysis are chemical recycling methods that utilize water, alcohols (such as methanol or ethanol), or other organic solvents to depolymerize plastics into their original monomers or oligomers (Figure 3). These techniques are particularly effective for condensation polymers like PET and polyamides (e.g., nylon) [51]. In hydrolysis, water reacts with ester or amide bonds under acidic, basic, or neutral conditions, often with the aid of heat and catalysts, to cleave the polymer chains into monomeric units such as terephthalic acid and ethylene glycol in the case of PET [52]. Solvolysis, in contrast, uses alcohols or other solvents in a process known as alcoholysis, glycolysis, or aminolysis, depending on the solvent type. For example, glycolysis of PET with ethylene glycol produces bis(hydroxyethyl) terephthalate (BHET), a precursor for repolymerization into new PET [53].

Depolymerization via these methods is highly selective and efficient for specific polymer types and offers the potential to produce monomers of near-virgin purity (Figure 3). This distinguishes it from mechanical recycling, which physically melts and reshapes plastics but often results in polymer degradation over repeated cycles. Moreover, advanced chemical recycling processes incorporate solvent purification steps, such as distillation, filtration, or crystallization, to remove dyes, additives, and other contaminants from the recovered monomers. These purification techniques enhance the quality and consistency of the output, making it suitable for high-performance applications, including food-grade packaging [26, 54].

Because chemical recycling operates at the molecular level, it can effectively process complex waste streams, including multi-layered, contaminated, or composite plastics that are challenging for mechanical systems. It also minimizes microplastic formation, as polymers are not fragmented but rather broken down completely. Additionally, since the resulting monomers can be repeatedly re-polymerized without loss of quality, these processes offer the potential for closed-loop recycling, enabling the development of a truly circular plastic economy [55, 56].

Nonetheless, chemical recycling has high energy consumption. Processes like pyrolysis and gasification require high temperatures, increasing energy demands. If powered by non-renewable energy, it can generate high carbon emissions [57]. It requires advanced chemical processing plants, which are costly to build and maintain. Some processes release toxic chemicals, such as dioxins, furans, or volatile organic compounds, and necessitate proper emission control systems [58]. Pyrolysis could produce low-quality liquid fuels rather than true circular materials. Gasification is efficient but primarily generates fuel rather than new plastics [57, 58]. While promising, chemical recycling is not widely adopted due to high costs, energy requirements, and regulatory barriers [59]. Table 1 shows a comparison between chemical and mechanical recycling approaches.

Table 1 Comparison between the mechanical and chemical recycling approaches.

Feature	Mechanical Recycling	Chemical Recycling
Process	Melts and reshapes plastic waste	Breaks plastics into monomers or chemical feedstocks
Quality of recycled plastics	Degraded after multiple cycles	Virgin-quality
Plastic types	Requires clean, sorted plastics	Can handle complex and contaminated plastics
Energy use	Lower	High
Infrastructure cost	Lower	High
CE contribution	Limited due to downcycling	Infinite recycling potential
Scalability	Well-established	Limited adoption

3.3 Bio-Based and Biodegradable Plastics Approach

The bio-based and biodegradable plastics approach is an important approach within the plastic CE, aiming to reduce reliance on fossil-based plastics and minimize environmental pollution. This approach emphasizes the use of renewable resources to produce plastics and ensures their biodegradability for sustainable end-of-life management [60]. Bio-based plastics are made from renewable biological sources, such as corn starch, sugarcane, cellulose, and algae. Examples of bio-based plastics are polylactic acid (PLA), polyhydroxyalkanoates (PHA), and bio-based polyethylene.

Some bio-based plastics, such as bio-based polyethylene and polypropylene, are not biodegradable [28, 61]. Biodegradable plastics are designed to break down into natural elements like carbon dioxide, water, and biomass through microbial activity. They can be petroleum-based, e.g., polybutylene adipate terephthalate, or bio-based, e.g., PLA and PHA. Their decomposition rates depend on environmental conditions and may require industrial composting facilities [29].

The bio-based and biodegradable plastics approach integrates with the 3Rs (Reduce, Reuse, Recycle) and introduces biodegradation and composting to close the material loop [62]. By using agricultural waste, non-food biomass, or dedicated bio-feedstocks, the approach promotes sustainable sourcing and reduces dependence on fossil fuels. The products are often designed for biodegradability, recyclability, or compostability, thus encouraging eco-design. Some bio-based plastics, like bio-polyethylene, can enter conventional mechanical or chemical recycling [63]. Certified biodegradable plastics decompose into non-toxic substances, supporting organic waste management [62]. Nonetheless, the approach faces the challenge of resource competition since bio-based plastics can compete with food production for land and water. Many biodegradable plastics degrade only in controlled composting conditions, not in natural settings. Mixing biodegradable plastics with conventional plastics can disrupt recycling processes. Higher production costs compared to fossil-based plastics limit widespread adoption [64, 65].

3.4 Extended Producer Responsibility (EPR) Approach

The EPR is a key policy approach in the plastic CE, shifting the responsibility for post-consumer plastic waste management from governments and consumers to the producers who manufacture, distribute, and sell plastic products [30]. EPR mandates that producers take financial and/or operational responsibility for the collection, recycling, and disposal of plastics, encouraging more sustainable product design and waste management practices [31]. Under EPR, producers are required to implement take-back programs, fund recycling initiatives, and ensure proper waste disposal. This approach incentivizes companies to design products with longer lifespans, improved recyclability, and reduced environmental impact [66]. For instance, manufacturers may choose to use mono-material plastics instead of complex multi-layered plastics to enhance recyclability. Additionally, companies may invest in reuse strategies, such as refillable packaging, or support the development of biodegradable and bio-based alternatives to conventional plastics [66, 67].

A well-structured EPR system includes mandatory recycling targets, eco-modulated fees, and reporting obligations. Producers often pay EPR fees based on the recyclability and environmental impact of their products—items with difficult-to-recycle plastics may incur higher fees, encouraging businesses to shift toward more sustainable materials [68]. Governments and regulatory bodies oversee compliance, ensuring that funds are allocated to waste collection, sorting, and recycling infrastructure. This financial support strengthens local waste management systems and reduces the burden on municipalities, promoting a more circular approach to plastic use [69].

Despite its benefits, EPR implementation faces challenges such as inadequate enforcement, lack of standardized regulations, and varying levels of industry participation. In many regions, weak infrastructure and poor waste segregation hinder the effectiveness of producer-led recycling efforts [70]. However, when properly enforced, EPR can significantly reduce plastic waste leakage into the environment, increase recycling rates, and encourage a transition from a linear “take-make-dispose” approach to a regenerative CE where plastics are continuously recovered and reused [71].

3.5 Deposit-Refund Schemes and Take-Back Systems

Deposit-refund schemes (DRS) and take-back systems are essential mechanisms in the plastic CE, designed to incentivize the return and proper recycling of plastic products and packaging [32]. These systems promote waste reduction, resource efficiency, and pollution prevention by ensuring that plastics remain within a closed-loop system rather than ending up in landfills or the environment [72]. DRS works by charging consumers a refundable deposit when purchasing products in plastic packaging, such as beverage bottles. Consumers can reclaim the deposit by returning the used packaging to designated collection points [73]. This system significantly improves collection rates and recycling efficiency, reducing littering and environmental pollution. Countries with well-established DRS, such as Germany and Sweden, achieve recycling rates of over 90% for PET bottles due to consumer participation driven by financial incentives [72, 74]. Moreover, a well-managed DRS helps maintain high-quality plastic material streams, allowing for closed-loop recycling where plastics are reprocessed into new products of similar quality rather than being downcycled [75].

Take-back systems, on the other hand, place the responsibility on producers, retailers, or waste management companies to collect and properly manage plastic waste at the end of its life cycle [76]. These systems can be voluntary or mandatory, requiring manufacturers to provide collection points or reverse logistics systems for used plastic products. Take-back programs are widely used for electronic plastics, plastic packaging, and industrial plastic waste, ensuring that valuable materials are recovered and reintegrated into production cycles [76, 77]. Some companies implement a closed-loop take-back approach, where plastics from returned products are directly reused in manufacturing new items, reducing reliance on virgin plastic production [66].

Both systems align with EPR principles, encouraging businesses to design for recyclability, reduce waste, and invest in sustainable packaging alternatives. However, successful implementation depends on consumer awareness, infrastructure development, and regulatory enforcement [78]. Challenges such as collection inefficiencies, contamination of materials, and logistical costs must be addressed to maximize their effectiveness [79]. When properly executed, deposit-refund schemes and take-back systems play a crucial role in transitioning from a linear economy to a sustainable CE for plastics.

3.6 Design for Circularity Approach

The design for circularity approach is a fundamental approach in the plastic CE, ensuring that plastic products and packaging are designed to be recyclable, reusable, or biodegradable from the outset [33]. This approach moves away from the traditional linear economy (“take-make-dispose”) by integrating sustainability principles into product design, thereby reducing plastic waste, minimizing environmental impact, and keeping plastic materials within a closed-loop system [34]. A key aspect of designing for circularity is the use of mono-material plastics instead of complex, multi-layered plastics that are difficult to recycle. For example, many food packaging materials consist of multiple plastic layers fused together, making separation and recycling challenging. By shifting to single-type plastics, manufacturers enable easier collection, sorting, and high-quality recycling. Additionally, modular design allows products such as electronics or packaging to be disassembled, facilitating material recovery and reuse [80, 81].

Another critical strategy is lightweighting and material efficiency, where products are designed using fewer raw materials without compromising performance. This reduces plastic consumption at

the source and lowers the carbon footprint of production and transportation [82]. Furthermore, incorporating recycled content into new plastic products helps close the material loop, reducing dependence on virgin plastics derived from fossil fuels. Some companies now use post-consumer recycled (PCR) plastics in packaging, which supports the demand for recycled materials and strengthens the market for secondary plastics [83]. Designing for circularity also involves enhancing product durability and reusability. Refillable and reusable packaging solutions, such as returnable bottles and bulk dispensing systems, extend the life cycle of plastics and reduce the need for single-use packaging [84]. Biodegradable and compostable plastics, when properly designed and certified for specific environments, further contribute to circularity by ensuring that plastics break down safely at the end of their life.

Despite its benefits, challenges such as technological limitations, cost barriers, and consumer behavior still hinder widespread adoption. Effective implementation requires collaboration between manufacturers, policymakers, and waste management systems to standardize recyclable designs and establish efficient collection infrastructures [85]. By prioritizing circular design principles, industries can significantly reduce plastic waste, lower environmental impact, and contribute to a more sustainable and resource-efficient plastic economy.

3.7 Digital and Smart Waste Management Approach

The digital and smart waste management approach is a technology-driven approach that enhances the efficiency, traceability, and sustainability of plastic waste management within the plastic CE [35]. By integrating IoT, AI, blockchain, and data analytics, this approach optimizes waste collection, sorting, and recycling processes, ensuring that plastics remain in a closed-loop system rather than polluting the environment [86].

One key application of smart waste management is the use of IoT-enabled waste bins and sensors that monitor fill levels and send real-time data to waste collection services. These smart bins help optimize collection routes, reduce transportation costs, and minimize carbon emissions by ensuring that waste is only collected when necessary [87]. Complementing this infrastructure, AI plays a transformative role in the automated classification and sorting of plastic waste. AI-powered systems, often combining high-resolution cameras, hyperspectral imaging, and machine learning algorithms, can accurately detect and classify plastics based on attributes such as polymer type (e.g., PET, high-density polyethylene, polyvinyl chloride), color, shape, and contamination level. For example, convolutional neural networks (CNNs) are trained on large datasets to distinguish subtle differences in surface features and reflectance spectra, enabling real-time decision-making during the sorting process [88, 89].

Advanced robotic arms integrated with AI classifiers can then precisely separate items at high speed, significantly outperforming manual sorting in both accuracy and throughput. Furthermore, these systems continuously improve over time through feedback loops and adaptive learning, enhancing their performance in diverse and contaminated waste streams. By increasing the purity of sorted materials, AI-based sorting enhances the efficiency and economic viability of downstream recycling processes, particularly in facilities that handle mixed or post-consumer plastic waste. In doing so, AI technologies not only reduce human labor and error but also play a critical role in scaling circular economy practices through more intelligent, data-driven waste management.

Blockchain technology plays a crucial role in ensuring transparency and traceability in the plastic supply chain. By recording every step of a plastic product's lifecycle—from production to disposal—blockchain creates a digital passport for plastics, helping industries track and verify the use of recycled materials [90]. This promotes compliance with EPR policies, prevents plastic leakage into the environment, and incentivizes manufacturers to incorporate more PCR plastics in their products.

Furthermore, mobile apps and digital platforms empower consumers to participate in the CE by providing waste disposal guidance, incentivized recycling programs, and deposit-refund schemes (DRS) [91]. Some platforms use QR codes or radio-frequency identification (RFID) tags on plastic packaging, allowing users to scan and access information about proper disposal methods, recycling locations, or return incentives. This enhances consumer awareness and increases the likelihood of plastics being disposed of correctly [92].

Despite its potential, the adoption of digital waste management systems faces challenges such as high initial costs, lack of standardized data systems, and digital infrastructure gaps in certain regions [86]. However, with continued investment and policy support, the integration of smart technologies into waste management can significantly enhance plastic recycling rates, reduce pollution, and drive the transition toward a fully circular plastic economy [92].

3.8 Comparison of Plastic CE Approaches

A comparison of the plastic CE approaches discussed above, in terms of their feasibility, scalability, technical maturity, environmental impact, and economic viability, is shown in Table 2.

Table 2 Comparison of the feasibility, scalability, technological maturity, environmental impact and economic viability of various plastic CE approaches.

Approach	Feasibility	Scalability	Technological Maturity	Environmental Impact	Economic Viability
Mechanical recycling	Established globally with proven infrastructure	Constrained by contamination and polymer mixing	Mature technologies like extrusion, shredding, and washing	Lower greenhouse gas emissions than virgin plastic production, but quality degrades over cycles	High for clean, mono-material streams; low for contaminated/mixed plastics
Chemical recycling	Technically viable but energy-intensive	Growing, investments increasing, but still emerging	Some processes (e.g., PET glycolysis) are mature, others are still at pilot scale	Closes the loop with virgin-quality output, but energy use is a concern	High initial cost, but promising for hard-to-recycle plastics
Bio-based and biodegradable plastics	Depends on feedstock availability and local policies	Global production remains <1% of total plastics	PLA, PHA, and starch blends exist, but are limited in durability or functionality	Potentially low if sourced sustainably and composted industrially	More costly than fossil-based alternatives
EPR	Legislated in many countries (e.g., European Union (EU), Canada)	Policy-driven; scalable through regulations and compliance schemes	Not applicable as it is a policy instrument	Indirect benefits through incentivizing better design, recycling, and collection	Shifts cost from public to producers; effectiveness varies by enforcement
DRS and take-back systems	Successfully implemented in regions, such as EU and US	Proven to boost recycling rates of PET bottles and cans	Mature logistics and collection systems	Beneficial through increasing return rates and reducing litter	Funded through deposits; cost-effective for targeted streams
Design for circularity	Depends on producers' willingness and standards	Scalable through regulations and industry coalition	Design strategies are well known but implementation is lagging	Beneficial through enabling easier reuse, repair, and recycling	Initial redesign costs, but lifecycle savings
Digital and smart waste	Early-stage implementations in smart cities	Requires investment in infrastructure and data integration	Image recognition and robotics are advancing rapidly	Beneficial through improving recycling rates and reducing carbon footprint	High upfront cost but long-term operational savings

4. Cases of Implementation of the Plastic CE Approaches

In reality, the plastic CE has been implemented to different extents in different parts of the world. Germany has one of the most successful DRS for plastic beverage bottles, achieving a recycling rate of over 90%. The system, known as Pfand, requires consumers to pay a small deposit (typically €0.25) when purchasing plastic bottles, which is refunded upon return at reverse vending machines located in supermarkets and convenience stores [78, 93]. This initiative has significantly reduced plastic litter and ensured that high-quality PET plastic is collected and recycled efficiently. The success of the German DRS has influenced similar systems in other European countries, such as Sweden and the Netherlands [72].

Moreover, a Frankfurt-based materials-regeneration start-up leverages glycolysis technology in the chemical depolymerization and regeneration of post-industrial and post-consumer polyester textiles [94]. The process starts with a combination of contaminated polyester feedstocks, which are frequently mixed with cotton, dyes, or elastane. This mixture is then purified through crystallization and filtration to eliminate impurities. The clean material is subsequently chemically depolymerized using ethylene glycol and a reusable catalyst under milder conditions (lower temperatures and energy requirements), resulting in pure monomers like BHET or poly(hydroxyethyl terephthalate) (PHET). These are subsequently repolymerized into pellets, producing a high-purity product and emitting about 50% less CO₂ compared to virgin polyester [94, 95].

In the Netherlands, Dutch companies and policymakers have prioritized design for circularity, particularly in plastic packaging. The Netherlands-based company Unilever has developed packaging solutions that are 100% recyclable, reusable, or compostable, integrating PCR plastic into their bottles [96]. The country also encourages mono-material packaging, reducing the complexity of recycling processes. These efforts align with the Plastic Pact Netherlands, which aims to reduce virgin plastic use and increase recycling rates through improved product design [97].

In Italy, a chemical subsidiary of an Italian energy company is playing a leading role in advancing plastic circularity through mechanical and advanced recycling initiatives. In 2022, a post-consumer plastic mechanical recycling plant was established in Porto Marghera, Venice, with a processing capacity of around 20,000 tons per year [98]. This facility specializes in converting sorted polyethylene and polystyrene waste into high-quality secondary raw materials suitable for applications in packaging, construction, and automotive industries. Beyond mechanical recycling, the company has expanded into advanced recycling through its investment in pyrolysis and depolymerization technologies. It is piloting systems to convert mixed plastic waste into synthetic oil, which can be refined and reused in traditional polymer production [98]. This dual approach—mechanical and chemical—enables the handling of both clean and contaminated plastic waste streams, thus extending the life cycle of materials otherwise destined for incineration or landfill. By embedding circularity into its industrial model, the company is aligning with the EU Green Deal objectives and contributing to Italy's transition toward a more resource-efficient, low-carbon economy [99].

Japan has implemented an advanced smart waste management system that relies on IoT technology, AI-driven sorting, and meticulous waste segregation [100]. Cities such as Kamikatsu have adopted a zero-waste approach, where residents sort waste into more than 40 different categories, ensuring high levels of recycling and resource recovery [101]. Additionally, Japan has

invested in AI-powered sorting machines that use optical sensors and deep learning to separate plastic waste by polymer type, improving recycling efficiency. The integration of digital tools into waste management has helped Japan maintain one of the highest plastic recycling rates in the world, at approximately 85% [102].

Chile has taken a strong regulatory approach by implementing the EPR Law, which mandates that producers of plastic packaging and products take responsibility for their post-consumer waste [103]. Under this law, companies are required to finance collection, recycling, and proper disposal. The regulation has encouraged businesses to adopt eco-design principles, incorporate recycled plastics into new products, and participate in take-back programs. By 2030, Chile aims to double its plastic recycling rates through EPR initiatives [104].

In India, mandatory take-back systems for plastic packaging have been introduced under its Plastic Waste Management Rules. Companies like Coca-Cola and Nestlé have partnered with waste collection and recycling enterprises to establish return and recycling infrastructure for multi-layered plastic waste [105]. These efforts are particularly crucial in addressing the country's high plastic pollution levels. Cities such as Pune and Bengaluru have also pioneered waste-picker inclusion programs, where informal recyclers play a key role in collecting and sorting plastics for recycling [106].

Sweden has invested heavily in bio-based and biodegradable plastic alternatives, particularly in the packaging and food service industries. Companies such as Tetra Pak have introduced bio-based cartons made from plant-derived polymers, reducing reliance on fossil-based plastics [107]. Sweden also promotes industrial composting facilities for biodegradable plastics, ensuring proper decomposition and integration into circular waste management systems. These initiatives align with Sweden's goal of achieving a fossil-free economy by 2045 [107].

Typically, plastic CE approaches are not implemented independently. The examples mentioned earlier necessitated the investment and development of mechanical and chemical recycling systems, allowing the collected plastics to be either recycled or repurposed. In the case of biodegradable plastics, composting facilities have been established for organic recycling, facilitating the breakdown of plastics and the utilization of their nutrients. In Germany, for instance, the implementation of CE approaches is highly integrated. Germany has one of the highest recycling rates globally (~67%). Its "Green Dot" system requires manufacturers to use recyclable packaging [108]. BASF and other companies are developing chemical recycling for plastic waste, converting hard-to-recycle plastics into raw materials [109]. Research into bioplastics and compostable alternatives is expanding, with some cities offering separate collections for compostable plastics [110]. The Packaging Act (VerpackG) makes producers responsible for waste collection and recycling. A Pfand system (bottle deposit refund) ensures high recovery rates for beverage containers (~98%) [111]. Electronics and batteries must be collected by retailers and manufacturers for recycling under Germany's ElektroG law. Germany's eco-design standards push for durable and repairable products, reducing electronic and plastic waste [112].

As for Japan, it has strict sorting systems for mechanical recycling, achieving a plastic recycling rate of approximately 85%. Companies like JEPLAN use chemical depolymerization to recycle polyester into new fibers [113]. Japan is investing in bio-based plastics from seaweed and plant-based materials. Under the Home Appliance Recycling Law, producers must collect and recycle refrigerators, televisions, and air conditioners. PET bottles have collection points in supermarkets for efficient deposit refunds. Retailers must take back used electronic goods when selling new ones,

ensuring proper recycling [114]. Cities like Kamikatsu use QR codes for waste tracking, improving recycling rates [101].

Generally, the EU has adopted a comprehensive and multi-faceted strategy to transition plastics toward a circular economy, emphasizing prevention, design innovation, and systemic transformation across the value chain. Central to this vision is the EU Plastics Strategy, a key component of the Circular Economy Action Plan, which mandates all plastic packaging on the EU market to be recyclable or reusable by 2030 [115]. The European Environment Agency (EEA) further supports this transition through detailed assessments such as *“Plastics, the circular economy and Europe’s environment”*, highlighting both environmental challenges and circular opportunities. Recent updates emphasize growing capacities for mechanical recycling, a shift toward bioplastics, and reduced plastic waste exports [13]. Complementing these policies, initiatives like “ReShaping Plastics” by Plastics Europe and SYSTEMIQ offer scenarios to cut plastic waste and greenhouse gas emissions by combining upstream (e.g., reduced demand, eco-design) and downstream (e.g., recycling technologies) measures [116]. Together, these policies and roadmaps reflect the EU’s integrated approach, combining regulation, innovation funding, and stakeholder engagement to close material loops and retain plastic value within the economy.

Globally, the United Nations (UN), led by the UN Environment Programme (UNEP), frames plastic pollution as a planetary crisis requiring global, systemic change. UNEP 2023 annual report outlines a roadmap to reduce plastic pollution by 80% by 2040 through a combination of circular strategies: reducing unnecessary plastic production, promoting reuse systems, improving recycling infrastructure, and implementing EPR schemes. These approaches emphasize lifecycle thinking and equity, recognizing the need for international cooperation and support for developing nations [117]. In parallel, the UN Global Plastics Treaty negotiations, a historic process launched in 2022, aim to create a legally binding instrument covering the full life cycle of plastics. The draft treaty considers measures such as global caps on virgin plastic production, mandatory recycled content, and monitoring of plastic leakage [118]. Additionally, UNDP’s community-based circular solutions, supported by the Global Environment Facility, showcase bottom-up approaches to plastic reuse, recycling, and livelihood enhancement [119]. Together, these efforts signal a bold move toward a globally coordinated circular economy for plastics, combining policy, finance, and grassroots action.

Nonetheless, the implementation of the plastic CE in developing countries remains limited and fragmented, though it is gaining momentum. Most developing nations still rely heavily on linear plastic economies, dominated by informal waste management systems, low recycling rates, and limited infrastructure. However, increasing awareness of plastic pollution, policy shifts, and international cooperation are slowly fostering CE approaches. In many countries across South Asia, Sub-Saharan Africa, and Latin America, informal waste pickers handle a significant portion of plastic recycling (e.g., up to 90% in India) [120, 121]. While they play a critical role in material recovery, the sector lacks regulation, safety standards, and access to modern technology, limiting efficiency and scalability. Only a few nations, such as Nigeria and Bangladesh, have established extensive EPR frameworks; however, when they do exist, enforcement is frequently ineffective [122, 123]. Pilot DRS are being tested in countries like Kenya and Indonesia [70]. Digital technologies (e.g., mobile platforms for waste collection coordination, blockchain traceability) are emerging through donor-funded and NGO-led initiatives. Eco-design and design for circularity remain minimal, with most packaging still optimized for cost rather than reuse or recyclability [124].

5. Barriers to Implementing the Plastic CE Approaches

Despite the fact that the plastic CE approaches have achieved success in certain countries, challenges in their implementation remain, especially in developing countries. Developing countries often lack the necessary infrastructure for efficient collection, sorting, and processing of plastic waste, leading to high contamination rates and low-quality recycled materials. Informal waste-picking sectors dominate waste management, but they typically focus on high-value plastics (e.g., PET and high-density polyethylene), while lower-value plastics are discarded or burned [125]. Additionally, limited public awareness and inadequate waste separation at the source further reduce recycling efficiency [8]. Another major challenge is the economic viability—imported virgin plastics, often subsidized or cheaper due to fluctuating oil prices, make recycled plastics less competitive. In India, for instance, approximately 90% of plastic recycling is handled by the informal sector, where waste pickers manually collect and sort plastic waste. However, due to poor segregation at the source and contamination from food residues and non-recyclable plastics, much of the plastic waste cannot be effectively recycled [122]. Additionally, small-scale recyclers struggle with low-profit margins, as virgin plastics are often cheaper due to government subsidies on petrochemicals. As a result, a large proportion of plastic waste ends up in landfills or the environment [124].

High capital investment requirements and a lack of technical expertise hinder the adoption of chemical recycling in developing countries. These processes demand stable energy sources, which can be unreliable in regions with frequent power shortages [126]. Moreover, the fragmented nature of waste streams, often containing a mix of non-recyclable plastics, food residues, and hazardous materials, complicates the feedstock supply for chemical recycling. Additionally, weak environmental regulations and enforcement mechanisms increase the risk of pollution from emissions and toxic byproducts [125].

The transition to bio-based and biodegradable plastics in developing countries is limited by high costs, weak consumer demand, and inadequate composting infrastructure [29]. Many biodegradable plastics require industrial composting conditions, which are rarely available. Furthermore, there is widespread misinformation, leading to improper disposal. Many people assume these plastics decompose naturally in the environment, contributing to littering issues [127]. Agricultural land competition is another challenge, as using crops for bioplastic production could affect food security in regions already struggling with agricultural sustainability [128].

Developing countries struggle with implementing deposit-refund and take-back systems due to inadequate logistics, lack of consumer participation, and weak financial support. Many consumers do not return plastic waste because of low awareness or because informal recyclers already collect valuable waste items [93]. Setting up collection centers requires significant investment, which governments and businesses may be reluctant to provide. Additionally, the lack of digital tracking systems increases the risk of fraud and inefficiency. In many cases, existing informal recycling networks operate in parallel to formal schemes, creating conflicts and reducing the effectiveness of deposit-refund initiatives [123].

Manufacturers in developing countries often focus on low-cost production, prioritizing cheap, non-recyclable materials to remain competitive in the market. Many products are designed for single use, and there is little investment in research and development for sustainable alternatives [120]. Moreover, a lack of standardized regulations and incentives for eco-design discourages

businesses from adopting circularity principles. Consumers in these regions also tend to favor inexpensive, disposable plastics due to affordability, making it difficult to shift towards durable and recyclable alternatives [85, 129].

The implementation of digital waste management solutions in developing countries faces multiple challenges, including poor internet connectivity, limited access to technology, and financial constraints [92]. Smart waste tracking systems, AI-driven sorting technologies, and blockchain-based transparency initiatives require substantial investment, which many municipalities cannot afford [91]. Furthermore, a lack of skilled professionals to operate and maintain these technologies further hampers progress. Privacy concerns and weak data protection laws also create hesitancy in adopting digital waste monitoring systems. In many cases, informal waste collectors lack access to technology, making it difficult to integrate them into digital waste management frameworks [130]. Bangladesh has attempted to introduce digital waste tracking systems, but adoption remains limited due to poor internet connectivity and lack of funding for smart waste infrastructure [131]. While some cities have implemented pilot programs using AI-powered waste sorting, scaling these technologies has been difficult because of financial constraints and a lack of skilled workers. Additionally, many waste collectors lack access to digital tools, making it hard to integrate them into smart waste management frameworks [132].

6. Conclusion

The increasing severity of global plastic pollution has prompted a shift from the traditional linear economy of processing plastics from fossil fuels, using them, and discarding them at the end of their life to the circular economy. The plastic CE, which emphasizes resource efficiency, waste minimization, and closed-loop material cycles, has been progressively developed. The most popular approaches of this economy are the mechanical recycling approach, the chemical recycling approach, bio-based and biodegradable plastics, the EPR approach, deposit-refund schemes and take-back systems, the design for circularity approach, and the digital and smart waste management approach. Although there is a growing emphasis on CE principles, the implementation of CE for plastics varies significantly among different regions and industries. Various obstacles impede broader acceptance, such as economic constraints, technological challenges, expertise shortages, regulatory discrepancies, consumer habits, and a lack of infrastructural development. The following are recommended to overcome these challenges:

1. **Formalizing and Supporting the Informal Sector:** Governments can integrate waste pickers into the formal waste management system by providing training, safety equipment, and fair wages.
2. **Public-Private Partnerships for Investment:** Governments can attract investors by offering tax incentives and subsidies for chemical recycling plants.
3. **Developing Industrial Composting Facilities:** Governments should invest in composting infrastructure and incentivize businesses to set up biodegradable waste collection systems.
4. **Enforcing Clear Labeling and Disposal Instructions:** Public education campaigns should clarify biodegradable versus conventional plastics to prevent misuse and contamination in recycling streams.
5. **Mandating EPR with Strict Enforcement:** Governments should require producers to finance collection and recycling through taxes, eco-levies, or deposit schemes.

6. Expanding Collection Points and Accessibility: Establishing widespread, easy-to-access collection centers in markets, schools, and transport hubs can improve participation.
7. Banning Non-Recyclable Multi-Layer Plastics: Governments should phase out multi-layer packaging that is difficult to recycle and promote mono-material plastics for easy processing.
8. AI and Blockchain for Waste Tracking: Developing countries can use AI-powered sorting systems and blockchain waste traceability.

In line with the recommendations, future studies can focus on optimizing waste sorting, improving the efficiency of chemical recycling, developing business and policy models that scale up plastic circularity in the informal sector, improving the effectiveness of EPR in developing economies, studying consumer perceptions and behaviors towards sustainable plastic alternatives, and developing AI and blockchain technologies for plastic waste management.

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Competing Interests

The author declares that there are no known conflicts of interest.

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