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An Integrated Analysis of Plastic Packaging Value Chain: Identifying Barriers and Enablers for a Circular Economy

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Abstract: This study investigates the exponential growth of plastic waste, a critical global environmental concern exacerbated by rapid population expansion. It examines the packaging plastic value chain by focusing on associated environmental impacts, challenges, and opportunities for advancing a circular economy (CE). The objectives are to trace the evolution of the CE concept, identify key opportunities and implementation barriers, and devise strategies for enhancing its effectiveness. Through a systematic literature review and qualitative interviews, the research delineated the complexities in the lifecycle of post-consumer packaging plastics. The findings highlighted that CE efficacy was significantly influenced by interrelated factors, including product design, consumer behaviour, collection systems, sorting efficiency, and economic viability of mechanical and chemical recycling pathways. Although CE models are promising, this research indicated that the complete elimination of plastic waste remained an uncertain goal. The study, therefore, advocated a comprehensive transformation of the plastic value chain, necessitated by challenges such as heterogeneous waste streams, inconsistent quality of recycled output, and competing economic factors. It is concluded that strategic investments in research, recycling-friendly design, advanced recovery methods, and efficient sorting are essential for producing cost-effective and high-quality recycled products, thereby moving beyond incremental efforts toward a systemic solution.

Keywords: Circular economy; Recycling; Packaging plastics; Life cycle analysis; Waste management; Design-for-Remanufacture

1 Introduction

Waste management is a universal challenge that threatens the environment and its resources, with plastic pollution being a particularly pervasive issue [1, 2]. Plastics have been identified as one of the five vital areas requiring urgent attention [3]. This challenge is exacerbated by rapid population growth and its associated pressure on resources [4]. Current growth rates suggest that plastic production will increase exponentially, yet this trend is unsustainable. According to the study [5], approximately 6300 Mt of plastic waste was generated between 1950 and 2015, representing about 70% of global production; this volume is predicted to rise rapidly towards 2050 [6]. Currently, some plastic waste has been managed through recycling, reuse, and incineration for energy recovery. Nevertheless, a significant amount still enters the environment through improper disposal and environmental processes such as run-off, floods, and wind [7]. Most plastics are derived from fossil fuels, which contradicts efforts to transition to cleaner and renewable resources [8]. Packaging accounts for a significant proportion of approximately 40% of total plastic production [9], equating to roughly 380 Mt annually [10]. Packaging also serves as a platform for brand loyalty by displaying product information, e.g., ingredients, safety concerns, disposal instructions, etc. Additionally, its preservative characteristics help mitigate food waste globally [11].

Recently, increasing environmental degradation, including plastic waste proliferation, perceived rapid resource depletion, and visible effects of climate change has necessitated a shift from a linear economy towards a more sustainable approach [12]. This transformation involves not only managing plastic waste but also re-evaluating its applications and sourcing alternatives.

The accumulation of plastics and its visible impact on the environment, particularly the marine ecosystem, have drawn public attention [13, 14]. For instance, the death of aquatic animals is usually caused by plastic entanglement and gastrointestinal obstruction [7]. Stakeholders have made efforts to address this issue through diverse mitigation strategies. However, plastic flows are complex, and beyond this, the emergence of microplastics and nanoplastics may pose an even greater environmental challenge. Nevertheless, many unknowns remain regarding their health and environmental effects. Microscopic size and elusive detection make their impact potentially devastating [15]. Moreover, many additives used to modify the physical characteristics of plastics are now declared Substances of High Concern (SHC) or Emerging Organic Pollutants (EOPs), which are predicted to be toxic to humans and ecosystems.

Given these concerns, the emergence of the circular economy (CE) as a viable solution has been widely discussed and CE momentum has increased steadily within organizations, especially large manufacturing firms [16]. As most initiatives have focused on corporate responsibility and sustainability [17], some companies appear to adopt this concept primarily to gain a competitive advantage [18]. Consequently, the circular business model has emerged as an adaptive measure, requiring organizations to balance economic benefits and value creation with CE principles. This is achieved through processes like repair, remanufacturing, and other means of maximizing embedded material value. Adequate implementation of CE could contribute nearly $1 trillion to the global economy by creating jobs in emerging industries [19]. Although many studies have been conducted on CE, the efficiency of its implementation, available operational infrastructure, policies, public acceptance, organizational drivers, and barriers remain controversial among scholars [20]. Indeed, the study [21] argued that CE represented more than merely a solution to environmental impact; it is an anticipatory measure that proactively addresses waste management from the initial phase of its life cycle. This entails moving away from a raw material consumption-based linear economy towards modifying product designs, e.g., using environmentally friendly, easily recovered, or reused materials to enhance sustainability and mitigate the depletion of mineral resources. There are reservations about the implementation and transparency of recycling as an option of CE, particularly in developing economies where CE is a relatively novel approach [22]. A sustainable and integrated waste management model like CE is required to mitigate the impact of growing waste volumes on health and the environment. As widely cited, the promising advantages of CE at micro, macro, and meso levels include reduced production costs, resource optimization, and environmental benefits.

The concept of CE is not straightforward. Dissipation and entropy within the loop (e.g., loss of quality, quantity, etc.) mean that virgin material and energy inputs are still required [19]. Aside from its complexities and the surrounding contradictory remarks, CE remains a relatively novel and evolving theory [22, 23]. It encompasses not only recycling and environmental concepts but also economic and social dimensions. It encourages continuous use of materials with consistent quality within a system, thus decreasing pressure on non-renewable resources through proactive recyclable eco-design and waste avoidance. While CE, proposed by many as a solution for plastic waste management, has shown promising advances, the recycling processes within these models do not guarantee that recycled or reused plastics will not eventually enter the environment. The primary difference from the traditional linear economy is the duration for a material to remain in the economic cycle before it is eventually lost. This indicates that CE is not a perfectly closed system, as material entropy ensures eventual loss from the economy.

The objective of an effective CE is to take proactive measures to mitigate waste from the initial product phase while exploring all available alternatives to reduce the environmental impact of products throughout their lifespan. To further understand the sources and environmental concerns generated by increasing plastic waste, the following sections will highlight the aim and objectives of this study and present an extensive literature review.

1.1 Research Aim and Objectives

Despite progress in applying CE principles, proliferation of plastic persists as a critical environmental issue [24]. Yet, achieving an effective CE for plastics faces multifaceted challenges spanning their entire lifecycle, from design and production to use, recovery, and End-of-Life (EoL) management [12]. Therefore, developing an effective CE for post-consumer packaging plastics (PCPP) requires a deep understanding of the associated opportunities and challenges. This study aims to provide this critical analysis. The specific objectives are to:

(a) Map the current development and implementation of CE frameworks for PCPPs;
(b) Evaluate the primary opportunities for advancing CE within the PCPP lifecycle;
(c) Diagnose the key challenges hindering the effectiveness of existing CE systems for PCPPs; and
(d) Propose a strategic framework to overcome the identified challenges and enhance CE efficiency.

The expected outcome is a proposed framework for a more effective CE for PCPPs, developed through a holistic analysis of lifecycle challenges. Section 2 presents an extensive literature review to establish the necessity and relevance of this research.

2 Literature Review

Research has explored various dimensions of the CE, including its definition [19, 25], associated metrics and indicators [24], implementation barriers and drivers [26], innovations [27], and its specific application to the plastics industry as a solution to pervasive plastic pollution. The management of plastic waste, particularly single-use plastics (SUP) for packaging, remains a significant challenge. Paradoxically, despite advancement in recycling, large quantities of plastic waste are still incinerated or landfilled, often due to the prevalence of multi-material products that incorporate difficult-to-recycle materials like Polyvinyl Chloride (PVC). Such EoL outcomes not only cause environmental harm but also represent a substantial loss of material resources, fundamentally contradicting the core principles of CE.

Actualizing a CE for plastics necessitates a critical transition from the current linear system; the process requires integrated strategies such as eco-design, incentivized reuse, enhanced recycling, knowledge sharing, and research and development [22], alongside social and economic measures.

However, applying CE principles to plastics is inherently more complex than in other sectors. This complexity arises from the challenge of maintaining material quality through successive recycling loops while simultaneously aiming to keep plastics in the economy for as long as possible. The degradation of quality through cycles of use and recovery is described by the cascade model, where the value and quality of a material decrease in accordance with each loop [28].

Critics further argued that an absolute CE for plastics might be thermodynamically infeasible, hence suggesting that the entropic nature of material flows renders any circular system inherently linear [21]. This perspective was supported by analyses indicating that the total energy consumed in circular processes is not always as environmentally benign as it often proclaimed. Nonetheless, the global shift toward renewable energy could mitigate these concerns, to align CE with future energy advances. The journey toward adoption is also complex; barriers to CE implementation for plastics are frequently internal to businesses, while the drivers are external [20]. This dynamic implies that external pressures can hinder even motivated businesses from adopting CE practices. Consequently, effective multi-stakeholder cooperation is widely recognized as essential for achieving CE targets [10].

While CE presents a promising framework for addressing sustainability challenges, significant reservations persist regarding its efficacy and potential unintended consequences. A primary concern, which is often overlooked, is the uncertainty surrounding the complete life cycle of environmental implications, both in the short and long term of circular systems. Some scholars concluded that the distinction between linear and circular models might merely be a temporal delay in environmental impact [12]. However, it remained difficult to understand the nature and scale of this cumulative long-term impact. The waste hierarchy, which prioritizes management options for post-consumer plastics from most to least preferred, is illustrated in Figure 1.

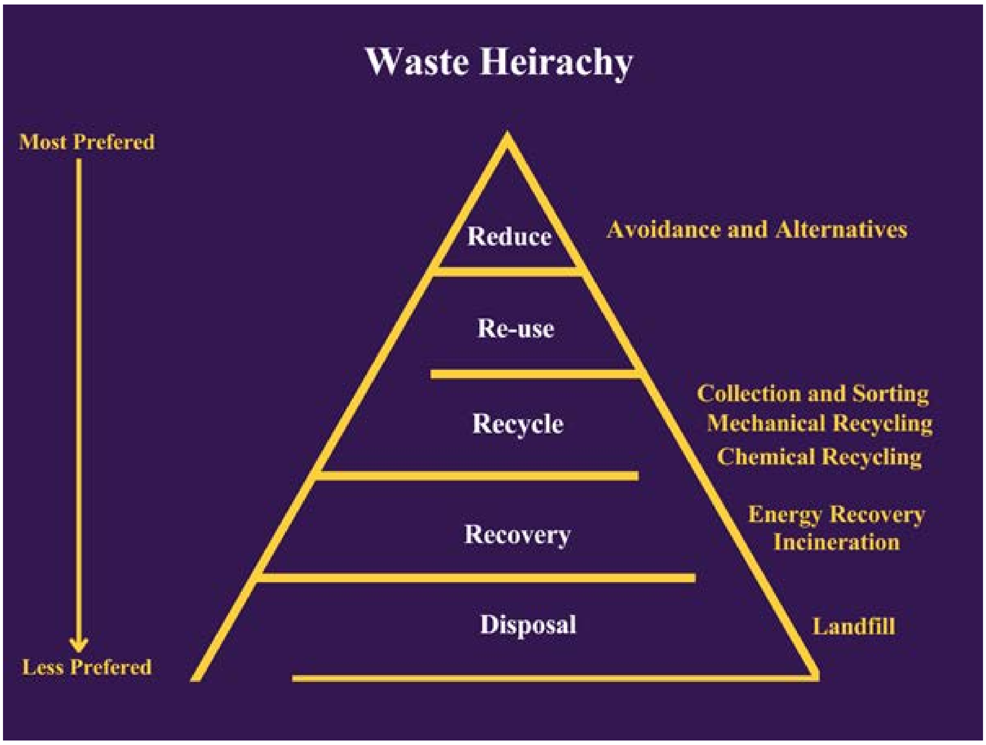

Figure 1. Waste hierarchy pyramid

Despite efforts to promote CE principles, plastic pollution remains a persistent environmental challenge [24]. Achieving a functional CE for plastics requires confronting multifaceted challenges across the entire value chain, from design and manufacturing to usage, recovery, and EoL management. This section examines these interconnected challenges, as well as the emerging opportunities to address them [29].

2.1 Design and Production: Avoidance, Alternatives, and Manufacturing

The design and production phases of plastic consumer packaging are critical for a circular transition. Current systems remain largely linear, prioritizing volume output over material recovery, despite the growing incorporation of alternative materials. Fossil-based plastics retain market dominance due to their economic advantages, though their environmental impacts underscore the urgency of systemic reform [16, 30].

EU strategies such as the waste hierarchy emphasize avoidance and material substitution [16, 30]. However, many producers still neglect Design for Recycling (DfR) principles, hence perpetuating waste accumulation and hindering circularity.

Selection of materials involves critical trade-offs between functionality and sustainability. Bio-based and biodegradable alternatives such as cellulose, starch, and paper present promising pathways, but are often incompatible with existing recycling infrastructure. For example, while easily decomposable, sugarcane-based biopolymers are typically non-recyclable and their utility is limited within a closed-loop system [16]. Large-scale production of bioplastics may also compete with food supply chains, thus introducing ethical concerns. Similarly, the expanded use of paper-based packaging risks increased pressure on forests and land resources, with potential offset of environmental benefits.

Scalability remains a key challenge for innovative materials. Second- and third-generation bioplastics derived from agricultural residues or food waste offer considerable potential, yet constitute a minor share of global plastic production and face integration barriers with conventional recycling streams [31]. Substitution with materials such as aluminium or glass introduces new complications; the study [32] noted that such alternatives could triple packaging weight, hence increasing energy demands during production and transport. Although recyclable, these materials carry substantial embodied energy and carbon footprints, leading to diminished appeal within a CE framework.

Nevertheless, certain strengths exist within the current systems. Some biodegradable plastics can reduce landfill burdens, and emerging feedstocks such as algae-based polymers demonstrate innovative potential [11]. Traditional plastics remain cost-effective and functionally versatile but are misaligned with recovery processes, forming a fundamental obstacle to circularity. Material substitution efforts highlight unavoidable trade-offs among energy, cost, and environmental impact [32].

In summary, the design and production phase involve complex tensions between established systems and promising alternatives. A coherent strategy integrating DfR, material innovation, and scalable infrastructure is essential to advance circularity in plastic packaging.

2.2 Plastic Use: Consumer Behaviour and Perception

Consumer behaviour critically shapes the lifecycle of plastic packaging. Initiatives such as plastic bag charges and Deposit Return Schemes (DRS) demonstrate the potential of economic incentives to promote sustainable practices [4]. However, broader progress is hindered by low consumer awareness, habitual behaviours that prioritize convenience, and structural barriers.

A central issue is the limited public understanding of both the environmental impacts of single-use plastics and the principles of circular behaviours. Despite outreach efforts, many consumers remain unaware or unconcerned, influenced by the convenience and the low cost of disposable plastics. Furthermore, inconsistent recycling systems and ambiguous labelling generate consumer uncertainty, leading to contamination of recycling streams and exacerbating inefficiencies in recovery systems.

2.3 Disposal: Collection and Sorting

The collection and sorting phase is critical for determining the quality, purity, and yield of recyclable plastics, thus directly influencing the efficiency of downstream recycling processes and the viability of secondary material production. Despite its pivotal role, this phase faces persistent technical, economic, and operational challenges that impede optimal performance and require innovative and scalable solutions.

Conventional sorting technologies, including manual sorting, automated optical sorting (AOS), and near-infrared (NIR) spectroscopy, have improved operational efficiency but remain limited in scope [33]. For instance, NIR-based systems cannot accurately identify black plastics due to pigment-induced infrared absorption, leading to their systematic diversion to incineration or landfill [33]. Furthermore, these methods struggle to differentiate multi-layered and composite plastics, which are increasingly prevalent in packaging applications. Emerging technologies such as tracer-based sorting (TBS), which uses fluorescent markers to identify polymer types and intended uses, are promising to address these gaps. However, high capital costs and the extensive retrofitting required for material recovery facilities (MRFs) currently limit the widespread adoption of TBS [34].

Contamination presents another major impediment to high-quality sorting. Additives such as flame retardants, colorants, and stabilizers, commonly used to enhance material performance, can compromise the quality of recycled output [16]. Current purification methods, including mechanical washing and thermal processing, often fail to achieve the purity levels required for closed-loop recycling, resulting in down-cycled materials or disposal.

Inconsistencies in collection systems further exacerbate sorting challenges. The absence of standardized collection frameworks in many regions leads to commingled and contaminated waste streams, thus complicating subsequent sorting processes. This issue is especially acute in low- and middle-income countries, where informal waste collection predominates and investment in advanced sorting infrastructure is limited. The proliferation of new plastic types, including biodegradable and compostable variants, introduces additional complexity, as these materials often require separate processing streams to avoid compromising conventional recycling systems.

Economic barriers are also decisive. Investments in advanced sorting technologies are frequently deemed economically unviable, particularly in regions with low waste collection rates or limited regulatory support. This financial constraint underscores the need for cost-effective and scalable solutions that could bridge the gap between technological innovation and practical implementation.

In summary, while effective sorting is indispensable for improving recycling rates, significant challenges such as inconsistent feedstock quality, material diversity, and economic constraints remain. Addressing these barriers through technological innovation, standardized systems, and strategic investment is essential to advancing circularity in plastic waste management.

2.4 Recycling

Recycling plays an indispensable role in realizing a circular economy for plastics, yet progress remains unsatisfactory. In Europe, only 4 million tonnes (Mt) of the estimated 29 Mt of plastic waste generated in 2019 were effectively recycled, while 20Mt were incinerated or landfilled [35]. Despite offering employment opportunities and potential cost savings, the recycling sector remains underutilized [36]. Although recycling supports Sustainable Development Goals (SDGs) through both open- and closed-loop approaches, significant barriers persist. Key challenges [5] include contamination, variable material quality, underdeveloped markets for recycled materials, and negative consumer perceptions. The quality of recyclates is largely determined during the product design and manufacturing phases. Furthermore, recycling processes themselves entail environmental trade-offs; in some cases, preferred methods may inadvertently favour linear economy approaches over more energy-intensive chemical recycling. While polymers such as HDPE, PP, and PET are routinely recycled, others including LDPE, PS, and PVC face substantial technological, economic, and structural barriers.

Mechanical recycling has been extensively examined in the literature [37, 38]. For instance, the study [38] demonstrated that virgin polymers could exhibit significantly lower environmental impacts, sometimes by a factor of four compared to their recycled equivalents. While the study [39] acknowledged that mechanical recycling offered environmental advantages over linear disposal pathways, they argued that source reduction and reuse represented more sustainable strategies. Efficient mechanical recycling requires advanced sorting technologies, though the diversity of plastic grades and types continues to pose challenges. Although PET and unpigmented HDPE remain economically viable, logistical complexities and energy consumption present ongoing concerns [6]. As emphasized, robust collection systems and recycling innovations were essential for effective eco-design; they noted that mechanical recycling often proved more cost-effective than alternative technologies despite higher production costs [10].

Chemical recycling including pyrolysis, solvolysis, and gasification has also been widely investigated [40, 41]. Pyrolysis demonstrates flexibility in processing mixed plastics but faces criticism for complex reaction chemistry, variable output quality, and a dependence on high-volume inputs [34]. Gasification can accommodate diverse feedstocks but may emit toxic by-products and lacks efficient pathways for monomer recovery [42]. Solvolysis enables molecular degradation for specific polymers but is sensitive to contaminants and requires extended processing times. Although concerns remain regarding environmental performance and economic viability, particularly due to high energy intensity and costly catalysts, chemical recycling may help improve overall recycling rates [43]. Its primary value lies in complementing existing mechanical processes, despite current limitations in polymer compatibility and operational scalability.

2.5 Incineration

Incineration provides an alternative disposal pathway for non-recyclable plastic waste, diverting material from landfill and enabling energy recovery. However, this approach raises significant environmental concerns, primarily due to emissions of greenhouse gases (GHGs) and other pollutants. Studies suggest that approximately 70% of plastic waste may be suitable for energy recovery through incineration [3, 8]. Beyond environmental impacts, which are influenced by factors such as collection efficiency and feedstock composition, the economic feasibility of incineration is a crucial determinant of its viability as a waste management strategy. Ultimately, achieving a successful circular economy for plastics requires a clear understanding of commercial incentives and stakeholder capacities, as business motivations significantly influence the transition toward circular practices.

2.6 Policies

In 2018, the European Union produced 62 million tonnes of plastic, 40% of which was for packaging; however, only 6% of this plastic packaging waste was reintegrated into the value chain [3, 35]. Manufacturers face substantial recycling challenges due to low profitability, which discourages investment, coupled with the intensive effort required for waste processing. These factors often render recycled materials more expensive than virgin plastics [44]. Proactive Recyclable Design (PRD) encounters obstacles from rapidly evolving technologies and conflicting product requirements [45]. While Extended Producer Responsibility (EPR) frameworks aim to incentivize waste reduction by shifting management obligations to producers [36], their effectiveness is often hampered by complex product designs that hinder recycling efforts [14].

Eco-design principles promote environmentally conscious product development, though some approaches that advocate for designed decomposition may conflict with the goal of maintaining material value within a CE [15]. Broader barriers to effective CE implementation include supply chain ambiguities, high production costs, and limited consumer awareness. Furthermore, technological advancements, market dynamics, and environmental considerations significantly influence organizational adoption of circular models [27], prompting government initiatives to address commercial barriers and promote circular material flows.

Paradoxically, China's 2017 restrictions on waste imports accelerated the transition toward circular economy practices in Europe, complementing existing goals for resource conservation and landfill reduction [15]. EU policies, such as the Circular Economy Package, establish ambitious targets, including recycling rates of 65% -75% for municipal and packaging waste and a landfill limit of 10% by 2030 [46]. Policy instruments include bans, taxes, and EPR schemes. Early plastic taxation measures, for instance, proved ineffective until the financial burden was shifted to consumers through direct levies. Policy approaches vary globally: China's comprehensive national CE strategy contrasts with the EU's more targeted regulatory focus, while other nations like Portugal emphasize environmental certification programs to promote sustainability [14]. Despite many countries having developed CE policies, implementation remains fragmented, and inadequate stakeholder accountability persists. Achieving meaningful progress necessitates comprehensive behavioural changes at both local and international levels [3].

2.7 End-of-Life (EoL)

The circular economy model for plastics aims to extend material utility through strategies including closed-loop recycling, upcycling, and downcycling, thereby prolonging the residence time of materials within the economic system. Despite these efforts to minimize EoL waste, the inevitable generation of residual materials from products lacking feasible reuse or recycling pathways presents an ongoing challenge to achieving complete circularity.

This review has identified multiple systemic barriers that impede the development of an efficient circular economy for plastics. While existing desk research has established a foundational knowledge base for CE implementation [22], the current literature remains fragmented. Most studies focus selectively on isolated aspects of CE, such as specific lifecycle phases [47], environmental concerns, technological innovations, economic feasibility, or particular polymer types, offering a somewhat siloed perspective. Furthermore, recent research has predominantly emphasized anthropogenic health implications [48], while the study [49] developed a conceptual framework for evaluating plastic recycling value chains through a systematic review.

Although these phase-specific investigations provide valuable insights, they frequently overlook the critical interconnections and systemic interactions between different stages of the plastic value chain. Many downstream challenges are, in fact, rooted in decisions made during early design and production phases. This study aims to address this research gap by employing an integrated, systems-level approach to circular economy implementation for plastic packaging. By identifying and analysing barriers and opportunities across all lifecycle phases, this research seeks to contribute to the development of a holistic CE framework. The methodological approach designed to address this knowledge gap is detailed in Section 3.

3 Methodology

Research on the CE for plastics requires methodological pluralism to capture its complex technical, economic, and social dimensions. Previous studies have adopted various approaches. For instance, the study [26] employed qualitative methods to emphasize policy's critical role in overcoming CE barriers for packaging plastics, while the study [45] utilized a systematic review to highlight systemic issues such as data insufficiency and the importance of the design phase. However, the latter approach lacked the qualitative depth needed to explore stakeholder perspectives. To address this limitation, the present study adopts a mixed-methods approach, integrating a systematic literature review with qualitative expert interviews. This design facilitates a comprehensive analysis, combining documented evidence with nuanced, practical insights from industry experts to enable a more holistic understanding of the challenges and opportunities in developing a CE for PCPP.

The systematic review component of this study was guided by the PRISMA guidelines to ensure a transparent and rigorous selection process, drawing inspiration from the methodologies of studies [49, 50]. The process involved identifying records through database searches in Web of Science and citation tracking, screening them based on titles and abstracts, and performing a full-text eligibility assessment. Searches were conducted using a combination of keywords, including "circular economy", "plastic*", "recycling", and "packaging", covering literature published between 2018 and 2025.

Figure 2 illustrates the PRISMA flow diagram. The search strategy identified 1,316 records from databases and an additional 5 through citation searching. After the removal of duplicates, 994 studies were screened by title and abstract. This initial screening phase led to the exclusion of 540 records. The full texts of the remaining 454 articles were assessed for eligibility, resulting in the exclusion of 404 articles for reasons such as an insufficient focus on CE challenges, a lack of empirical data, or inapplicability to the PCPP value chain. Ultimately, 55 studies met all inclusion criteria and were included in the qualitative synthesis.

Exclusions were based primarily on relevance and methodological rigor. Key reasons for exclusion included an insufficient focus on CE challenges, weak methodology, a lack of empirical data or case studies, and proposed solutions not directly applicable to PCPP. Studies were also excluded due to omitted critical barrier analyses, duplication of findings, or inaccessible full texts. This stringent process ensured the inclusion of only high-quality, pertinent studies.

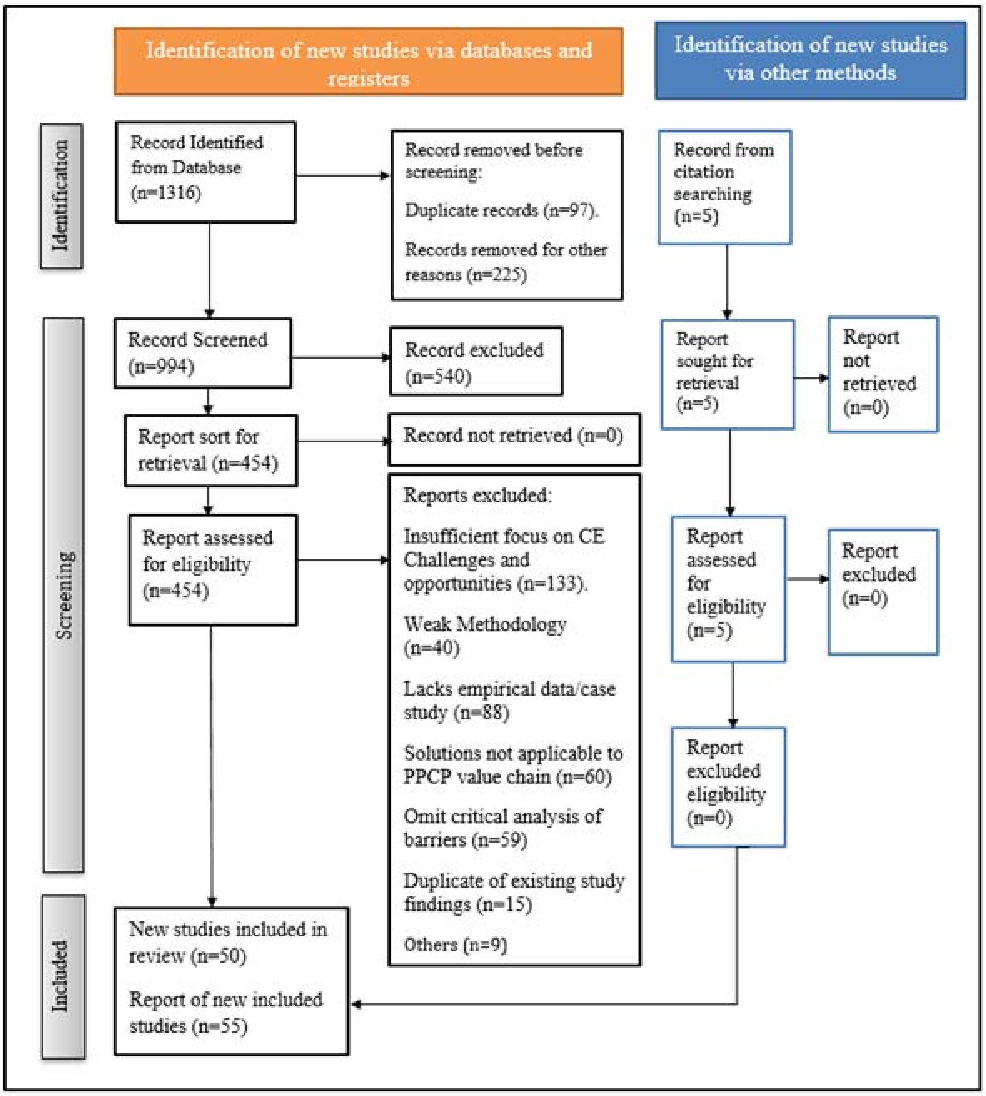

Figure 2. Systematic review methodology using PRISMA flow chart [49–51]

To complement the systematic review and address its inherent limitations in capturing current perspectives, a qualitative approach was employed. Semi-structured interviews were conducted with three key experts to elicit in-depth, contemporary insights into the practical challenges and opportunities for advancing a CE for PCPP. The expert panel comprised a Professor of Waste Management, a Professor of Engineering specializing in bioplastics, and an Innovative Manufacturing Expert. While the initial recruitment target was 10 participants, the three in-depth interviews conducted are deemed sufficient for generating rich, nuanced data in exploratory qualitative research [52], where the depth of insight is often prioritized over sample size.

3.1 Interview Data Analysis

The interview data were analysed using thematic analysis. Following transcription, an initial inductive coding phase identified emergent themes directly from the data. These themes were subsequently refined and aligned, through a deductive phase, with key categories established from the systematic review [53, 54]. This hybrid inductive-deductive approach facilitated the integration of novel, data-driven insights with concepts from the existing literature, ensuring findings were both grounded and contextualized.

To enhance analytical rigor, methodological triangulation was employed by cross-validating themes across the interview data and the systematic review findings. This comparative analysis revealed significant points of convergence, such as a strong consensus on the critical importance of design-for-recyclability. It also highlighted key divergences; for instance, experts placed a greater emphasis on industrial-scale infrastructure gaps, an issue that was comparatively underrepresented in the published literature.

3.2 Mitigation of Bias and Enhancement of Rigour

To enhance the credibility and trustworthiness of the qualitative findings and mitigate potential biases, several validation strategies were employed. Triangulation was a primary method, whereby themes from the interviews were systematically cross-referenced with findings from the systematic literature review [45, 55]. This process contextualized individual expert perspectives within the broader scholarly discourse. Participant validation was also utilized by sharing summarized key interpretations with interviewees to confirm accuracy. Furthermore, a clear audit trail, documenting the analytical process from raw transcripts to final themes was maintained to ensure transparency and allow for the scrutiny of conclusions.

While the sample size of three experts is acknowledged as a limitation, the strategic selection of participants across complementary domains of the plastic value chain (waste management, material science, and manufacturing) provided a multifaceted, in-depth perspective on CE for PCPP. The insights from these interviews were systematically integrated with evidence from the literature review. This convergence of quantitative bibliographic data and qualitative expert opinion enabled a comprehensive and nuanced analysis, which is presented in Section 4.

4 Results and Discussions

4.1 Results

The results of the systematic literature review are summarized in Figures 3, 4, 5, and 6. The initial search identified 1,361 articles. After the initial screening, 994 English-language publications from the period 2018-2025 were retained for further evaluation. These were refined based on relevance to the research objectives, resulting in 454 articles for full-text assessment. Following this assessment, 50 studies that directly addressed specific phases of the circular economy for plastic waste management were selected for in-depth analysis.

The final 50 studies were categorized according to the seven distinct phases of the plastic circular economy value chain. Five additional relevant articles were identified through citation snowballing, reinforcing and complementing the core selection. This rigorous process ensured the inclusion of pertinent, high-quality literature. A detailed analysis of the findings from these articles is presented in Section 4.2.

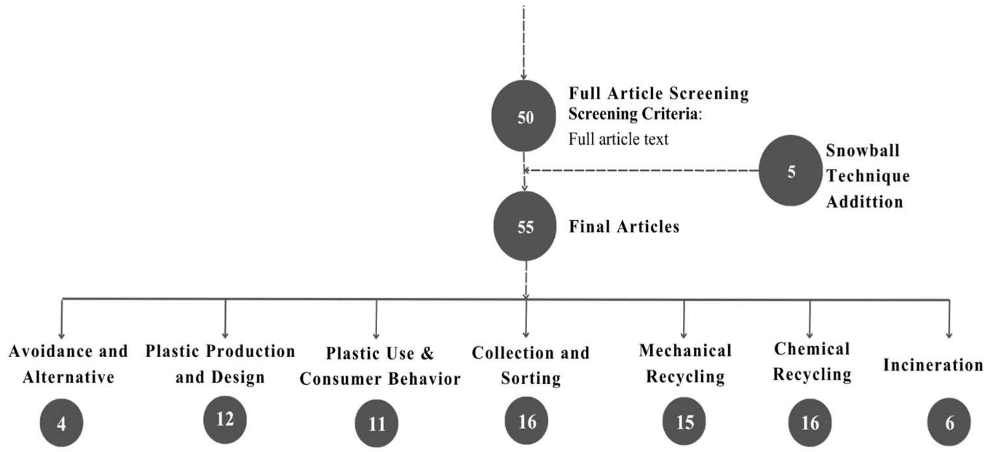

Figure 3. Overview of systematic review result

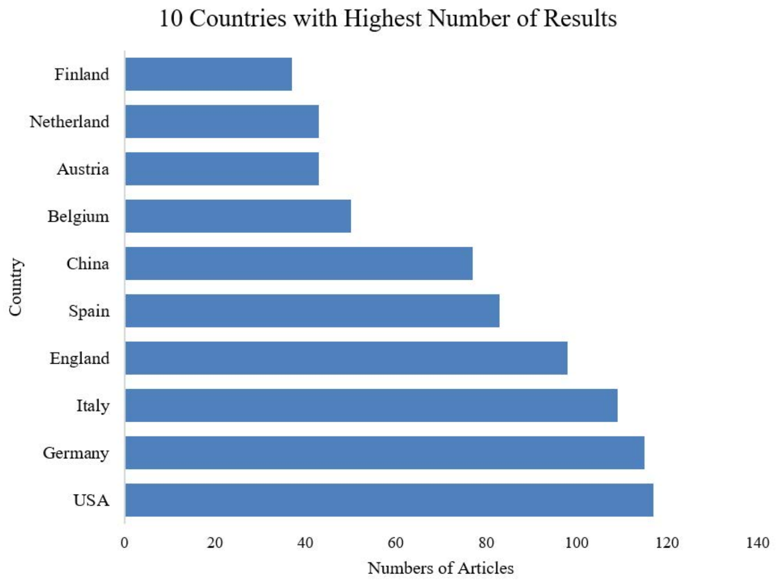

Figure 4. Top 10 countries with highest number of articles from search result

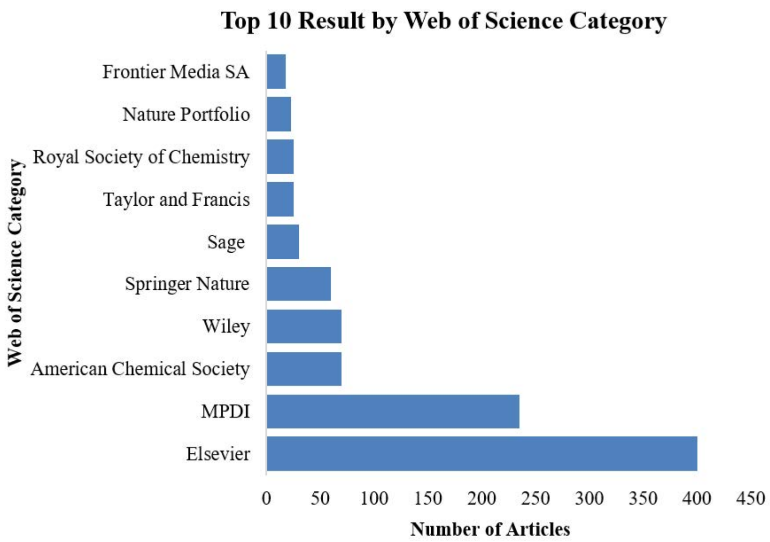

Figure 5. Top 10 Web of Science categories from search result

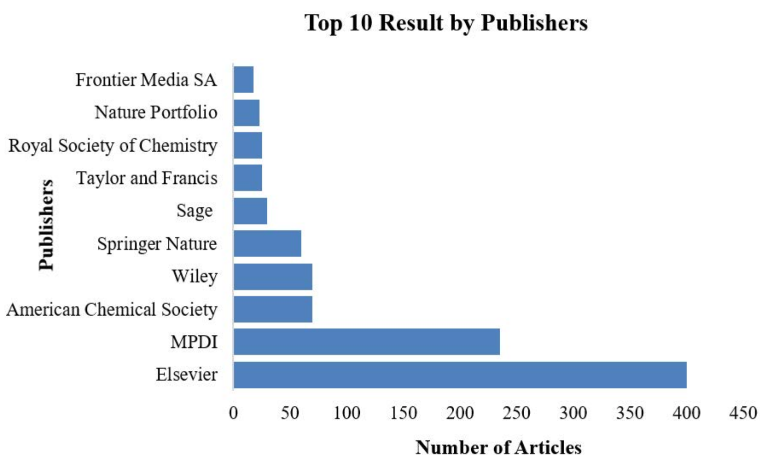

Figure 6. Top 10 publishers with highest number of articles from search result

4.2 Discussion of Results

This discussion synthesized evidence from a systematic review of 55 relevant studies and qualitative expert interviews to critically analyse challenges and opportunities across the PCPP value chain. Building upon the foundational knowledge established in the literature review (Section 2), this analysis introduced novel perspectives, emergent themes, and critical tensions identified through this integrated and system-level approach. The discussion was structured around the waste hierarchy (prevention, reuse, recycling, and recovery) to evaluate the relative efficacy of each strategy within a holistic circular framework.

4.2.1 Design and production

Although the literature firmly established eco-design (DfR, DfS) as a cornerstone of the CE [29, 56], this analysis revealed a persistent implementation gap between its theoretical principles and widespread industrial adoption. This gap was exacerbated by a scarcity of research; this systematic review identified few studies [57, 58] that directly addressed the operational challenges of scaling these designs. The literature predominantly identified a critical commercial tension between performance demands, cost-effectiveness, and recyclability [17, 59]. This is not merely a technical barrier but a strategic one, where prevailing economic models favour virgin materials to create a pervasive disincentive for upfront investment in advanced eco-design.

Moreover, our interview data introduced a crucial dimension underemphasized in the literature: the centrality of energy considerations in material selection. One expert in innovative manufacturing noted that the pursuit of novel alternatives, such as advanced bioplastics, should be rigorously evaluated against their entire lifecycle energy footprint, encompassing processing, performance, and EoL management. This insight critically nuanced the prevailing discourse on material innovation [30, 31], thus suggesting that a narrow focus on feedstock sustainability (e.g., bio-based origin) without concurrent analysis of energy-intensive processing could yield suboptimal environmental outcomes. Therefore, this research contended that effective design for a CE necessitates integrating material science with energy systems analysis, a holistic approach that remains emergent in both literature and practice.

4.2.2 Plastic use and consumer behaviour

While the literature correctly identifies inadequate consumer awareness and confusing labelling as key barriers [4, 26], our analysis demonstrates that consumer action is fundamentally constrained by systemic failures. The reviewed studies [60, 61] consistently show that even environmentally motivated consumers encounter fragmented, inconvenient, and unreliable systems. The critical insight from this synthesis is that the primary burden of circularity cannot rest on consumers in the absence of accessible and reliable infrastructure.

Therefore, this analysis reframed the core challenge from one of "consumer education" to one of fundamental systemic redesign and enabling policy. Initiatives such as Deposit Return Schemes (DRS) and reuse incentives are promising [62]; however, their efficacy is contingent upon seamless integration into municipal waste management systems and robust regulatory backing. The evidence indicated that without this essential top-down support, bottom-up behavioural change remained inefficient and limited in scale. Consequently, consumer behaviour is positioned not as an independent driver, but as a dependent outcome, shaped predominantly by the design of the encompassing policy and infrastructure system.

4.2.3 Disposal: Collection and sorting

The analysis identified collection and sorting as the most significant technical bottleneck in the PCPP value chain; this is a finding strongly corroborated by a professor of waste management. While the literature extensively documented technological solutions like Tracer-Based Sorting (TBS) and NIR spectroscopy [34, 63], this analysis highlighted a more fundamental barrier: the prohibitive cost and infrastructural inertia that prevent their widespread adoption [17, 64].

A key insight from this synthesis is the critical interdependence between the design and sorting phases. The proliferation of multi-material packaging [29] creates sorting complexities that even advanced technology struggles to resolve economically. This establishes a vicious cycle: complex packaging designs lead to inefficient sorting, which yields low-quality recyclate. The resulting diminished economic value of recycling, in turn, disincentivizes investment in advanced sorting facilities. Therefore, this research concludes that breaking this cycle necessitates robust policy interventions. Stringent Extended Producer Responsibility (EPR) schemes are critical, as they compel producers to internalize the EoL costs of their design choices, creating a direct financial incentive for simplicity and mono-material structures.

4.2.4 Recycling: Mechanical and chemical

The systematic review offers a nuanced critique of mechanical and chemical recycling, challenging the simplistic narrative that often positions one method as superior to the other.

For mechanical recycling, the synthesis confirms its economic and environmental advantage for clean, single-polymer streams such as PET and HDPE [10]. However, it foregrounds a fundamental limitation: mechanical recycling is intrinsically a downcycling process [65]. Thermo-mechanical degradation causes a cascading decrease in material quality with each cycle, fundamentally contradicting the CE ideal of maintaining value. This finding repositions mechanical recycling not as a closed-loop solution, but as a means of delaying final disposal.

The analysis of chemical recycling across multiple studies [40, 66, 67] reveals it is far from a panacea. Its primary value lies in handling contaminated and complex plastic waste that mechanical processes cannot, thereby diverting it from incineration or landfill. Yet, the findings consistently highlight major drawbacks, including prohibitive energy intensity, high operational costs, and concerns regarding chemical safety and output quality. Consequently, the relationship between the two methods should be viewed as complementary and sequential. Mechanical recycling must be prioritized for suitable waste streams to conserve resources, while chemical recycling should be developed as a targeted, niche solution for problematic plastic waste that currently has no viable recovery pathway.

4.2.5 Incineration: A pragmatic, though limited, role in a circular system

While the core tenets of a circular economy rightly prioritize keeping materials in use, a purely ideological dismissal of incineration fails to address the practical realities of contemporary waste streams. Incineration with energy recovery (WtE) is undeniably a linear and end-of-pipe process, a fact well-documented in the literature [60, 64]. However, a more nuanced analysis positions it not as a goal, but as a critical damage-control mechanism within an imperfect system.

The reviewed evidence indicated that for specific problematic waste streams, particularly non-recyclable, heavily contaminated, or complex composite plastics, modern WtE serves as the least environmentally damaging option when the only alternative is landfilling. This comparison is crucial. Landfilling organic waste generates methane, a potent greenhouse gas with a global warming potential many times that of CO_2. In contrast, state-of-the-art WtE facilities the destroy of methane-generating potential and can offset fossil fuel consumption by generating electricity or district heat, leading to a net reduction in greenhouse gas emissions for these non-recyclable fractions.

Consequently, this analysis argued for a recalibrated view of WtE. Its role is not to compete with recycling for high-quality materials but to function as a managed endpoint for what is currently unrecoverable, as it exists further down the waste hierarchy. It acts as a necessary backstop, preventing waste from entering the environment as landfill leachate or marine debris while extracting residual energy value. This function represents a pragmatic, transitional necessity. Therefore, its continued use must be coupled with relentless upstream efforts in design, collection, and recycling innovation to progressively shrink the waste stream destined for thermal treatment. Acknowledging this limited and diminishing role is essential for a realistic and responsible transition towards a circular economy.

4.2.6 Overview of an effective CE for PCPP

By integrating a systematic literature review with qualitative analysis, this study systematically identified key challenges and solutions across all phases of the plastic circular economy, as summarized in Table 1. The analysis emphasized their critical interconnectedness in Figure 7, and demonstrated how efficiency gains in one phase could directly mitigate challenges in subsequent phases.

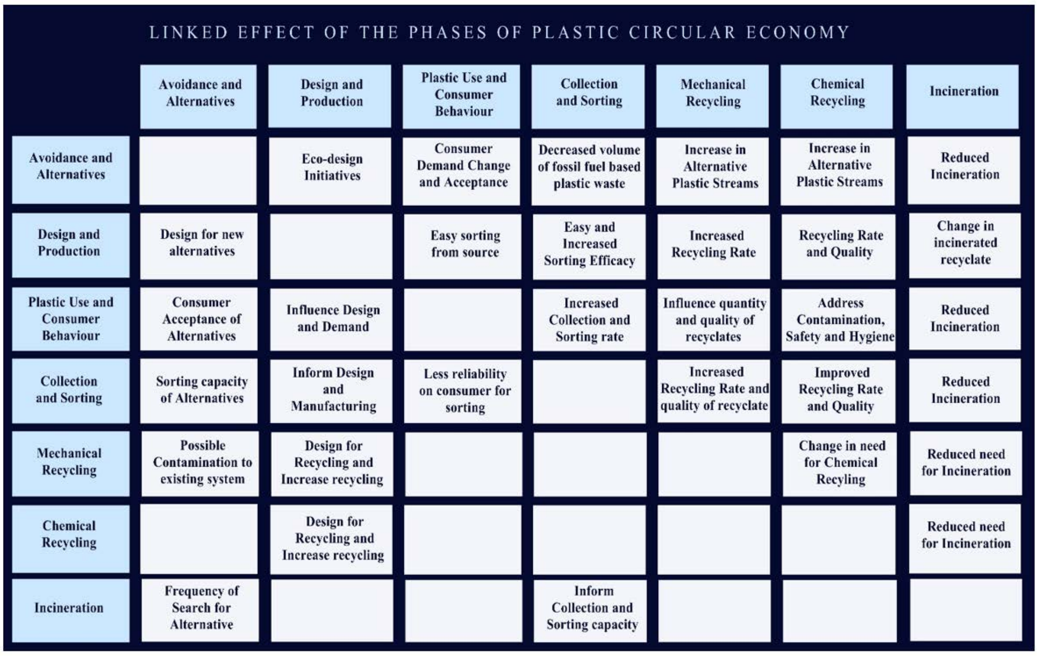

Figure 7. Linked effect of plastic circular economy phases

Table 1. Summary of challenges in CE and recommended solutions for improved efficiency

CE Phases	CE Challenges for PCPP	Recommended Solutions for Effective CE for PCPP
Avoidance and alternatives	Lack of cost effective and sustainable alternative [29, 65].	Research and Development for more sustainable, functional, and cost-effective alternatives.
	Alternatives are still novel and developing like Algal biomass and other bioplastic streams [59, 64].	Increased research and development for novel alternatives.
	Alternatives might contaminate existing fossil fuelbased recovery systems [30].	Existing systems should be developed to delineate novel alternatives.
Manufacturing and design	Health issues from toxic additives [66].	Transparency regarding the use of chemicals and their effect [68].
	Complex design (use of multipolymers and other non-plastic materials) [60, 67].	Simple and easily recyclable designs like eco-design, Life Cycle Thinking (LCT), Design for Sustainability (DfS), Design for Remanufacture (DfM) [29, 69].
Plastic use and consumer behaviour	Lack of consumer knowledge about plastic types, recycling, and their role [17, 26].	Behavioural transition through consumer awareness, incentives, and regulations [60, 70].
	Unsustainable consumer behaviour and perception [4, 60, 65].	Returnable/Reusable Packaging, Refill possibilities [17, 62].
Collection and sorting	Cost of Collection and Sorting [17, 64, 65].	Enhanced collection and sorting systems.
	Inefficient management and monitoring of waste collection systems [60, 66, 67, 71].	Harmonized collection and sorting standards, Extended Producer Responsibility (EPR) policies [72].
	Multi-polymer/ Mixed material sorting problems [29].	Racer-based sorting for easy multi-polymer types [73].
	Poor and Inefficient Sorting Technique [65].	Automation, Enhanced sorting technology like Near and mid-infrared spectroscopy [74].
	Potential Contamination and Reduced Sorting efficiency [26].	Improve source segregated waste and Extended Producer Responsibility [75].
	Inadequate Resin Characterization Database [57, 71].	Development and Promotion of Standardize Collection and Sorting Techniques [71].
Mechanical recycling	Reduced quality from thermomechanical degradation [30, 57, 60, 64].	Wet mechanical recycling, upstream washing processes, etc [76].
	Contaminants from plastics (multi-layered materials) and non-plastics (foils, metals, and aluminium, etc) [29, 60, 65].	Improved sorting capacity and other pre-processing phases like design and manufacturing [77].
	Market and Price Instability of Recyclates [72]. Supply chain of inputs [67, 70].	Government regulations and effective monitoring Improved collection and sorting systems [74].
Chemical recycling	Cost effectiveness [29].	Reduce energy consumption and commercialization
	Reduced mechanical properties of the material (Downcycling) [63, 69].	Improved Research and Development [77].
	Energy Intensive [61, 71].	Improved processes.
	Low Technological Readiness Level [78].	Improved Research and Development to support commercialization.
	Chemical Safety Concerns [65, 66].	Transparency regarding the use of chemicals and their effect [68].
Incineration/energy optimization	Energy recovery capacity [67].	More research into the benefit-risk-ratio and novel technology like 3D filament printing.
	Environmental concerns (bottom ash, POPs, GHGs, microplastics, etc.) [61, 64, 71].	Utilisation of renewables and other sustainable energy source with less emission.

5 Conclusions

In conclusion, achieving a viable CE for post-consumer plastic packaging (PCPP) necessitates an integrated and system-level approach across the entire product lifecycle. The design and production phase are foundational, as prioritizing selection of sustainable materials and recyclability fundamentally determines the downstream efficacy of sorting, collection, and recycling processes. Concurrently, enabling informed consumer behaviour is critical for reducing waste generation at the source and ensuring the quality of collected materials. Furthermore, the establishment of robust collection and sorting infrastructure, enhanced by advanced technology and multi-stakeholder collaboration, is indispensable for generating high-quality feedstocks. The efficiency of subsequent recycling processes is paramount for retaining material value within the economy and minimizing environmental impacts. For managing non-recyclable fractions, modern incineration with energy recovery provides a necessary transitional solution, mitigating the environmental burden of landfill. Ultimately, a systemic strategy that synergistically leverages technological innovation, supportive policy, and engaged stakeholder action at each phase of the lifecycle is imperative to close the loop and realize a sustainable CE for PCPP.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The author declares no conflict of interest.

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