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Innovative recycling strategies for non-recycled plastics: advancing the circular economy for a sustainable future

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Plastic waste presents a critical environmental challenge, with reports of global production surpassing 390 million tons annually and an effective recycling rate of less than 10%. This study investigates advanced recycling methodologies aimed at mitigating plastic waste and promoting a circular economy. Mechanical, chemical, and emerging advanced recycling technologies are evaluated based on efficiency, scalability, and environmental impact. Mechanical recycling achieves material recovery rates up to 60%, accompanied by a 30% reduction in greenhouse gas emissions compared to virgin plastic production; however, polymer contamination and degradation restrict its long-term effectiveness. Chemical recycling processes, including microwave-assisted pyrolysis and enzymatic plastic depolymerization, demonstrate recovery efficiencies exceeding 90%, producing high-quality feedstocks suitable for industrial reuse. Life-cycle assessments reveal that chemical recycling can reduce environmental footprints by approximately 45% relative to conventional disposal practices. Advanced recycling technologies, such as enzymatic and catalytic hydrocracking, blockchain-enabled plastic waste tracking, and bioplastic waste valorization conversion, exhibit conversion efficiencies ranging from 85 to 95%, though scalability remains limited by economic and technological constraints. Integration with digital innovations, such as AI-enabled waste sorting and blockchain-based supply chain transparency, enhances material recovery rates by up to 20%. Policy instruments, notably extended producer responsibility (EPR) schemes and consumer engagement initiatives, further reinforce recycling outcomes. Case studies from Europe and Asia demonstrate landfill diversion rates reaching 75%, underscoring the effectiveness of integrated approaches. The analysis highlights the urgent necessity for multifaceted recycling strategies to curb the escalating plastic waste crisis and facilitate a transition toward a sustainable circular economy. Through the strategic application of technological advancements and policy interventions, it is feasible to achieve a 50% reduction in global plastic waste by 2030, thereby contributing significantly to environmental protection and resource conservation, while mitigating climate change impacts.

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Sustainability spotlight

This study proposes cutting-edge recycling strategies for non-recycled plastics, addressing one of the most persistent challenges in waste management. By integrating technological innovation with circular economy principles, the work offers actionable pathways to reduce plastic pollution, recover valuable materials, and minimize environmental impacts. It contributes to global climate change mitigation efforts by unlocking new opportunities for circularity in the plastics value chain.

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1. Introduction

The global surge in plastic production, exceeding 450 million tons annually with a 4% growth rate, presents critical environmental and sustainability challenges.[1] Valued for its durability and cost-effectiveness, plastic is pervasive in packaging and consumer goods. However, its environmental persistence and ineffective waste management have intensified ecological degradation. In India, approximately 5.6 million tons of plastic waste (PW) are discarded annually, with a daily generation of 15 300 tons.[2] Mitigating plastic pollution is essential for achieving the United Nations Sustainable Development Goals (SDGs), specifically SDG#12 (responsible consumption and production), SDG#13 (climate action), and SDG#14 (life below water).[3,4]

In Japan, approximately 50 000–75 000 tonnes per annum (TPA) of non-recycled plastic waste remain unrecoverable through mechanical recycling, with projections indicating an increase to 100 000 TPA by 2025. Landfilling remains the predominant disposal method; however, it is unsustainable due to plastics' extremely slow degradation rates and limited land availability.[5] Landfilling also represents a significant loss of energy resources, as plastics are derived from crude oil. Alternative disposal by incineration is practiced but leads to the emission of hazardous gases, including N_2O, SO_2, and dioxins, posing serious environmental and health risks.[6] People have continued to rely on incineration and landfilling processes, highlighting the urgent need for more sustainable plastic waste approaches like energy recovery and chemical recycling approaches. Fig. 1 shows the details of different plastics, with their volume and quantities.

This can minimize environmental burden/impact with conservation of valuable natural resources. People have developed innovative techniques for end-of-life PWs, essential for promotion of circular economy principles with achievement of long-term environmental sustainability.[5,6] A preliminary study found that the escalating accumulation of PWs poses significant risks to marine and terrestrial ecosystems.[7] The key concerns of microplastic accumulation and contamination are reported to be associated with its long-term persistence in the environment. Inadequacy in the current plastic waste (PW) management infrastructure is reported to be a big challenge. These challenges underscore the urgent need for well-developed advanced recycling approaches with implementation for PW mitigation. Inadequate response to these issues can undermine global sustainability objectives, accelerate natural resource depletion, greenhouse gases, and biodiversity losses.[8] Recycling initiatives can offer a viable pathway to reduce dependency on virgin feedstock and mitigate ecological degradation. Further, it fosters the transition toward a circular economy.[9]

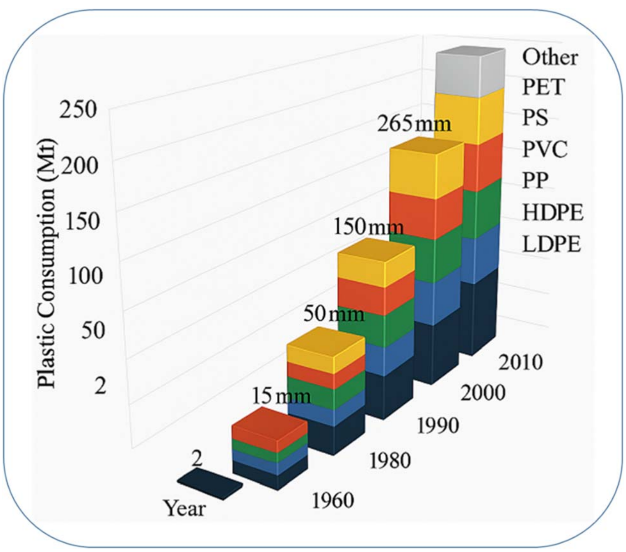

Fig. 1 Non-recycled plastic waste (1950–2010).

Non-recycled PWs constitute a huge quantity of untapped resources, especially when leveraged for energy recovery and fuel production tasks with the help of chemical recycling techniques. These approaches can convert such PWs into synthetic fuels, potential alternatives to fossil-derived crude oils/fuels. This can present a strategic opportunity for localized resource conversion with global implications.[8,9] Next, this approach contributes to GHG emission reduction and decreases reliance on conventional fossil fuels. There are some reports of many nations with substantial PW burdens continuing to import oil; it would be beneficial to equip them with the technical capacity to extract energy from PWs. This can transform PW management with energy security paradigms. Within a circular economy framework, it can achieve high plastic recycling rates, which are instrumental in addressing material scarcity and advancing resource efficiency capacity.[7]

This approach can be further pushed with the support of the integration of a circular plastic economy that needs to apply plastic recycling technologies like chemical, mechanical, and energy recovery techniques. Each modality can offer unique benefits and limitations. Mechanical recycling involves the physical reprocessing of PWs into secondary products without altering chemical structures or polymer chemistry.[10] This technique can typically encompass a series of operation steps such as washing, shredding, separation, drying, pelletizing, and compounding. Further, it can be widely implemented for recyclables like plastics, glass, and paper products.[11] However, the mechanical recycling approach is constrained/limited by polymer degradation over successive cycles, which can result in reduced material quality due to the phenomenon of cascade recycling processes. But, this product can be utilized/repurposed for lower-grade applications.[12] Fig. 2 shows the potential of PWs for new products development *via* utilization of a suitable recycling technique. Plastic waste mitigation was achieved with the circular economy efforts, and it is vital for sustainable development with the aim of minimizing wastes, and maximizing resource efficiency. This can be achieved by reusing, recycling, and regeneration of plastic materials with an effort towards the reduction of environmental impacts, promotion of economic resilience, and conservation of natural resources. This model supports long-term ecological balance while fostering sustainable growth, and innovation across industries, and communities.[13] The chemical recycling technique can offer a transformative approach to PW management by achieving effective depolymerization of polymers into monomers or other high-value products/compounds. Advanced

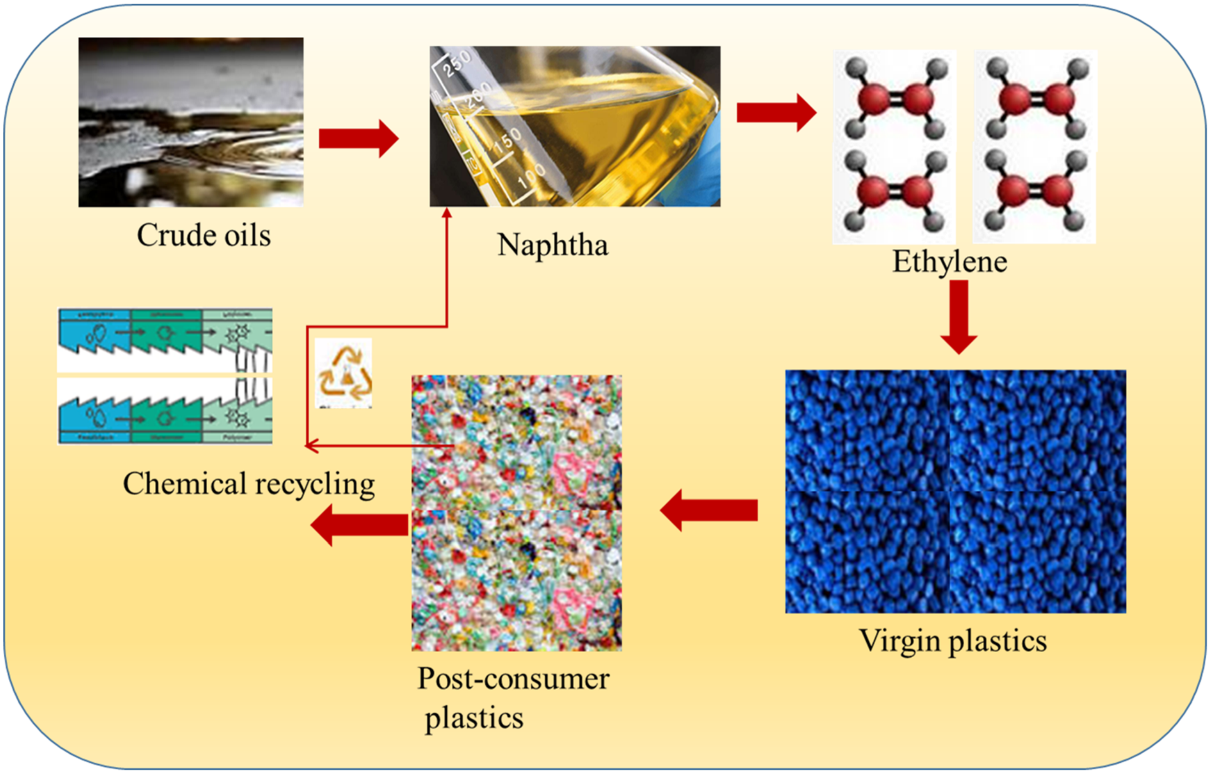

Fig. 2 Circular economy concept toward crude oils and new plastic products.

thermochemical techniques like gasification, and pyrolysis can exemplify this technique.[14] In the pyrolysis process, plastic wastes are subjected to elevated/high temperatures (typically 400–800 °C) under oxygen free/anoxic conditions.

This yields liquid hydrocarbons (like naphtha), gaseous products, and solid residues. Further, these outputs can serve as potential feedstocks for petrochemical synthesis.[15] Gasification, by contrast, involves partial oxidation, and steam reforming at high temperatures (above 800 °C). This approach converts PWs into synthesis gas (a syngas ∼ mixture of primarily H_2 and CO gas), which can be utilized for chemical production, and also energy generation.[16]

The depolymerization process is another chemical route for PW polymer conversion that selectively breaks down into constituent monomers, suitable for direct repolymerization, bypassing intermediate oils/gas stages. This can enable closed-loop recycling.[17] Energy recovery *via* incineration is employed in space-constrained regions to generate electricity, and thermal energy, with countries like Japan and several EU states integrating this into urban waste systems.[18] Despite technological strides, several gaps hinder widespread implementation. Data on long-term scalability, energy efficiency, and environmental emission of these methods/techniques, especially under industrial conditions, remain limited.[19] Energy intensiveness and emission profiles of pyrolysis and gasification are under-characterized in real-world scenarios. Additionally, the degradation kinetics of emerging plastics like bioplastics/microplastics are poorly understood, complicating predictions about their behavior in recycling systems/processes and the environment.[18,19]

Economic viability remains a critical barrier, due to high capital cost, and inconsistent output quality challenges in industrial adoption. Moreover, lifecycle assessments (LCA) of chemical recycling systems are sparse, making holistic evaluations difficult. Policy fragmentation and enforcement deficiency further impede the global integration of these advanced systems.[20] This study seeks to address these gaps by analyzing the techno-environmental, and economic performance of emerging recycling technologies with a focus on catalytic pathways for high-value products recovery. The work contextualizes these innovations within the framework of the UN Sustainable Development Goals (SDGs) and proposes actionable strategies for the scalable, sustainable deployment.[21]

Importantly, this research moves beyond traditional mechanical recycling by integrating catalytic pyrolysis, and other advanced methods. For instance, catalytic pyrolysis using modified natural zeolites (NZ) can yield fractions with beating values of 41.7–44.2 MJ kg^{-1}, comparable to conventional diesel.[22] Recycling approaches can convert one ton of plastic waste into approximately 5.7×10^{-3} kW h of energy, and reduce reliance on virgin feedstock, enabling up to 80% energy savings.[23] This review discusses the catalytic hydrocracking of mixed plastics, enzymatic plastic depolymerization, electrochemical plastic upcycling, and microwave-assisted pyrolysis, which are some innovative approaches for plastic waste mitigation, and recycling to achieve a circular economy. The objective of this study is to achieve comprehensive mitigation of plastic waste through its transformation into newly engineered plastic products.

2. Classification of non-recycled plastics

2.1. Production and uses of plastics for daily applications

Non-recyclable plastics (such as epoxy resins, polyurethanes, phenolic resins, and Bakelite) are primarily thermosetting polymers. These materials undergo irreversible curing processes, resulting in extensive cross-linking that forms permanent covalent bonds resistant to thermal decomposition, and reprocessing.[24] The complete degradation of various plastics is hindered by their complex molecular architectures. Additionally, many non-recyclable plastics exist in the form of composite materials, such as multi-layer packaging. These structures integrate multiple polymer types, and functional additives.[25] This can lead to incompatible interfaces, and strong interfacial adhesion, which significantly impedes mechanical or chemical separation during recycling processes.[24,25] The author examines the environmental implications of large-scale synthetic plastic production, utilization, and subsequent accumulation.

2.1.1. Types and characteristics. Plastics are valued globally for their affordability, sterility, and functional versatility, making them essential in various sectors, including healthcare, consumer goods, packaging, and construction. With annual global production exceeding 460 million metric tonnes (MT), plastic utilization continues to rise across both industrialized, and developing regions.[26] Patterns of plastic waste (PW) generation vary by geography, and are closely tied to socioeconomic development and consumption behaviours. For instance, the United States reports the highest per capita PW generation at 221 kg annually. In comparison, the average for OECD countries such as Belgium and Denmark is 114 kg, while Japan, and South Korea report lower figures at 69 kg per capita.[13,26] Improper collection, disposal, and management of plastic waste have resulted in pervasive environmental contamination. Plastic debris is generally categorized into macroplastics (particles larger than 5 mm), and microplastics (fragments smaller than 5 mm) that originate from the degradation of larger plastics through mechanical, photolytic, or biological processes.[27] Common sources of microplastics include synthetic fibers, tire abrasion, and industrial pre-production pellets, all of which raise significant ecological, and health concerns.[13,25,26]

It is currently estimated that approximately 20 MT of plastic waste enters terrestrial, and aquatic ecosystems annually, with projections indicating a sharp increase by 2040 if mitigation efforts remain insufficient.[28] This persistent accumulation affects marine, freshwater, and terrestrial habitats, disrupts ecological balance, contributes to biodiversity loss, and exacerbates climate change. Marine plastic pollution stems from diverse sources, including urban runoff, maritime transportation, and abandoned fishing gear.[29] Solar radiation, hydrodynamic forces, and microbial action fragment macroplastics into microplastics, and nanoplastics (<100 nm), which are readily ingested by organisms and may bioaccumulate within food webs.[30] Macroplastics constitute approximately 88% of total plastic waste, and are primarily associated with urban, industrial, and mismanaged municipal sources.[29] Plastics derived from fossil fuels dominate markets due to their durability, lightweight nature, and cost-effectiveness. Nonetheless, these very characteristics render plastics environmentally persistent, with degradation timescales extending over centuries.[29,30] Unmanaged plastic waste not only contributes to landscape and aquatic pollution but also facilitates the dissemination of toxic substances and invasive species, intensifying ecological degradation.[31]

Plastic pollution disproportionately impacts vulnerable populations, particularly in regions with inadequate waste management infrastructure. Indigenous communities, and women often face elevated exposure risks. Wildlife is severely affected, with documented cases of ingestion, entanglement, and suffocation leading to injury, impaired mobility, and population decline.[31,32] In Sub-Saharan Africa, for example, disorganized waste disposal practices have led to alarming rates of entanglement in whales, and ingestion in marine turtles.[33] Household activities are significant contributors to plastic waste, with items such as packaging, bags, and disposable materials comprising a substantial fraction of domestic refuse. Approximately 150 MT of plastics produced globally are allocated for single-use products like packaging films and bags.[34] There is an alarming statistic that up to 50% of all produced plastics are discarded without adequate utilization. Next, it highlights the urgent need for a circular economy solution, and advanced recycling technologies.[35] Systematic recycling, and sound environmental waste treatment can not only reduce pollution but also create economic opportunities.[36] Given the longevity of systematic polymers, plastic waste persists in ecosystems, and leaches carcinogens into soils, and waterways, posing risks to both human health, and environmental components.[37] Coordinated global efforts to curb production, eliminate harmful subsidies, and enforce strict regulatory mechanisms are essential to mitigate the multi-faceted impacts of plastic pollution.[35,36]

Blockchain technology (BCT) can offer significant potential to enhance transparency, and traceability within the PW management supply chain, contributing to a more sustainable, and efficient system. Through the creation of a decentralized, and immutable ledger, blockchain enables the accurate tracking of PWs, including their origin, material composition, and final destination.[38] This level of traceability ensures accountability among all stakeholders, and minimizes the risk of contamination by verifying handling processes at each stage. Moreover, blockchain can facilitate incentive mechanisms such as token-based rewards for individuals, and organizations participating in recycling initiatives, thereby promoting active engagement, and supporting the development of a circular economy.[39] BCT can facilitate real-time visibility in supply chains by recording every transaction in a distributed ledger, allowing authorized stakeholders to continuously monitor product movement, and operational performance.[38,39] Each transaction is embedded with a unique cryptographic identifier, enabling precise traceability from the point of origin to the final destination. The immutability of blockchain ensures that once data is recorded, it cannot be altered or depleted, thereby providing a secure, and tamper-evident audit trail. This transparency enhances stakeholder trust, as all participants access a single, verified source of truth. Additionally, the integrity of the ledger significantly reduces the risk of fraud, since any unauthorized modifications are immediately detectable within the network.[40]

2.1.2. Sources and usage sectors of plastics. We find the widespread utilization of plastics in different sectors like packaging, construction, electronics, agriculture, and healthcare, and these have resulted in a significant escalation in PW generation, posing substantial environmental risks, including air and water pollution/contamination, landfill saturation, and GHG emission.[41] Despite increasing global awareness, many nations lack robust regulatory frameworks governing plastic production, consumption, and end-of-life management. This regulatory gap necessitates a transition toward integrated strategies encompassing reduction, reuse, and recycling to promote resource efficiency, and environmental sustainability.[42] Fig. 3 shows different types of PWs from different sectors, and sources with challenges to their mitigation, and also new productdevelopment.

Among waste management strategies, degradation techniques including mechanical recycling, pyrolysis, and, biodegradation are critical for conserving non-renewable petrochemical resources, and mitigating ecological impacts.[43] Industrial plastic wastes, generated predominantly by sectors such as construction, automotive, and electronics, are often homogeneous, uncontaminated, and produced in bulk, making them ideal candidates for material recovery, and closed-loop recycling.[43,44] However, the absence of standardized collection, sorting, and processing protocols limits the effectiveness of these methods, emphasizing the need for systematic and enforceable recycling guidelines.[41,42]

Municipal solid waste (MSW), by contrast, contains a heterogeneous mixture of degradable, recyclable, and non-recyclable plastics. While alternatives to landfilling, such as pelletization and material remanufacturing, offer potential,[45] challenges persist due to the complex composition of mixed polymer resins, and their incompatible thermal, and mechanical processing requirements.[46] In agriculture, plastics are widely employed for mulching, irrigation systems, and protective covers, enhancing crop yield and water efficiency. However, improper disposal leads to soil and water contamination.[45,46]

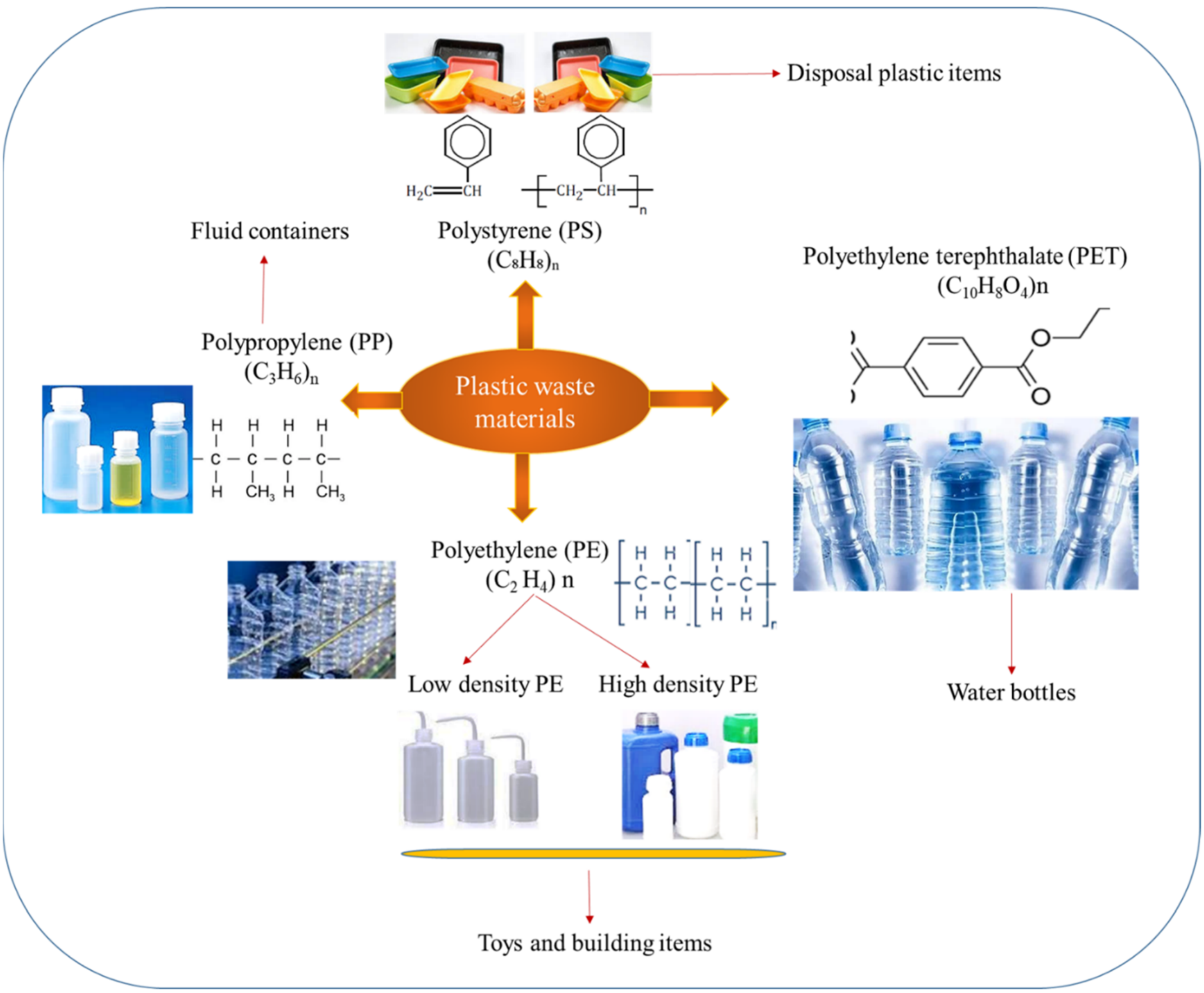

Fig. 3 Sources and composition of the major sources of plastic waste from different packaging material utilization locations.

Recycling rates for agricultural plastics remain notably low due to poor on-site collection infrastructure, and limited access to specialized recycling technologies.[47] Similarly, the healthcare sector produces substantial quantities of medical plastic wastes (MPWs), including disposable personal protective equipment (PPE), syringes, and sterile packaging. The Covid-19 pandemic intensified MPW accumulation, necessitating the urgent deployment of environmentally responsible disposable methods like high-temperature sterilization, chemical treatment, and advanced incineration systems.[48] Plastic pollution significantly threatens marine ecosystems, where macroplastics fragment into microplastics, and nanoplastics, infiltrating food chains and posing risks to human and ecological health.[47,48]

PW generation is correlated with population density, urbanization, and socioeconomic conditions. Urban centres, due to higher income levels, and industrial activity, generate more PWs than rural areas.[49] Socio-economic analyses, such as those from Dhanbad, India, indicate that higher-income groups contribute disproportionately to per capita PW generation.[50]

Emami *et al.* (2024)[51] have provided a 20-year update on plastic production, and consumption, offering a comprehensive evaluation across all polymer types, and end-use sectors. Their study includes a detailed material flow analysis for the period 2018–2019, especially addressing significant data gaps related to post-consumer plastic streams.[51] This study estimates total plastic production at 9.3 million tonnes (Mt) with polyethylene comprising 22%, making it the most widely utilized polymer. The mass of plastics embedded in distributed products across various applications totals 23.9 Mt. Major consumption sectors include packaging (30%), textiles (17%), building, and construction (16%).[52] PW generation stands at 15.5 Mt, predominantly originating from packaging, and textile use. Of this, only 13% is recycled, 46% is mismanaged, and the remainder is either incinerated or landfilled. The study employs nationally representative, mass-balanced, and transparent technology, providing a scientifically robust baseline for policy and strategic decision-making.[51,52]

Artificial intelligence (AI) is revolutionizing PW management by enabling advanced sorting, automation, and real-time operational optimization processes. Further, AI-driven image recognition, and sensor-based systems can accurately identify, and differentiate between various plastic types, including those with similar visual or material properties, thereby improving the purity, and quality of recyclates.[53] These technologies enhance the efficiency of recycling processes by minimizing contamination, and reducing manual labor. Furthermore, AI facilitates the automation of material recovery facilities (MRFs), streamlining material handling, and throughput. Real-time data analytics supported by AI enable dynamic system adjustments and predictive maintenance, ensuring continuous process optimization. According to ecoex market, such innovations significantly contribute to the scalability, and effectiveness of modern PW management systems.[54] Next, AI systems, leveraging computer vision, and deep learning algorithm, are capable of distinguishing between different plastic types like HDPE (high density polyethylene), PET, LDPE (low density polyethylene), and PP with high precision. By analyzing shape, color, texture and spectral signatures, there models ensure accurate classification, and routing of plastics into appropriate recycling streams thereby enhancing the purity, and quality of recovered plastic materials.[53,54] Additionally, AI can detect, and identify contaminants like food residues, non-recyclable materials, or foreign objects within the waste stream, which are critical to remove to prevent the degradation of recycled output, and ensure compliance with quality standards in downstream processing.[55] The performance of advanced AI models like Mask R-CNN, and YOLO v8 has been checked with systematic evaluation for their effectiveness in enhancing the PW sorting process. These models were assessed based on key performance metrics, including accuracy, mean average precision (mAP), precision recall, F1 score, and inference time. Few researchers have attempted hyperparameter optimization that was conducted using grid search to ensure optimal model configurations.[56] Mask R-CNN has achieved an accuracy of 0.912, and a mAP of 0.911, outperforming YOLO v8 in tasks that required precise object segmentation such as distinguishing overlapping or irregularly shaped plastic items.[57] However, its longer inference time of 200–30 milliseconds limits its suitability for real-time processing environments. In contrast, YOLO v8 demonstrated superior performance in speed-sensitive applications, with an inference time of only 80–160 milliseconds.[58] Although its accuracy (0.867) was slightly lower than that of Mask R-CNN, it achieved a higher mAP of 0.922, indicating strong object detection capabilities. This study highlights the trade-off between detection precision, and processing speed, emphasizing the need to select AI models based on specific operational requirements such as high-resolution sorting *versus* real-time throughput in MRFs.[53,57]

2.2. Barriers to recycling on accumulated locations

Plastic waste (PW) recycling faces multi-faceted barriers spanning technical, economic, and socio-political domains. A major constraint lies in the sorting, and cleaning of heterogeneous plastic materials. Post-consumer plastics are often contaminated with food residues, pigments and multilayer polymers, rendering them incompatible with conventional recycling technologies.[59] Thermoplastic polymers such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET), though recyclable in theory, require intensive energy, and water inputs for effective reclamation, making virgin resins more economically viable for manufacturers.[59,60] Infrastructural deficits, especially in low- and middle-income regions, exacerbate the inefficiencies in plastic waste collection, segregation, and processing. Informal sectors, including waste pickers, and scrap dealers, play a central role in the plastic recovery chain, albeit with limited institutional support. The integration of machine learning models such as support vector machines, and random forest algorithms has been explored to predict waste generation patterns, and optimize recovery logistics.[61] However, systemic limitations in technology access, funding, and governance hinder scalable implementation. Globally, the proliferation of non-biodegradable plastics including PP, PE, and PET is expected to double by 2050, driven by increasing consumer demand, and industrial dependence.[62]

Table 1 Literature information for different recycling/conversion approaches for PWs

Plastic waste types	Approaches for PW mitigation	Products from plastic wastes	References
Polyolefins – polyethylene (PE), polystyrene (PS), polypropylene (PP)	Microbial, and enzymatic degradation	Plastic generated monomer, and also fuels with less toxic nature	1
Polyurethanes in foams, coatings, and textiles	Using an organoboron Lewis acid under mild conditions (60–80 °C, toluene or tetrahydrofuran, ambient pressure) is found	Production of new polyurethane precursors with toxicity to the environment	4
Poly(bisphenol A carbonate) (PC)	*N*,*N*′-dimethyl-ethylene- diamine (DMEDA) as a depolymerization reagent, an efficient chemical recycling agent	This chemical treatment improves the recycling efficiency of PC, and promotes the development of plastic reutilization	6
Plastic wastes of various types including polyethylene (PE), and polystyrene (PS)	Air plasma torches at a flow rate of 10–30 g s^{-1}, average temperatures (15 000 to 19 000 K, and average velocity of the exiting plasma jet (1677.3–2763.2) m s^{-1}	Recovered pyrolysis oil with huge economic returns on investment ∼80%, the payback period (PBP ∼ 1.2 years), and the gross profit (129%)	7
Non-biodegradable plastic waste microplastics (MPs) in water source sites	Biodegradation or catalytic-chemical degradation including advanced oxidation processes (AOPs), and photocatalysis	This method helps in solving the problem of MP pollution *via* making aquatic systems toxicity free	14
Polyester plastics	Catalytic depolymerisation approach helps to stimulate their efficient recycling to value-added chemicals, and materials	PET, and PLA can easily achieve selective depolymerization to their corresponding monomers	17
Plastic waste char from PS	Pyrolysis of polystyrene (PS) plastic waste and co-precipitation	Carbon-metal double layered oxides (C/MnCuAl-LDOs) nano-adsorbent	22
A synthetic mixture of real waste packaging plastics	Thermal and catalytic pyrolysis utilization at 370 °C, 450 °C, and 650 °C using a bench scale reactor	This has generated high yield of oil, gas, and char with analysis of its compositions	25
Plastics or polymers at rivers, and sea	Pyrolysis, microwave treatment, and material-based processes	This approach helps in PW mitigation with a push to strive for the concept of the circular economy	41
Diverse waste plastics including terephthalate (PET), polyethylene (PE), and polypropylene (PP)	Versatile organo-photocatalytic upcycling method that uses phenothiazine derivative, PTH-3CN	It decomposes into active triarylamine species. It offers a scalable route for sustainable plastic upcycling with broad applicability	50
Waste plastics including polypropylene and polystyrene	Pyrolysis approach with different input datasets comparison including decision tree (DT), artificial neuron network (ANN), and Gaussian process (GP)	DT model exhibited generalisable, and satisfactory accuracy (R^2 > 0.99) with training data for oil, and wax predictions	57
Non-biodegradable plastics (NBPs) with high toxicity and stability	CO_2, and carbon-radical-mediated photocatalytic cracking	This approach cleaves inert C–C bonds, and abstract the carbon atoms from these wastes into valuable chemicals, and fuels	59

These materials, designed with chemical additives for enhanced durability, exhibit high environmental persistence. Approximately 79% of PW accumulates in terrestrial or aquatic environments, where it contributes to ecological degradation. Marine ecosystems are particularly vulnerable; macroplastics cause entanglement, and ingestion injuries to marine fauna, while microplastics adsorb persistent organic pollutants (POPs), facilitating their entry into trophic networks, and raising toxicological concerns for humans and wildlife.[62,63] Municipal plastic waste management (MPWM) models in regions such as Borås (Sweden), Kamikatsu (Japan), and Flanders (Belgium) emphasize high-efficiency sorting, extended producer responsibility (EPR), and public engagement.[63] While advanced economies like the EU and UK have adopted circular economy (CE) frameworks, many developing nations face legislative inertia, infrastructural inadequacy, and low community participation, limiting their capacity to scale sustainable waste systems.[64] Plastic packaging especially single-use plastics remain a dominant contributor to environmental pollution. Soil, and freshwater ecosystems are adversely affected by plastic leachates and debris, which compromise both biotic, and abiotic integrity. Mitigation strategies have included the development of biodegradable, and bio-based alternatives, yet their widespread adoption is constrained by high production costs, and limited performance equivalency to conventional polymers.[65,66] Policy interventions such as single-use plastic bans in countries like France and the UAE demonstrate progress but require broader global alignment and enforcement.

Reports highlight that the transition from a linear economy to a circular economy (CE) is both imperative and sustainable for effective plastic waste (PW) mitigation. CE approaches can prioritize resource efficiency by reintegrating recycled plastics into value-added product development application through uses of chemical depolymerization and mechanical reprocessing.[20,67] Table 1 presents different types of plastic waste with respective techniques. Integrating these strategies into national waste plastic management frameworks will not only reduce the environmental burden but also unlock socio-economic opportunities across the recycling value chain.[20,66]

3. Current recycling technologies, and their limitations

The study reviews a range of plastic recycling, and conversion technologies, explores advancements in the development of regenerated plastic materials, and evaluates their potential contributions to climate change mitigation and the advancement of a circular economy framework.

3.1. Mechanical recycling

The mechanical recycling approach is currently the most common, and widely implemented PW management strategy, primarily due to its operation feasibility, and cost-effectiveness. Its adaptation has been further driven by increasing environmental awareness, the transition towards circular economy frameworks, the enforcement of more stringent regulatory policies on waste disposal, and recycling approaches. Further, it monitors its comparatively lower processing cost relatives to alternative recycling technologies.[68] Nevertheless, the effectiveness of mechanical recycling is being increasingly challenged by the growing heterogeneity of PW streams. This includes the coexistence of diverse polymer types, the introduction of novel biodegradable polymers, and the prevalence of complex multilayer packaging systems composed of incompatible polymeric materials, many of which lack established recycling pathways.[69] These complexities contribute to inefficiencies in material recovery, and result in environmental leakage. The scientific community is actively investigating these issues, and this review aims to present recent advancements in the mechanical recycling process of emerging, and technically challenging polymer systems.[68,69] Emphasis is placed on the recovery and reintegration of materials previously destined for landfill, incineration or composting processes, with a focus on innovative techniques/approaches that can improve recyclability, and material circularity processes.[70] Mechanical recycling involves converting plastic waste into secondary raw materials without altering their chemical structure/bonds, and it can be a widely used method in Europe to recycle materials like PET or HDPE into new products.[71] Despite this effectiveness, challenges such as contamination, and quality consistency hinder its application at the commercial scale. Localized efforts, like those in the UK, have shown promise in optimizing collection, and recycling processes.[72]

The research results/findings indicate that chemical recycling of mixed plastic waste (MPW) *via* pyrolysis exhibits approximately 50% lower greenhouse gas (GHG) emissions, and life cycle energy demand compared to energy recovery processes.[72,73] When accounting for recyclate quality, the global warming potential (GWP), and energy consumption associated with pyrolysis are comparable to those of mechanical recycling. Notably, pyrolysis-derived recyclates demonstrate substantially reduced climate change impacts (-0.45 *vs.* 1.89 t CO_{2eq} per tonne of plastic) relative to plastics produced from virgin fossil feedstock.[73] However, pyrolysis is associated with significantly higher environmental burdens across several other impact categories compared to mechanical recycling, energy recovery, and virgin plastic production.[74] Sensitivity analyses reveal that key variables, including regional energy mix, pyrolysis carbon conversion efficiency, and the quality of the resulting recyclate, substantially influence the environmental performance outcomes. These insights hold relevance for stakeholders in the chemical, plastics, and waste management sectors, as well as for regulatory bodies shaping sustainability policies.[72,74]

Polyvinyl chloride (PVC) is examined in terms of its chemical structure, global annual production volumes, and primary application sectors. The review subsequently addresses mechanical recycling strategies, encompassing separation methodologies, incorporation into composite materials, and alternative (non-conventional) mechanical recycling techniques. The respective advantages, and limitations of each mechanical approach are critically evaluated.[75]

3.2. Energy recovery methods

Energy recovery from municipal plastic waste (MPW) has emerged as a critical strategy for mitigating PW accumulation, and reducing reliance on conventional fossil fuels/products. The production of pyrolytic oils, and gas from PWs significantly contributes to alternative energy generation, and resource conservation. This review further provides an overview of global plastic generation and consumption trends and then it focuses on energy recovery techniques/methodologies, particularly the application of various pyrolysis reactor systems.[76]

The primary objective is to examine the conversion of PWs into value-added products like bio-oils/syngas while also addressing the associated formation of hazardous byproducts, especially polycyclic aromatic hydrocarbons (PAHs), during the thermal treatment of MPWs and electronic wastes.[77,78] The review further explores the implications of PAH emission for human health, noting their carcinogenicity, and also links to respiratory disorders/developmental conditions like childhood obesity. A comprehensive analysis of the pyrolysis technique/methodology is presented with emphasis on the microwave-assisted pyrolysis technique, which demonstrates several advantages over conventional thermal processes in terms of efficiency, selectivity, and process controllability.[76,78]

Key operational parameters like feedstock type, particle type, and reactor temperatures are shown to influence product yield, and compositions. Moreover, optimization of reactor conditions is critical in minimizing the release of toxic gaseous

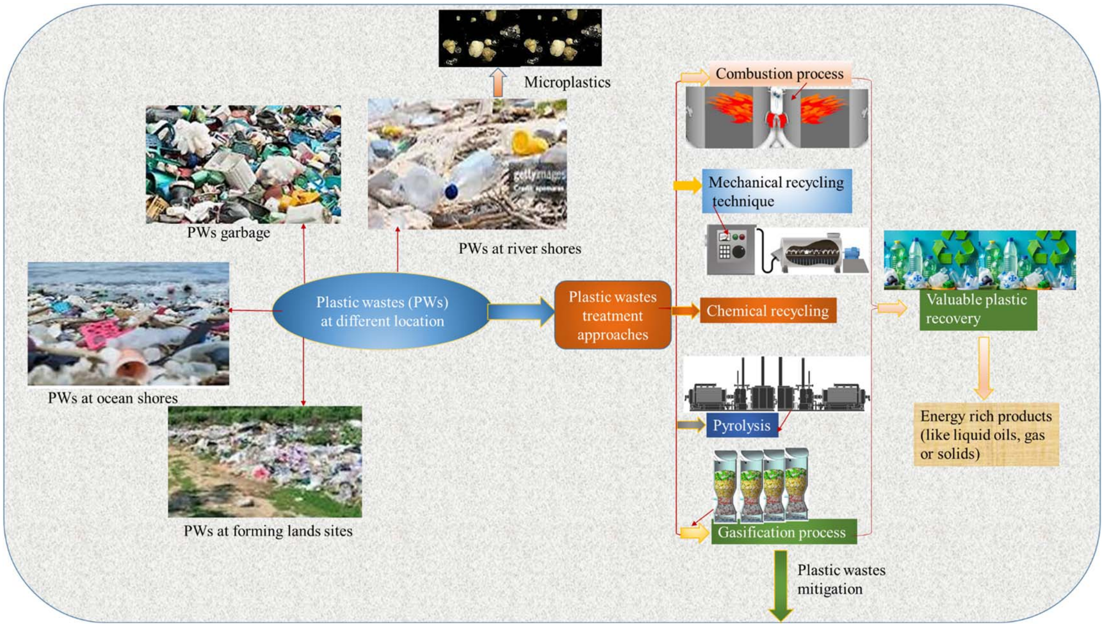

Fig. 4 Different plastic sources for different approaches for transformation into new plastic products that help in waste plastics mitigation in the environment.

emissions, including the suite of 16 priority PAHs identified by regulatory agencies.[79] Fig. 4 shows the impact of conversion approaches of plastic wastes into new product development with PW mitigation. Overall, this review aims to highlight the dual potential of pyrolysis for sustainable waste management and energy recovery, while also underscoring the environmental and health risks associated with PAH emissions. These findings underscore the importance of developing cleaner, safer pyrolysis technologies, and implementing stringent control measures to mitigate their adverse effects.[76,80]

3.3. Chemical recycling

The chemical upcycling approach of PWs can present an effective, and high-value approach for transforming post-consumer polymers into a broad spectrum of valuable products such as fuels, platform chemicals, and advanced materials. As established in scientific literature, and technical reports, plastics that are synthesized from petrochemical feedstock can be chemically depolymerized back into oil-derived products.[81] It facilitates resource recovery for subsequent polymer re-synthesis or energy production. Recent advancements in the chemical upcycling of the PW process, particularly within the past three to five years, are comprehensively reviewed, highlighting a paradigm shift toward the development of plastic-based refinery systems.[82]

Furthermore, various chemical recycling pathways for the valorization of PVC waste are analyzed in detail, including gasification, pyrolysis, and dechlorination processes, with a focus on their potential to enhance environmental sustainability. The review concludes with a discussion of the key challenges associated with PVC waste management, and outlines future directions for improving the circularity, and recyclability of PVC-based materials.[83] This emerging concept envisions PWs not merely as pollutants, but as a valuable secondary resource that can serve as a platform feedstock for the synthesis of high-value monomeric, and oligomeric compounds, thereby facilitating reintegration into a circular economy. Various chemical upcycling strategies are systematically explored, including hydrogenolysis, photocatalysis, pyrolysis, solvolysis, and other emerging techniques/methodologies.[81,82]

Chemical recycling is discussed as thermochemical depolymerization, and metal-catalyzed depolymerization. Biological catalysis, photocatalysis, and photo/electrocatalysis are also shown as novel catalytic degradation methods. Additional strategies include macromolecular transformation, and carbonization.[84] Each of these processes offers distinct advantages, and disadvantages with systematic evaluation, based on their operational principles as well as their environmental, and economic implications.[85] Finally, future directions are presented for the recycling of polyethylene (PE) that emphasizes the need to balance process efficiency with environmental impact. This can be achieved through advances in material innovation, mechanistic understanding, system-level design, and interdisciplinary collaboration.[84,85]

Each approach is discussed with respect to its capability that can convert heterogeneous plastic streams/wastes into value-added products such as specialty chemicals, functional materials, and alternative fuels. This can help to address both environmental, and also resource recovery challenges.[11,81] Among such processes, pyrolysis especially thermal depolymerization has emerged as a promising technology for valorizing PWs. This process involves the thermal degradation of a high molecular weight polymer chain in an oxygen-free environment. This can yield short-chain hydrocarbon gases, and liquid oil fractions with better calorific properties comparable to conventional fossil fuels.[86] Owing to the high heat of combustion intrinsic to polymers, pyrolysis is regarded as both economically viable, and environmentally favourable for addressing PW accumulation, and also the production of alternative liquid fuels.[87] Catalytic pyrolysis enhances efficiency and product quality. Catalytic pyrolysis enhances process efficiency, and product quality. Catalysts reduce the average molecular weight of the pyrolysis products, lower their boiling point (BP), and facilitate more complete thermal degradation.[86,87]

Homogeneous catalysts, such as aluminium chloride ($AlCl_3$), and heterogeneous catalysts, notably nanocrystalline zeolites, are employed for this purpose.[50] Heterogeneous catalysts are preferred for their thermal stability, and ease of recovery from the reaction medium. However, the pyrolysis of mixed plastic waste is complicated by synergistic or antagonistic interactions among polymers due to their differing thermal degradation behaviours, and feedstock compositions.[88] Broader chemical recycling methods-such as pyrolysis, chemolysis (*e.g.*, glycolysis, methanolysis), and gasification-depolymerize plastics into basic molecular constituents, which can be reconstituted into new polymers or converted into fuels.[50,88] These advanced recycling technologies address many of the limitations inherent in mechanical recycling, particularly with regard to heterogeneous, contaminated, or multilayer plastic waste streams. Nevertheless, their widespread industrial deployment remains constrained by technical, economic, and scalability challenges.[89] The global plastic waste crisis necessitates a comprehensive, and integrative strategy. Progress toward a circular economy, underpinned by the development, and implementation of innovative recycling technologies, is essential.[90] While both mechanical, and chemical recycling have demonstrated potential, further improvements in process efficiency, scalability, and economic feasibility are imperative. Robust policy frameworks, continued technological innovation, and international cooperation will be vital in achieving sustainable plastic waste management.[88,90]

3.3.1. Conversion of plastic wastes to molecular intermediates. Chemical recycling offers a pathway for converting plastic wastes (PWs) into molecular intermediates, which are later used to produce new products. This process promotes sustainable raw energy sources, mitigates greenhouse gas (GHG) emissions, and enhances economic efficiency. Technologies like polymer thermolysis, which require high temperatures and efficient catalysts, achieve high recycling yields, including gases, and liquid fuels.[91] However, challenges such as high energy requirements remain. The depolymerization of plastic waste into monomers, oligomers, or other intermediate derivatives is reported with subsequent transformation into value-added chemical products.[90,91] Next, oxidative or reductive degradation of plastic wastes into low-molecular-weight platform molecules (*e.g.*, CO_2~carbon dioxide, CH_4~ methane, formic acid, methanol) is reported that can undergo catalytic upgrading approaches.[92] Direct catalytic transformation of polymer chains is found that resulted in high-value chemicals without complete depolymerization. These approaches underscore emerging opportunities for the development of advanced catalytic upcycling methodologies that utilize plastic waste as a feedstock for sustainable chemical manufacturing.[91,92]

3.3.2. Thermal-based recycling techniques. Thermal conversion techniques like gasification, pyrolysis, and liquefaction have been extensively investigated for the treatment of mixed, and contaminated PWs. Among these approaches, catalytic pyrolysis has demonstrated enhanced selectivity, and higher yield of targeted products, and it is increasingly recognized as a viable strategy for the conversion of heterogeneous PWs into liquid fuels.[93] These thermal techniques/methods are primarily applied to commodity polymers like polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET). These were utilized for the generation of intermediate compounds, which subsequently upgraded into fuels, and valuable chemicals/products.[94] Recent advances in chemical recycling technologies for PET have shown significant potential in depolymerization processes, which better enable the production capacity of virgin-quality resins, thereby reducing reliance on fossil-derived feedstock.

The efficiency, and product distribution of such recycling processes are highly dependent on the process parameters including operating conditions, catalyst composition, and reaction kinetics.[95] Recycled PET (rPET) finds application across diverse sectors such as construction, textile, and biomedical engineering. However, the implementation of these processes often requires capital-intensive infrastructure to maintain economic, and operational viability.[96] Furthermore, life-cycle assessment (LCA) methodologies play a critical role in informing decision-making in PW management by quantifying environmental impacts, and also evaluating the resource efficiency of recycling pathways. The development of sustainable recycling strategies for PP, PE, and PET can provide a promising avenue for transforming low-value commodity plastic into higher-value materials/products.[95,96] Fig. 5 shows chemical recycling assisted products with development of new products.

Microwave-assisted pyrolysis (MW-assisted pyrolysis) is recognized as an advanced thermal conversion technique/process. It utilizes microwave radiation to uniformly, and rapidly heat PWs, facilitating their decomposition into valuable products like chemical feedstock, liquid fuels, and carbon-rich solid residues.[95,97] According to research papers published in many high-quality journals, this methods offers enhanced energy efficiency, faster reaction rate, and improved product selectivity compared to conventional pyrolysis processes.[97]

It presents a more sustainable alternative to traditional disposal practices like incineration, and landfilling practice that contribute to resource recovery, and circular economy objectives in PW management/strategies. MW radiation is employed to heat PWs of heterogeneous nature with better penetration into materials, and interacts with its polar or conductive components.[98] This interaction induces molecular vibration, and dipole rotation, generating internal energy through a dielectric heating process. The rapid, and uniform heating system can facilitate the breakdown of polymer chains, enabling efficient thermal decomposition into value-added chemicals/products during MW-assisted pyrolysis.[97,98]

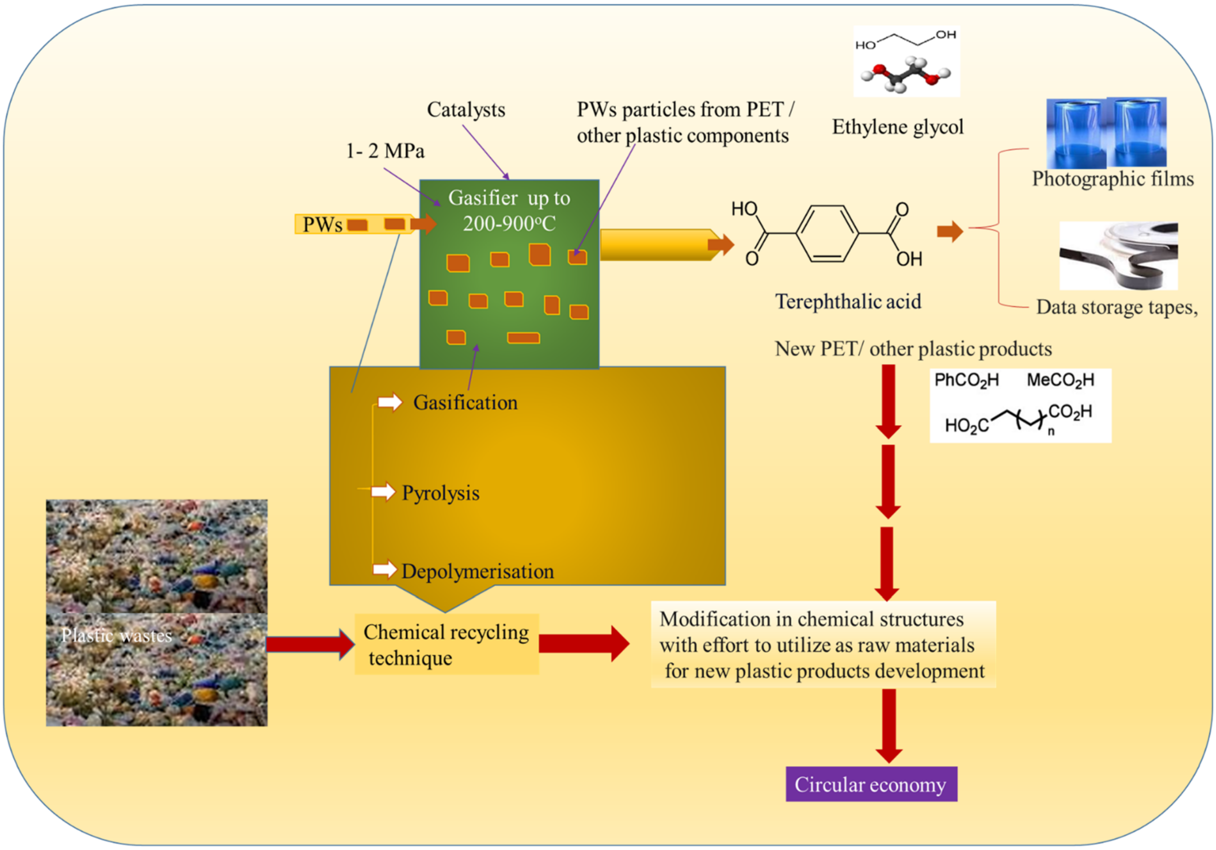

Fig. 5 Chemical recycling approaches for plastic waste into recycled and new materials development with promotion of the circular economy.

The thermal energy generated by MW radiation can help in breaking long polymer chains of PWs in plastic streams. It can result from pyrolytic degradation that generates smaller molecular compounds. This process yields a distribution of gaseous products (like hydrogen, and methane), liquid hydrocarbons (oils/fuels), and solid residue (*i.e.*, char and carbonaceous materials). These products depend on process parameters, and feedstock compositions.[99] The gaseous, and liquid fractions can be produced during MW-assisted pyrolysis, and then they can be captured, and refined into fuels like diesel, gasoline or syngas or precursor chemicals for industrial uses.[100] The solid residue, commonly referred to as char or biochar, possesses high carbon contents and can be utilized in the application of construction materials, soil amendments or activated carbon production that may be dependent on its physicochemical properties.[99,100]

3.3.3. Catalytic pyrolysis for sustainable energy recovery. Polyethylene (PE), polypropylene (PP), and polystyrene (PS) are considered optimal feedstocks for production of liquid hydrocarbons *via* a thermal or catalytic pyrolysis process. This is due to their chemical compositions, comprising solely carbon, and hydrogen atoms, closely resembling those of conventional hydrocarbon fuels like gasoline, and diesel.[101] These polymers also exhibit comparable calorific values to fossil-based fuels, further enhancing their suitability for energy recovery applications. Notably, PE, PP, and PS collectively represent approximately 70% or more of total plastic materials, used in packaging, contributing significantly to the post-consumer PW stream.[102] In contrast, polyvinyl chloride (PVC) is an unfavourable feedstock due to its chlorine content, which can lead to the formation of corrosive, and environmentally hazardous by-products during thermal decomposition. Fig. 6 shows pyrolysis product, and novelty. The pyrolytic fuels derived from PE, PP, and PS are inherently sulphur-free, offering a key environmental advantage; the absence of sulphur prevents the formation of sulfur dioxide (SO_2) upon combustion, a major contributor to air pollution, and associated health risks.[101,102] The pyrolysis process occurs under anaerobic conditions, without the presence of oxygen, and therefore does not involve combustion. The hydrocarbon products obtained typically span a wide range from C_1 to C_{80}, encompassing light hydrocarbons such as liquefied petroleum gas (LPG), gasoline, and kerosene, as well as heavier fractions akin to diesel.[103]

The broad molecular weight distribution of these products includes both volatile, and high-molecular-weight hydrocarbons, making further upgrading, and fractionation critical for fuel refinement.[103,104] Catalytic pyrolysis of plastic wastes (PWs), including polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyethylene terephthalate (PET), facilitates their conversion into high-value products, particularly liquid hydrocarbon oils.[104] The use of modified natural zeolite (NZ) catalysts significantly enhances the efficiency of this process. Among these, acid-

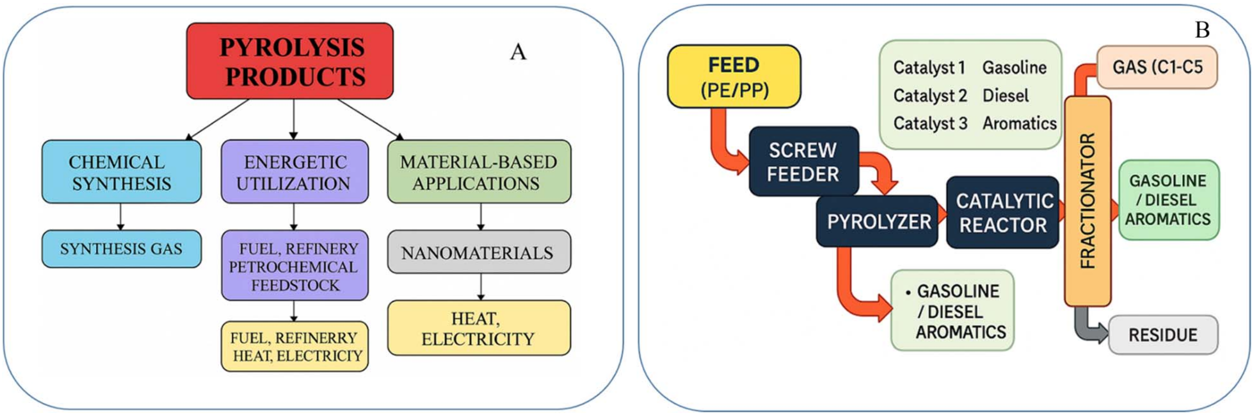

Fig. 6 (A) Novelty of pyrolysis; (B) different products of pyrolysis.

activated natural zeolites (AA-NZ) have demonstrated superior performance in terms of both liquid oil yield, and product quality compared to thermally activated zeolites (TA-NZ).[105] The resulting pyrolysis oils exhibit high heating values comparable to those of commercial diesel fuels, indicating strong potential for application as alternative transportation fuels.[106]

The depolymerization of plastics such as PS during catalytic pyrolysis primarily involves radical chain scission, and hydrogenation mechanisms, both of which are strongly influenced by the physicochemical properties of the catalyst. The reaction mechanism typically follows a three-step pathway: initiation, propagation, and termination.[107] Fig. 7 shows the novelty, and products of the pyrolysis process for plastic waste management.

In the initiation phase, large polymer chains are thermally cleaved into primary free radicals. During propagation, these radicals undergo further cleavage into smaller hydrocarbon radicals, and molecules. In the case of PE, β-scission is the predominant mechanism, driving radical propagation, and it leads to the formation of short-chain hydrocarbons, and olefins.[106,107]

Initiation:

$$\text{R-CH}_3\text{-CH}_3\text{-CH}_3\text{-R} \rightarrow \text{R-CH}_2\text{*} + \text{*CH}_2\text{-CH}_3\text{-R}$$

Propagation (β-scission):

$$\text{R-CH}_2\text{-CH*-CH}_2\text{-CH}_2\text{-CH}_2\text{-CH}_2\text{-R} \rightarrow \text{R-CH}_2\text{-CH{=}CH}_2 + \text{*CH}_2\text{-CH}_2\text{-CH}_2\text{-R}$$

$$\text{R-CH}_2\text{-CH}_2\text{-CH}_2\text{*} \rightarrow \text{R-CH}_2\text{*} + \text{CH}_2\text{{=}CH}_2$$

Termination/recombination:

$$\text{R-CH}_2\text{-CH}_2\text{*} + \text{*CH}_2\text{-R} \rightarrow \text{R-CH}_2\text{-CH}_2\text{-CH}_2\text{-R}$$

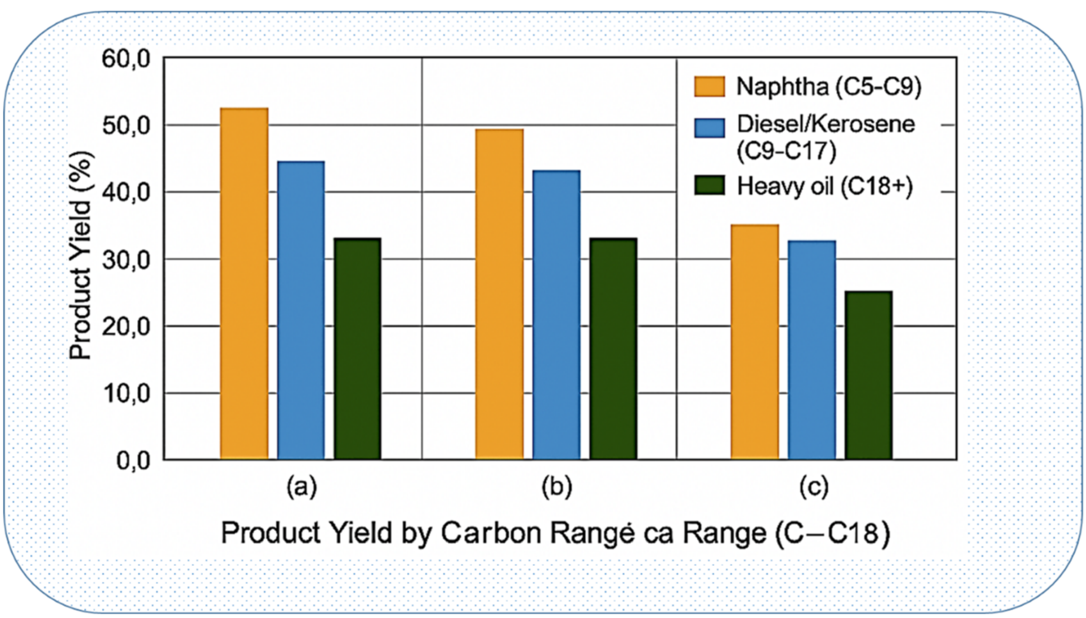

Fig. 7 Yield of pyrolysis for oil fractions by carbon range (C5 to C18).

Table 2 Technological approaches for plastic waste management and novel product development in the context of a circular economy

Plastic wastes	Sources	Approaches	New products	References
Plastic polymers like HDPE, LDPE, PP, PS, PVC, EPS, and PET	Packaging materials from the industrial sector of Norway	Systematic polymer classification was done by a high-resolution dynamic probabilistic material flow analysis	Utilized for safe, and sustainable recycling of plastic waste into new products, cap production, lower consumption, and prevent waste generation	52
Low-density polyethylene (LDPE) mixing with Ulva intestinalis at different ratios	This plastic was used in packaging materials in bottles and other products	Microwave vacuum co-pyrolysis of seaweeds and low-density polyethylene was applied	The bio-oil production from co-pyrolysis at a 75% LDPE blend ratio found better characteristics compared to individual pyrolysis	120
Polyvinyl chloride (PVC) as a plastic in various industries	This plastic is predicted to have a future production growth rate of 65 million metric tons by 2030	PVC undergoes co-pyrolysis with selected Zn-based transition metal oxides like ZnO, $ZnFe_2O_4$, and $NiZnFe_4O_4$	This approach facilitates the isolation, and extraction of the valuable zinc load in these MOs at temperatures between 300, and 500 °C. This can generate a peak value of 60.19% at 500 °C	80
LDPE, PP, and PET from the packaging sector	Losses, and plastic mismanagement along the value chain were reported	Plastic flow models for 9 sectors for 10 plastic polymers has helped to determine the total micro/macroplastic losses (39% ∼2.1 Mt), occurring during the use phase	This approach helps in the determination of total recyclates with consumption by plastic converters in 2025 ranging between 9.11 Mt, and 11.13 Mt	29
Blend of municipal solid waste (MSW) with biomass, and mixed plastic waste (MPW)	Various solid plastic wastes are collected through municipal solid wastes	Steam gasification of municipal solid wastes with the carbon capture approach with thermodynamic simulations with Aspen Plus® validation	Achieved 99.99% pure hydrogen, and over 90% CO_2 capture efficiency. With case 1: 68.80 mol of H_2 per kg feed with 92% CO_2 capture and case-2: yielded 100.17 mol of H_2 per kg feed with 90.09% CO_2 capture	79
Recyclable (HDPE), and compostable waste plastics	Both used, and unused compostable bioplastics, recyclable HDPE, grocery bags, and unused HDPE as a feedstock	Uses of a novel two-stage fixed-bed reactor to evaluate the catalytic pyrolysis for these PWs	A mixture of recyclable plastic, and compostable bioplastic with a 1 : 1 ratio was pyrolyzed at 500 °C, with analysis of pyrolyzed oil products	104
Feedstock recycling of cable plastic residue with a mix of PE, XLPE, and PVC	Cable plastic residue from metal recycling of electric wires with cross-linked polyethene (XLPE), and PVC	Thermochemical processes like steam cracking of cable plastic. Temperatures of 730 °C, and 800 °C are tested	This has resulted in various products of 27–31 wt% ethylene, and propylene; 5–16% wt% other linear hydrocarbons, and more than 10 wt% benzene	43
Poly(L-lactic acid) as a plastic material with huge accumulation due to its uses	Epimerization, and elimination reactions can impede its use on a large scale in packaging materials	Chemical recycling of poly (L-lactic acid) to the cyclic monomer. It uses solvent interactions on the monomer–polymer equilibrium to decrease the Tc of L-lactide	Chemical recycling of high-molecular-weight poly(L-lactic acid) directly to L-lactide, within 1–4 h at 140 °C, with >95% conversion, and 98–99% selectivity with recycled L-lactide	74
Plastic waste is due to huge plastic production predominantly from non-renewable sources	Huge plastic waste due to ineffective end-of-life management, and low recycling rates	Pyrolysis, and solvolysis, widely explored, with practical implementation at an industrial scale	It achieves a sustainable plastics economy. It further applies the recycling of C–C-containing polymers with the resultant of depolymerization into monomers *via* understanding the mechanisms of waste plastic conversion	121

Polystyrene (PS) typically yields higher quantities of liquid hydrocarbons during catalytic pyrolysis, primarily due to its aromatic, and cyclic molecular structure, which favours depolymerization pathways. In contrast, polypropylene (PP), and polyethylene (PE) tend to produce larger fractions of non-condensable gases under specific catalytic conditions.[108] The utilization of acid-activated catalysts further influences the pyrolysis process by enhancing the formation of char, and gaseous by-products, with the extent of enhancement being dependent on the polymer type.[109]

Polyvinyl chloride (PVC), when present in the feedstock, introduces chlorine (Cl_2) into the system, which occurs during thermal degradation resulting in the evolution of gaseous chlorine species (Cl_2). To ensure operational safety, and product purity, Cl_2 gas needs to be effectively separated, and removed prior to the condensation phase.[108,109] Post-treatment analysis confirms that chlorine concentration in the resulting pyrolysis oils is below 100 ppm, indicating a successful dechlorination process. The non-condensable gases (off-gas) generated during the process are redirected for combustion to supply thermal energy to the reactor, thereby minimizing atmospheric emission, and eliminating odor concern.[110] The cooling water, employed in a closed-loop system, remains uncontaminated throughout the operation, and can be safely discharged into the municipal sewage system without additional treatment. Similarly, hot air from the blower, not exposed to reactive species or contaminants, can be safely vented into the atmosphere.[108,110]

This continuous catalytic process is characterized by its operational safety, high efficiency, ease of use, and economic stability/viability. The system operates continuously for up to five days with a processing capacity of approximately 4800 kg per day. Catalyst deactivation due to coke deposition is managed by periodic regeneration *via* oxidative burning, allowing extended catalyst life without frequent replacement.[111] Catalyst replacement, and system cleaning are scheduled every five days as part of regular maintenance. The technology achieved a liquid fuel of approximately 60% by weight from the input PWs.[111] The total operational cost, encompassing utilities, labor, and depreciation, is estimated at $0.41 per gallon of liquid fuel produced. This cost structure remains competitive, particularly under current market conditions where crude oil processing costs fluctuate below US$ 50 per barrel.[111]

3.3.4. Catalytic hydrocracking for sustainable products. Catalytic hydrocracking is an advanced thermochemical process for PW valorization, in which long-chain plastic polymer molecules are cleaved into shorter, high-value hydrocarbons.[112] It is generated through the combined action of a catalyst, and hydrogen under elevated temperature, and pressure.[113] This method effectively transforms a wide range of PWs, including common PE, and PP, found in bag or bottles, into fuels like diesel, gasoline, and light olefins as well as valuable petrochemical feedstock.[114] The presence of hydrogen minimizes coke formation, and enhances product quality, making hydrocracking a promising route for sustainable PW management.

Hydrocracking involves the use of hydrogen gas in conjunction with a solid catalyst to cleave the long-chain polymer structure of PWs into smaller, more manageable hydrocarbon fragments.[113,114] This hydrogenolytic process not only reduces molecular weight but also saturates the resulting fragments, producing stable, high-quality liquid fuels, and chemical intermediates with minimal formation of unwanted by-products.[114,115] The resulting smaller hydrocarbon fragments from hydrocracking can be utilized as transportation fuels (*e.g.*, diesel, kerosene), industrial lubricants, or as chemical feedstock, and monomer precursors for synthesizing new plastic materials, thereby enabling closed-loop recycling, and supporting circular economy objectives.[115] Plastic waste presents a critical environmental challenge, with only a limited fraction undergoing effective recycling each year. Table 2 shows advanced conversion approaches for conversions from plastic wastes into various products.

Among emerging chemical recycling technologies, pyrolysis offers a promising route by thermally degrading plastic waste into liquid products, though challenges remain in refining these products for practical applications.[116] This study investigates the utilization of waste plastic pyrolysis oil (WPPO) as a feedstock for naphtha production *via* catalytic hydrocracking.[117] Two hydrocracking catalysts, nickel-molybdenum (NiMo) supported on microporous ZSM-5, and mesoporous ZSM-5, were synthesized, and characterized using X-ray diffraction (XRD), nitrogen adsorption–desorption isotherms, NH_3-temperature programmed desorption (NH_3-TPD), and transmission electron microscopy (TEM).[116,117]

The formation of hazardous substances during conventional thermal treatment of polyvinyl chloride (PVC) waste is analyzed, with particular attention paid to the emission of chlorine-containing compounds, greenhouse gases, and residual plasticizers.[118] Based on the origin, and composition of these pollutants, targeted environmental mitigation strategies are evaluated across three key categories: chlorine management, hydrocarbon control, and plasticizer removal. These approaches aim to minimize the environmental burden associated with PVC waste while enhancing material recovery, and resource efficiency.[119] The findings indicate that certain recycling techniques exhibit relatively low environmental impact and present potential economic advantages. However, the integration of these individual processes into a comprehensive PVC recycling system that simultaneously achieves ecological and economic viability remains a significant challenge.[118,119]

4. Innovative strategies for non-recycled plastics

4.1. Advanced chemical recycling techniques for plastic wastes

Advanced chemical recycling techniques/approaches (ACRTs) are found to encompass a suite of thermochemical, and catalytic processes, designed to depolymerize PWs/polymers into their fundamental chemical constituents. They are unlike the traditional, mechanical recycling approach, which often degrades the quality of polymers as is limited to specific plastic types. Next, the chemical recycling technique enables the transformation of a broader range of PWs/plastic materials, including contaminated, mixed, multi-layer plastics, into high-value-feedstock or a virgin-equivalent polymer.[122] Key methods within this domain include several thermal recycling approaches. Pyrolysis is discussed as a thermal decomposition process, carried out in the absence of oxygen, which converts PWs/plastic polymers into liquid hydrocarbons, gases, and char/biochar. These outputs can serve as precursors for fuels or as raw materials for new plastic synthesis.[123] The gasification approach involves the partial oxidation of PWs at high temperatures to produce syngas, a mixture of hydrogen, and carbon monoxide. These products can further process into fuels, methanol or other chemicals. Depolymerization is proceeded to target specific polymers like PET or polystyrene that break down into monomers or oligomers through many processes like solvolysis, glycolysis or hydrolysis. This allows for re-polymerization into new, high-quality plastics/its new products.[122,123] These technologies represent a transformative approach in the PW management strategy, offering the potential to close the loop in plastic production, reduce dependency on fossil resources, and enhance the circularity, and sustainability of plastic materials.[121,122] This approach shows a few benefits like handling of a wide range of plastics. This approach is capable of heterogeneous plastic streams including composite plastics, contaminated, and multi-layered plastics that are not suitable for the traditional mechanical recycling approach or technique.[121] According to circularity concepts, this expanded compatibility makes chemical recycling particularly valuable in addressing complex plastic waste streams that would otherwise be landfilled or incinerated. Further this technique can help in the depolymerization process of plastics. It can break plastics down into their original monomers, which can be re-polymerized into virgin-equivalent materials.[124] Plastic collectively highlights that this enables the creation of high-quality polymers that meet the same standards as those produced from petrochemical feedstock, without the quality degradation often seen in mechanical recycling.[121,124] Next, this approach can help in reduction in dependence on fossil resources by converting plastic waste into reusable feedstock, and advanced recycling reduces the need for virgin fossil-based inputs in the production of new plastics. This shift supports a more sustainable resource cycle, and contributes to lowering the environmental impacts associated with fossil fuel extraction, and processing.[125]

Further, this approach can achieve diversion of plastic waste from landfills, and incineration that utilizes a valuable pathway for diverting plastic waste from traditional end-of-life options such as landfilling, and incineration, thereby reducing methane emissions from landfills, and air pollutants from incineration. This approach showed many challenges, and considerations. It required high initial investment costs and complex operational requirements. Next, construction, and maintenance of these facilities often require substantial financial resources, posing a barrier to widespread adoption.[126] Pyrolysis, and gasification are energy-intensive, often requiring elevated temperatures, and controlled environments.[14,126] A comprehensive life-cycle assessment is necessary to evaluate the net environmental benefit of each technology. ACRTs require better infrastructures, and collaboration that can achieve scale up of chemical recycling, and requires significant investment in collection, sorting, and processing infrastructures, as well as robust collaboration among governments, industry stakeholders, and communities. The success of these technologies depends on integrated waste management systems, and supportive policy frameworks.[14,121]

4.2. Enzymatic and biocatalytic approaches for plastic wastes

Enzymatic and biocatalytic strategies represent a promising, and sustainable approach for the degradation of PWs, employing microbial-derived enzymes to catalyse the depolymerization of synthetic polymers into lower molecular weight oligomers/monomers.[127] These processes function under relatively mild physicochemical conditions, thereby eliminating the need for aggressive chemical treatment, and also helping in reducing environmental impact. Additionally, the specificity, and efficiency of biocatalysts may offer economically viable alternatives for large-scale PW management. This approach helps in the analysis of enzyme functions as highly specific biological catalysts that facilitate the cleavage of polymer chains into smaller fragments like monomers/oligomers.[128] This enzymatic hydrolysis targets ester, urethane, and amide bonds within the polymer backbone, enabling efficient depolymerization under controlled conditions. Later, it achieves better PW degradation compared to conventional thermochemical degradation methods. Enzymatic processes operate at ambient temperatures, and near-neutral pH values, significantly lowering energy input, and minimizing the release of toxic byproduct units.[127,128] This confers ecological advantages, and makes the process inherently more sustainable. This can help to identify, and optimize enzymes capable of degrading a broad spectrum of synthetic polymers/plastic wastes. Notable targets include PET, polyurethanes (PU), and polyamides (*i.e.*, nylon), each requiring tailored enzymatic mechanisms due to their structural diversity, and chemical resistance.[129]

Next, it provides a clear concept of the enzymatic degradation process typically involving initial adsorption of the enzyme onto the polymer surface, followed by catalytic cleavage of the polymer backbone. This process may be influenced by polymer crystallinity, surface morphology, and the presence of additives. It can exhibit the potential of some enzymes like PETase, and MHETase that are exemplary enzymes with demonstrated activity against PET.[120] PETase enzymes catalyzes the hydrolysis of PET to mono(2-hydroxyethyl) terephthalate (MHET), which is further degraded by MHETase into terephthalic acid and ethylene glycol components amenable to repolymerization or alternative valorization. This approach shows some major challenges like the discovery of enzymes with activity against recalcitrant plastics, improving enzyme robustness for industrial-scale applications, and optimizing process parameters for maximal efficiency.[129,130] Integration with mechanical or chemical pre-treatments may enhance substrate accessibility and degradation rates. This approach shows some advantages like a biocatalytic plastic recycling process that holds promise for enabling closed-loop systems and advancing a circular economy. Applications include the recovery of high-purity monomers for repolymerization, bioconversion into value-added products, and remediation of plastic-polluted ecosystems.[131] Several microorganisms capable of degrading petroleum-based synthetic polymers under *in vitro* conditions have been successfully isolated and characterized. In numerous cases, the genes encoding the relevant plastic-degrading enzymes have been cloned, sequenced, and expressed heterologously to facilitate further biochemical and structural studies.[132] The efficiency of microbial or enzymatic degradation of polymers is influenced by multiple physicochemical parameters, including the polymer's chemical structure, molecular weight, degree of crystallinity, and surface morphology. Synthetic polymers are macromolecules composed of both ordered (crystalline) and disordered (amorphous) regions. The crystalline domains contribute to rigidity and thermal stability, while the amorphous regions confer flexibility and enhance susceptibility to enzymatic attack.[131,132] Polymers such as polyethylene, characterized by extremely high crystallinity (~95%), exhibit substantial mechanical rigidity and poor biodegradability. In contrast, polyethylene terephthalate (PET) displays intermediate crystallinity (30–50%), which still significantly hinders enzymatic accessibility and hydrolysis.[133] The high degree of crystallinity, coupled with the recalcitrant aromatic backbone of PET, results in environmental persistence, with complete biodegradation estimated to exceed 50 years under terrestrial conditions and extending to several centuries in marine environments due to lower temperatures and reduced oxygen availability.[134] Enzymatic depolymerization of plastics typically proceeds *via* a two-step mechanism: initial adsorption of the enzyme onto the polymer surface, followed by catalytic cleavage of the polymer backbone through hydrolytic or oxidative reactions (*e.g.*, hydrolysis, hydroperoxidation). Plastic-degradation assisting enzymes have been identified from a diverse array of microbial sources, including fungi, and bacteria that were isolated from soil, compost, wastewater, and marine environments as well as from the gut of microbiota of certain invertebrates capable of ingesting synthetic polymers.[133,134] Microbial, and enzymatic degradation represent a viable, and environmentally sustainable strategy for the depolymerization of recalcitrant petrochemical plastics. This biocatalytic approach facilitates the recovery of monomeric building blocks of polymer recycling or their conversion into value-added bioproducts like biodegradable polymers or other bio-based materials *via* complete mineralization.[135] This review aims to summarize recent advances in the microbial degradation of synthetic plastics, with a particular emphasis on the enzymatic pathways, and molecular mechanism underlying this process.[135,136]

4.3. Upcycling and product redesign for plastic wastes

Upcycling and product redesign can represent advanced processing strategies in PW management, wherein post-consumer or discarded plastic materials are repurposed into high-value products. These processes contribute to the development of a circular economy by extending the lifecycles of plastic materials. This can help in decreasing the dependency on virgin polymer production/generation.[127] Through material revalorization, and functional transformation, these approaches mitigate environmental pollution, reduce solid waste accumulation, and enhance the economic, and functional utility of PW streams. Upcycling processes are described to innovative reuse of PWs to fabricate new products with equal or enhanced functional, and economic value compared to the original plastic materials.[138] This process emphasizes additional value without degrading material quality, thereby supporting sustainable resource utilization, and contributing to circular material flows. In this approach, the upcycling process can apply by converting plastic bottles into planters, fabricating bird feeders from repurposed bottled, and creating coasters from discarded plastic lids.[137,138] These applications demonstrate practical, and creative pathways for transforming PWs into functional, and value-added products, thereby reducing environmental impact, and supporting sustainable waste management practices. PW valorization can be achieved by a range of recycling technologies like mechanical, chemical or enzymatic recycling processes.[92] The mechanical recycling process is known to involve physical processing to reconstitute PWs into secondary or usable raw materials but the chemical recycling process is completed to break down complex plastic polymers into respective monomers or other chemical feedstock by using several processes like gasification, pyrolysis, and depolymerization.[139]

The enzymatic recycling process utilizes specific enzymes to catalyze the depolymerization of plastic polymers under mild processing conditions. These methods enable the transformation of PWs into high-value products, materials/specialty chemicals/fuels as output, thereby promoting better resource recovery, and advancing circular economy objectives.[92,139] These recycling, and upcycling strategies contribute to waste reduction, minimize environmental pollution, and foster the development of new economic opportunities though the creation of value-added products/sustainable industries.[140] Product redesign emphasizes the development of product with inherent sustainability, prioritizing materials, and structural features that facilitate reuse, repair, and end-of-life recyclability. This approach integrates principles of eco-design, and life cycle thinking to minimize environmental impact while enhancing product longevity and resource efficiency.[133] Recent advancements in the PW upcycling process have led to transformative technologies including vitrimerization, additive manufacturing, nanocomposite fabrication, catalytic transformation, and industrial biotechnology.[141] Vitrimerization enables the reprocessing of thermoset plastics *via* dynamic covalent networks, whereas the nanocomposite fabrication process can enhance recycled plastic by incorporating nanoscale fillers for superior performance.[142]

Additive manufacturing uses recycled plastic in 3D printing to support localized, low-waste production. The catalytic transformation process can be employed by selecting catalysts to depolymerize plastics into fuels/chemicals under milder processing conditions.[143] Industrial biotechnology utilizes the engineered enzymes, and microbes to biologically convert plastics into valuable bioproducts. However, challenges such as material heterogeneity, contamination, high processing cost, and limited infrastructure persist.[144] Future development include AI-assisted sorting, decentralized upcycling systems, and closed-loop manufacturing. These innovations offer promising pathways for advancing circular economy models and creating sustainable, high-value applications for PWs.[61,145]

4.3.1. Photo-catalytic plastic degradation. It is an advanced oxidation process that utilizes semiconductor materials, such as TiO_2 or ZnO, as photocatalysts. These photocatalysts decompose plastics, including microplastics, into smaller, less harmful molecules such as CO_2 and H_2O. Upon irradiation with light of suitable energy, typically UV or visible light, the photocatalyst generates electron–hole (e^-/h^+) pairs.[146] These charge carriers initiate redox reactions, producing reactive oxygen species (ROS) such as hydroxyl radicals ($^{\bullet}OH$), and superoxide anions ($O_2^{\bullet-}$). These ROS aggressively attack polymer chains, inducing chain scission, and oxidative degradation *via* radical-mediated pathways.[147] The process can lead to either partial fragmentation or complete mineralization of the polymer matrix. Recent advancements in nanostructured photocatalysts, and visible-light-responsive materials have enhanced degradation efficiency, and extended photocatalytic activity under solar irradiation. Additionally, emerging research focuses on value-added conversion of plastic waste into useful fuels, and chemicals *via* photocatalytic reforming.[148]

4.3.2. Electrocatalytic approaches for plastics. This review presents recent advances in the electrooxidation mechanisms of various plastic wastes, including polylactic acid (PLA), polyethylene glycol terephthalate (PET), polyethylene (PE), polyethylene furanoate (PEF), polybutylene terephthalate (PBT), and polyamides.[149] The electrooxidation of these polymers involves complex anodic degradation pathways, leading to partial oxidation or complete mineralization into CO_2 and smaller organic intermediates. Mechanistic differences arise due to variations in polymer backbone structure, crystallinity, and functional groups.[150] The progress in plastic waste-assisted electrolysis systems is then summarized, highlighting applications such as plastic-driven water splitting for hydrogen evolution, and oxygen reduction reactions (ORR), as well as electroreforming of plastics coupled with CO_2 reduction, and nitrate reduction reactions (NO3RR).[149,150] These integrated approaches not only mitigate plastic pollution but also enable value-added chemical and fuel production under electrochemical conditions.[151] Finally, the prospects, and challenges of plastic electroreforming are discussed, including catalyst stability, selectivity, energy efficiency, and system scalability. Selective electrooxidation of monomers was achieved through the hydrolysis of plastics.[152] It emphasizes the coupling of anodic and cathodic reactions to improve energy efficiency. The introduction of heteroatoms is explored as a strategy to diversify the functionality of target products.[151,152] Emerging strategies for processing non-hydrolyzable plastics is highlighted with the potential of integrating electrocatalysis with complementary techniques to enable broader applicability, and scalable circular recycling. A novel bifunctional Ru-Co_3O_4 heterostructured electrocatalyst was developed to simultaneously drive the nitrite reduction reaction (NO_2RR), and the ethylene glycol oxidation reaction (EGOR).[153] This system enables the effective upgrading of nitrite-rich wastewater, and poly(ethylene terephthalate) (PET)-derived ethylene glycol (EG) into high-value products ammonia (NH_3), and formic acid (FA).[150,152] The catalyst's optimized hydrogen (*H) generation, and utilization balance enables outstanding NO_2RR performance, achieving a high faradaic efficiency (FE) of 97.4%, and an NH_3 yield rate of 7.46 mg h^{-1} cm^{-2} at a low potential of −0.15 V *vs.* RHE. Concurrently, EG oxidation to FA reaches a high FE of 91% with robust durability at 1.3 V *vs.* RHE.[149,151] Furthermore, a Zn-nitrite battery using Ru-Co_3O_4/CF as the cathode was assembled to serve as a self-powered system. This battery successfully drives the coupled NO_2RR-EGOR two-electrode setup, achieving energy-autonomous electrocatalytic conversion of nitrite, and PET-derived EG into NH_3 and FA.[151,153]

5. Integration into the circular economy

5.1. Closed-loop systems and industrial symbiosis

The present work is discussed for various efforts that play a critical role in advancing global climate change mitigation but it supports operationalizing circular economy principles within the plastic value chain. It emphasizes the reduction of GHG emissions throughout the lifecycle of plastic materials by promising sustainable practices centred on resource recovery efficiency, waste minimization and closed-loop systems.[137,138] Conventional plastic production is predominantly dependent on fossil fuel-based feedstock, resulting in substantial GHG emissions. This study advocates for transitioning to high-efficiency recycling paradigms, both mechanical and chemical recycling techniques/approaches that can significantly reduce the need for virgin polymer synthesis.[154] Chemical recycling technologies like gasification and pyrolysis approaches enable the depolymerization of post-consumer PWs into reusable feedstock. It can enable offsetting the carbon-intensive processes associated with petroleum extraction and refining processes.[137,154] The integration of biodegradable and bio-based can further support the decoupling of plastic production from fossil fuel reliance, contributing to an upstream emission reduction effort.[155]

The circular economy model underpinning this work seeks to extend the functional life of materials through the reintegration of PWs into production cycle as secondary raw materials as recycled polymers. This approach reduces the demand for primary production and lowers the environmental footprint of plastic-intensive sectors. Industrial initiatives, such as those led by Loop Industries, focus on the conversion of PET and polyester waste into high-quality, high-purity recycled polymers, demonstrating the feasibility of scalable, low-emission recycling processes.[156] Landfill diversion is a key outcome, minimizing methane emissions in the environment that are generated by anaerobic degradation of plastics. The deployment of advanced thermochemical conversion methods including autothermal pyrolysis offers a lower-emission alternative (of GHG/methane) to the traditional incineration approach. These processes, when coupled with carbon capture and utilization (CCU) systems, provide an integrated solution for emission abatement in waste-to- energy applications.[157] Furthermore, this work highlights the intersection of circular economy strategies and renewable energy integration. Transitioning to low-carbon, energy-efficiency recycling infrastructures powered by renewable resources like wind or solar supports the decarbonisation of the recycling sector itself. The synergistic deployment of recovered plastics in renewable energy systems, including components for photovoltaic modules and wind turbines, exemplifies material circularity in sustainable infrastructure development.[156,157]

At a systematic level, the adoption of recycled inputs across industrial supply chains reduced product-level carbon intensity. Corporate initiatives such as Coca-Cola's "world without waste" target significant emissions reductions by incorporating 50% recycled content in PET packaging, aligning corporate operations with climate change/targets.[158] This framework also promotes regulatory and behavioural mechanisms, including extended producer responsibility (EPR) programs that incentivize design for recyclable and lifecycle stewardship.[120,158] Consumer awareness campaigns and global policy instruments, like the Basel Convention, support a cross-border regulation of PW flows and reinforce the global commitment to sustainable recycling practices.[159] In sum, this work integrates advanced recycling technologies, the circular economy, and policy mechanisms to address the interlinked challenges of PWs/plastic pollution and climate change issues. It provides a scalable, science-driven roadmap for reducing emissions, enhancing material recovery, and achieving long-term environmental sustainability.[160]

5.2. Design for recycling and reuse of plastic waste for a circular bioeconomy

This study presents advanced recycling technologies that use various approaches like chemical recycling, AI-enhanced sorting systems, and biodegradable material alternatives. Techniques like pyrolysis, and depolymerization facilitate the molecular reconstruction of polymers into feedstock-grade raw materials, enabling scalable, and circular economy material flows.[161] Moreover, AI-driven sorting platforms exemplified by AMP Robotics optimize waste stream classification, improving material recovery rates and operational efficiency. This work identified critical gaps in current recycling methodologies, particularly in processing composite, and multi-layered plastic wastes. By integrating LCA methodology, this study provides a quantitative basis for evaluating the environmental trade-offs and systematic impacts of various recycling approaches.[73, 162] In examining regulatory frameworks such as extended producer responsibility (EPR) and transboundary agreements like the Basel Conversion, this research offers evidence-based insights for policymakers. Japan's Packaging Recycling Acts, achieving a PET recycling rate of 85%, exemplified effective legislative implementation and compliance mechanisms.[73, 161]

Closed-loop systems, as implemented by Loop Industries, upcycle low-grade polymers into high-performance PET, enhancing industrial sustainability. This study highlights the emergence of secondary markets for post-consumer recycled materials across sectors like textiles, construction, and mobility. For instance, Adidas' collaboration with Parley for the Oceans exemplifies value creation through the repurposing of marine plastic in consumer goods.[162] By articulating scalable interventions, this work encourages cross-sectorial investment in recycling infrastructure. Financial instruments such as those mobilized by the Global Plastic Action Partnership (GPAP) facilitate capital flows to high impact initiatives, particularly within emerging economies.[163] The study's implications span research, social transformation and economic development. This highlights the integrative potential of recycling innovation in driving progress toward circular economy objectives. Through a synthesis of technology, policy, and participatory frameworks, this work advances a holistic approach to PW governance, aligning with global sustainability targets.[164]

The proposed strategies demonstrate a measurable reduction in plastic pollution, essential for safeguarding marine diversity, and public health. Enhanced waste treatment processes reduce microplastic infiltration into trophic systems, thereby directly impacting food safety and the integrity of potable water.[165] Concurrently, decreasing virgin plastic demand mitigates GHG emissions, contributing to climate change abatement.[166] The study underscores the role of civic engagement in circular economy transitions. Initiatives like India's Swachh Bharat Abhiyan illustrate the impact of mass mobilization and behaviour change in achieving sustainable waste management at small and large scales.[165,166] By addressing infrastructural inequities, the study ensures that marginalized regions benefit from technological diffusion. Programs such as Plastic Bank demonstrate how socio-environmental models can incentivize plastic collection while delivering community-level economic resilience.[167] Innovative recycling ecosystems catalyse job creation across waste valorization, materials science, and green tech sectors. Initiatives like BASF's is known to parts of ChemCycling™ and Plastic Bank. They illustrate how circular business models generate employment while tracking plastic externalities. Recycling decreases reliance on primary resources, notably petroleum yielding cost saving and conservation benefits.[162,167]

6. Conclusions and future perspective

The study elucidates the transformative potential of advanced recycling technologies in mitigating the global plastic waste crisis. It examines cutting-edge methods such as mechanical recycling, energy recovery methods, microwave-assisted pyrolysis, chemical recycling, and biotechnological conversion that enable the depolymerization and repurposing of PWs into high-value secondary raw materials. These approaches markedly reduce dependence on conventional waste management practices, including landfilling and incineration. This practice can deliver both ecological and economic benefits. Digitalization is identified as a key enabler, with artificial intelligence-driven sorting systems and Internet of Things (Iot)-based monitoring systems. These can help in enhancing material recovery efficiency and traceability. Integration of these innovations within a circular economy framework supports resource conservation, minimizes environmental leakage issues, and promotes systematic sustainability in plastic lifecycle management.

The research emphasizes the necessity of cross-sectoral collaboration, and enabling policy mechanisms. Strategic partnerships among regulatory bodies, industry stakeholders, and civil society are crucial for scaling technology deployment, and embedding advanced recycling into existing infrastructure. Employing life-cycle assessment methodologies, the study quantifies the reduced environmental burdens and economic viability of these technologies. This systems-based approach not only addresses the immediate issue of plastic accumulation but also contributes to long-term sustainability planning.

In conclusion, the study proposes a data-driven, integrative roadmap for transforming PWs into circular resource streams. By endorsing these innovations, stakeholders can accelerate progress toward circular economy objectives/model. This aligns with international sustainability commitments, and substantially lowers the environmental footprint associated with plastic materials. This review also focussed on an advanced chemical recycling approach. It offers innovative solutions for plastic valorization by breaking down complex non-degradable plastics into monomers or fuels. This process enables the recovery of high-quality materials, thus supporting a circular economy. It further reduces landfill waste, and lessens reliance on virgin fossil resources. This approach makes the use of waste plastic more sustainable and environmentally responsible. Future plastic recycling efforts must rely on innovative methods, such as chemical recycling, enzymatic degradation, and AI-driven sorting. These technologies can facilitate the efficient recovery of monomers, minimize environmental impact, and promote circular economies. Integrating renewable energy and decentralized systems further can enhance sustainability, shaping a cleaner, smarter future for global plastic waste management.

Conflicts of interest

There are no conflicts of interest to declare.

Data availability

All relevant data, including experimental results, analysis, and supplementary materials, have been provided in the manuscript.

Abbreviations

AA-NZ	Acid-activated natural zeolites
ACRTs	Advanced chemical recycling techniques
AI	Artificial intelligence
$AlCl_3$	Aluminum chloride
BASF's ChemCycling	Badische anilin-und soda-fabrik
CCU	Carbon capture and utilization
CE	Circular economy
CH_4	Methane
CO_2	Carbon dioxide
EPR	Extended producer responsibility
GHG	Greenhouse gas
GPAP	Global plastic action partnership
GWP	Global warming potential
HDPE	High density polyethylene
kWh	Kilo watt hour
LCA	Life cycle assessments
LDPE	Low density polyethylene
LPG	Liquefied petroleum gas
mAP	Mean average precision
Mask R-CNN	Mask region-based convolutional neural network
MHET	Mono (2-hydroxyethyl) terephthalate
MPW	Medical plastic waste
MPWM	Municipal plastic waste management
MRFs	Material recovery facilities
MSW	Municipal solid waste
MT	Metric tonnes
N_2O	Nitrous oxide
NCC	Naphtha cracking center process
NH_3-TPD	Ammonia-temperature programmed desorption
NiMo	Nickel–molybdenum
NZ	Natural zeolite
PAHs	Polycyclic aromatic hydrocarbons
PET	Polyethylene terephthalate
POPs	Persistent organic pollutants
PP	Polypropylene
PPE	Personal protective equipment
PS	Polystyrene
PU	Polyurethanes
PVC	Polyvinyl chloride
PWs	Plastic wastes
SDGs	Sustainable development goals
SO_2	Sulphur dioxide
TA-NZ	Thermally activated zeolites
tCO_{2eq}	Tonnes of carbon dioxide equivalent
TEM	Transmission electron microscopy
TPA	Tonnes per annum
XRD	X-ray diffraction
YOLO v8	You only look once version 8

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