International Journal of Industrial Engineering and Technology.
ISSN 0974-3146 Volume 18, Number 1 (2026), pp. 51-62

http://www.irphouse.com

Plastics in a Net-Zero World: Can Recycling Alone Meet Sustainability Targets?

Richa Khulbe, **Aditi Panjab Jadhao**, **Tanvi Bangal** and **Ashok Athalye**
Institute of Chemical Technology, Mumbai*, India.*

Abstract
Plastic recycling is a crucial tool for material reuse and reducing the carbon footprint of production. Inherent material losses, energy demands, and degradation during recycling limit the feasibility of a closed-loop system. A comprehensive strategy is essential to sustainably decrease plastic consumption by enhancing recycling, increasing reuse, adopting plant-based plastics, and designing plastics more intelligently. Policy actions such as extended producer responsibility, mandatory recycled-content requirements, and carbon pricing can encourage greener practices. Advanced technologies such as AI-powered sorting, renewable energy recycling, and reusable plastics offer additional opportunities; however, scaling these solutions requires adequate infrastructure, funding, and international collaboration. Transitioning from a linear "make-use-discard" model to a circular approach can make plastics a vital part of a resilient, low-carbon future.
Keywords: Carbon Currency, Circular Economy, Climate Change, Global Warming, Life Cycle Assessment

1. Introduction

Plastics in many forms are a major environmental concern due to their extensive use, durability, and complex life cycles. Their longevity in the environment leads to pollution, with microplastics polluting oceans and soils, and large landfills impacting ecosystems. Inadequate recycling facilities and inconsistent global policies worsen this issue, complicating waste management efforts [1]. As a result, it became central to debates about moving towards circular economies that focus on reuse and reducing environmental impact. Global plastic production has increased sharply, from 1.5 million metric tons in 1950 to 359 million metric tons in 2018 [2]. In 2019 alone, global production reached 376 million tons, with over one-third, more than 133 million tons, dedicated to single-use packaging [3]. Today, plastics are integral to virtually every sector, including electronics, healthcare, agriculture, and infrastructure. Without significant interventions, continued reliance on oil and gas will likely exacerbate the environmental and climate impacts of plastic pollution.

Plastic waste is expected to increase from 110 million tons in 2020 to around 205 million tons by 2040, resulting in an 86% rise if recycling is not taken seriously. The Geneva Environment Network notes that plastic production may increase CO_2e emissions by 63%, rising from 1.9 $GtCO_2e$ in 2019 to 3.1 $GtCO_2e$ by 2040. This highlights how plastics contribute significantly to climate change, not just to landfill issues [4]

Despite increased awareness, Plastic recycling worldwide accounts for only 9%, while nearly half is thrown away or buried in landfills, and about one-fifth is incinerated, generating limited energy and toxic fumes [5, 6]

Advances in technology are enabling higher-quality recycled plastics. Infrared scanners, specialised additives, and smart sorting systems now allow materials to regain their original strength and even colour, producing new blends comparable to virgin plastics[7] Chemical recycling further enhances this process by breaking down polymers such as nylon, PET, and polystyrene into nearly pristine building blocks.[8] Packaging designs that require fewer ingredients and single-use plastic also promote recycling. The main challenges persist in mixed-material packaging designs, the high processing costs of waste, and, lastly, regulatory restrictions on the use of recycled plastics in food and medical-grade applications[9]. Even with technological advancements in energy recovery and material conversion, properly managed landfills remain crucial in preventing contamination for recycling. Hence, the transition to a truly circular plastic economy relies on robust policies, including organisation responsibility programs, pricing mechanisms for virgin plastics, and public education initiatives.

2. Recycling Pathways in the Net-Zero Context

Plastic can be reused through various recycling methods, each with its own advantages and limitations, as shown in Table 1 and detailed further.

Table 1: Matrix of Plastic Recycling Technologies in a Net-Zero Context.

Feature	**Mechanical**	**Chemical**	**Solvent-Based**	**Enzymatic**
Output Purity	Low (Degrades over time)	High (Virgin-quality monomers)	Highest (Removes dyes/glues)	Highest (Specific breakdown)
Energy Intensity	High (Thermal heat)	High (Thermal heat)	Moderate	Low (No or Very low heating)
Input Flexibility	Rigid (Needs clean, sorted waste)	Rigid (Needs clean, sorted waste)	Specialised (Multilayer)	Niche (PET & PLA focus)
Economic Readiness	Market Leader (Profitable now)	High Capex (Pilot/Experimental)	Developing	Research Stage (Long-term)

Net-Zero Role	Core Efficiency (Low carbon footprint)	Loop Closer (For "un-recyclables")	Niche Solver (Complex waste)	Bio-Future (Sustainable pathway)

1.1.Mechanical Recycling

Mechanical recycling is primarily used to recycle plastics such as PE, PP, and PET. The process involves steps from collecting to sorting and cleaning plastic waste, then extruding it into pellets, suitable for new products with minimal structural alterations [10]. The benefits of this method are tempered by shortcomings, such as recurrent recycling, which, over time, weakens plastic, reducing mechanical properties such as strength and flexibility, and lessening its capacity for reuse compared to a virgin product [11].

Researchers are exploring solutions, including AI-driven smart sorting and additive treatments like compatibilisers or dynamic cross-linkers, to improve the uniformity and durability of recycled plastics and enhance their performance [12, 13]. Economically and environmentally, mechanical recycling surpasses other methods and virgin plastic production, although it results in lower material quality and technical performance. Although complications persist, polymers degrade after several cycles, reducing their strength and flexibility. Additionally, contamination from mixed materials further diminishes quality, rendering some plastics unsuitable for reuse. Improving recyclability will depend on smarter sorting, optimised processes, and the design of products specifically for reuse [14, 15].

1.2.Chemical Recycling

Chemical recycling offers a promising way to turn plastic waste into useful materials, which helps society move towards a more circular economy. It’s especially good at recycling contaminated, mixed, or multi-layer plastics that are difficult to mechanically recycle, opening a pathway to bring unrecyclable material to life [16]. Pyrolysis is the most common method because it can handle a wide range of raw materials and is highly adaptable. During pyrolysis, plastics are heated in an oxygen-free environment to break down their complex structures or convert polymers into simpler substances [17]. This process can be thermal, catalytic, or co-pyrolysis, depending on whether catalysts are involved [18, 19].

While promising, chemical recycling still faces hurdles, including high initial costs, technological challenges, variability in waste streams, and the need for more effective catalysts and reactor designs to boost efficiency and scalability. Regulatory uncertainties and the lack of standardised products also slow down market growth and investments in large-scale facilities. However, integrating chemical recycling with renewable energy and improved waste sorting can help minimise environmental impacts and complement mechanical recycling, paving the way for a more sustainable approach to managing plastic waste [20].

1.3.Emerging approaches in plastic recycling

Emerging recycling approaches that integrate chemical, biological, and renewable-energy-assisted methods are improving the efficiency of plastic reuse while reducing environmental impacts[21]

1.3.1. Solvent-based recycling

A developing physical recycling technique, solvent-based recycling, also known as dissolution-based recycling, can effectively handle mixed plastic waste. It isolates desired polymers by removing contaminants such as dyes and glues, yielding exceptionally pure material.

This technique shines with tricky materials, think layered food wrappers, mixed plastics, discarded electronics, or car parts, where standard recycling falls short because of blended plastics and glues [22].

1.3.2. Enzymatic/microbial recycling

Instead of discarding plastic, a new eco-friendly approach uses enzymes or microbes to break down plastics like PET and PLA, with organisms such as *Ideonella sakaiensis* playing a key role in enzymatic PET degradation [23]. Several organisms, including *Thermomyces lanuginosus, Bacillus, Ideonella sakaiensis, Candida antarctica, and Burkholderia spp.*, are among the bacteria and fungi that produce enzymes, such as cutinases, lipases, and esterases, that effectively depolymerise plastics [24].

2. Life Cycle Assessments (LCA) & Carbon Accounting

Researchers use life cycle assessment (LCA) to evaluate the environmental impacts of plastics throughout their life cycles, from raw material extraction to end-of-life management [25]. LCA results vary depending on data quality and system boundaries, yet the method remains essential for comparing recycling options. It helps identify responsible waste management strategies that may combine recycling with energy recovery [26, 27].

2.1.Regional Variability: EU vs. Asia vs. the United States

Across the European Union, thorough lifecycle assessments reveal that plastic produced with power from renewable resources and reclaimed materials can cut greenhouse gas emissions by as much as 70% compared with traditionally sourced plastics [28]. Because the EU integrates these assessments into its plans, particularly via the Circular Economy Action Plan, which has enabled industry standards regarding carbon footprints. Across Europe, producing new plastic generates roughly 2.5 to 3 kilograms of carbon emissions per kilogram produced. However, recycling plastic mechanically results in significantly fewer emissions, that's just 0.5 to 0.8 kilograms per kilogram [29, 30].

Across Asia, particularly in China and Southeast Asia, plastics exhibit higher lifecycle carbon footprints, largely due to coal-based energy systems and rapidly expanding production capacities [31]. Regional studies reveal that producing brand-new plastics can generate up to 5-7 kg CO_2e per kg of plastic produced [32], nearly twice the typical amount seen in Europe [33]. Open fires, poorly managed waste heaps, also a lack of

good facilities for separating or chemically reprocessing materials worsen the area's carbon footprint [34]. Several Asian nations, including South Korea and Japan, are experimenting with detailed methods to measure environmental impact to guide resource-efficiency efforts; however, regional approaches to tracking carbon emissions remain less consistent than in Europe.

The US plastic industry sits between Europe and Asia in terms of environmental impact. Because it relies more on ethane and less on coal, giving lower carbon intensity than coal-based regions, but still substantial emissions[35]. Low recycling, i.e. only 5–6% nationally, means we need more raw stuff, which worsens the overall carbon footprint. Initiatives such as the EPA program and the U.S. Plastics Pact attempt to standardise measurements, yet without required lifecycle assessments from the government, businesses struggle to accurately track their carbon impact [36, 37]

2.2. Limitations of existing LCA data

Existing life cycle assessment (LCA) data often fail to accurately represent the complexity of modern plastic products and packaging. Assessing environmental impacts becomes particularly difficult for multilayer or composite packaging that combines materials such as polyethene, polypropylene, polyamide, and aluminium[38, 39]. These structures provide essential protective properties but are rarely modelled accurately in LCAs, leading to underestimation of their environmental footprint (Faraca & Astrup, 2022). The use of adhesives, coatings, and additive packages affects both production impacts and end-of-life (e.g., recyclability, need for delamination, toxicity), but is often poorly specified in inventories, contributing to large variability in reported results[40]

Thermoset systems (epoxies, PU foams, fibre‑reinforced composites) are intrinsically hard to model because their cross‑linked networks prevent melting and standard mechanical recycling, pushing them toward landfilling and incineration. Reviews stress that the diversity of chemistries makes comparative LCA across thermoset recycling options difficult and call for more systematic environmental datasets as recycling scales up [41].

Another key limitation lies in the absence of standardised global databases and in the lack of data on geographical context, electricity mix, waste composition, and treatment options, making quantitative cross-study comparisons difficult and often unreliable[42]. Even when goals align, differences in system boundaries, functional units, and impact methods lead to divergent outcomes [43]Most LCAs rely on regional inventories such as Ecoinvent, GaBi, or Plastics Europe, which differ significantly in their energy mixes, production efficiency, and waste management practices [44]. For chemical recycling and pyrolysis, multiple reviews highlight the scarcity of industrial life-cycle inventory data and the reliance on lab- or pilot-scale information [45]

3. **Can Recycling Alone Deliver Net-Zero?**

Recycling substantially lowers life-cycle GHGs by avoiding virgin polymer production and associated fossil extraction [46]. Recycled polymers instead of new polymers could reduce emissions by up to 67 Mt CO_2e across the entire supply chain, from production

to delivery. On a per-unit basis, emission reductions typically range from 30% to 70%, depending on polymer type and regional energy sources [47]
However, expanding recycling alone will not be sufficient to achieve carbon neutrality in the plastics sector. Studies show that net-zero plastics are only possible when high recycling (effective rate ~70%) is combined with biomass and CO_2-based feedstocks and renewable energy, and material recovery peaks around 72% efficiency while maintaining ~97% purity [48, 49]

3.1.The "carbon gap"

A persistent "carbon gap" remains because even highly efficient recycling cannot fully eliminate the need for new resources or prevent all related emissions. Three main factors contribute to this limitation.
First, material losses occur at every stage of the recycling process. Despite advances in sorting and collection, certain products cannot be effectively reclaimed. Studies have shown that multilayer films, thermosets, and plastics containing additives are particularly resistant to recycling, so even a "best practice 2030" scenario achieves only ~49% recycling for packaging waste [50]. As a result, new polymers must still be produced to replace materials that cannot be reused.
Second, once carbon enters circulation, it tends to remain within the system. Reuse often prolongs the life of fossil-based carbon rather than replacing it with renewable materials. Ultimately, that carbon re-enters the atmosphere through degradation, incineration, or gradual release [51].
Third, recycling processes they are not entirely clean [52]. Some methods generate additional emissions when they rely on energy-intensive techniques, chemical treatments, or specialised equipment [53, 54]. Using low-carbon energy sources such as green hydrogen or renewable electricity could significantly reduce the environmental burden of recycling. Without such improvements, pollution from recycling operations may offset some of their potential benefits [55, 56].

4. Beyond Recycling: Complementary Pathways

While recycling remains a cornerstone of circular economy strategies, growing evidence shows that it cannot, by itself, secure a fully sustainable or net-zero future. Even with optimised collection, sorting, and processing, significant carbon emissions persist due to energy-intensive operations, material losses, and continued reliance on fossil-based feedstocks. Bridging this remaining carbon gap will require an integrated approach that combines improved recycling with reductions in plastic production, shifts to renewable energy, and the adoption of bio-based or low-carbon materials.

4.1. Reuse and Refill Systems

Reuse and Refill Systems suggests that these systems can greatly enhance the climate. Reusing materials reduces both energy use and emissions, as items last longer than when remade or recycled. For plastic takeaway containers, reusable plastic containers outperformed single-use after just 2-4 uses [57]

It speaks for a set of combined measures, such as reducing consumption, increasing reuse, boosting collection and recycling, and safe-disposal, that can cut plastic waste entering the environment by 78% relative to business-as-usual [58]

4.2. Bioplastics and Compostable Alternatives

Switching to bioplastics or other naturally degradable plastics could reduce reliance on oil-derived materials and advance circular systems, but performance depends strongly on feedstock, farming, energy mix, and end-of-life (EoL) [59, 60]. LCAs show that while many bioplastics reduce global warming potential, this can be offset by acidification, eutrophication, and land-use change from intensive agriculture and deforestation [61]

Reviews of comparative LCAs show bioplastics often achieve substantially lower GHG emissions and non-renewable energy use than petroplastics, but with a wide numeric range depending on system choices [62]

For specific polymers such as PLA and bio-PE, cradle-to-grave LCAs report bio-PE as low as –1.0 kg CO_2-eq/kg and PLA around 1.7 kg CO_2-eq/kg under favourable assumptions, versus higher values for HDPE/LDPE; including biodegradation at EoL can raise PLA emissions by 16–163% if landfill/compost gas is not well managed [63]

Bioplastics are not a complete solution for all of our plastic problems. Their large-scale adoption requires vast areas of farmland, risking forest loss and soil degradation and their biodegradability, which remains the primary cause to switch, is environment- and facility-dependent; many bioplastics only fully degrade in industrial composting, not in soil or marine environments, and in regular waste streams, they can emit methane and CO_2 or persist as microplastics [64, 65]. They remain more expensive than petroplastics, with higher production costs and the need for new infrastructure, which are the key barriers to scale [66, 67].

4.3. Demand Reduction & Material Redesign

Lightweighting, reducing the mass and complexity of plastic products, can cut virgin plastic demand by 20 to 30% in consumer goods, automotive, and packaging sectors without compromising functionality. Designing products with end-of-life in mind, such as single-material packaging, improves sorting and mechanical recycling, reducing reliance on new resources and the energy-intensive production of virgin plastics [68, 69].

Redesigning plastic items to be simpler and separable can make them 50% easier to recycle. Design-for-recyclability can lower lifecycle CO_2 emissions by 0.8 to 1.5 kg CO_2e per kilogram of plastic, primarily by reducing virgin polymer production[70].

Reducing consumption and rethinking materials are key to achieving circular carbon loops. Vidal et al. emphasise treating plastics as temporary carbon storage, combining plant-based materials, CO_2 use, and better product design to cut emissions by up to 45 per cent by 2050[71].

5. Policy, Industry, and Roadmaps

5.1. The Role of Extended Producer Responsibility (EPR)

Producers become responsible for the afterlife of plastics once consumers discard them, and this approach, called Extended Producer Responsibility, aims to create a more sustainable lifecycle by encouraging organisations to consider product design, use, and disposal to minimise waste. EPR schemes require producers to fund recycling infrastructure, collection networks, and waste sorting, enabling countries to develop domestic recycling capabilities rather than exporting waste [72]

Tracking climate commitments becomes easier when companies are mandated to increase recycled content in products. Consequently, we can better measure cuts in both carbon output and overall waste. Thus, bolstering efforts towards zero emissions likewise strengthens the move to a circular economy.

5.2. European Union

Europe aims to achieve a carbon-neutral future by 2050, focusing on recycling and reuse as its primary strategies. New regulations mandate that all packaging must be easily recyclable by 2030, with goals to cut packaging waste by 5%, 10%, and 15% before 2030, 2035, and 2040, respectively, relative to 2018 levels. By 2040, the EU aims to recycle two-thirds of plastic bottles and collect 90% of beverage containers via deposit return schemes by 2029. The Circular Plastics Alliance plans to incorporate 10 million tons of recycled plastic into manufacturing by 2025, supporting these targets. These efforts exemplify the EU's broader strategy to close material loops and promote circular economy practices through policies, infrastructure, and stakeholder cooperation [73–76]

5.3. United States

The U.S. Plastics Pact, a collaboration of industry and environmental groups, aims by 2025 to have all plastic packaging be reused, recycled, or biodegradable, with half of all packaging actually recycled and containing at least 30% recycled or biobased content. This initiative aims to eliminate certain problematic materials from packaging and is supported by leading companies responsible for a significant share of U.S. packaging production [77, 78]. The U.S. Environmental Protection Agency (EPA) backs these efforts through its National Recycling Strategy, aligning with federal objectives to eliminate single-use plastics in government operations by 2035, with interim milestones set for 2027. These policies reflect increasing recognition of the environmental harm caused by single-use plastics and emphasise the importance of systemic changes in how products are produced and waste is managed [79].

5.4. India

Driven by groups such as the Confederation of Indian Industry and WWF, India’s plastics initiative aligns with existing waste rules and supports a 2070 zero-emissions target. The Plastic Waste Management (PWM) Amendment Rules 2022 set stepwise EPR recycling targets for rigid, flexible, multilayer, and sheet plastics, rising to 80% for rigid and 60% for flexible/multilayer by 2027–28 [80]. These objectives aim to redesign packaging for recyclability, raise recycled content, and operationalise extended producer responsibility (EPR) in support of climate goals [81]. Their real impact will depend on closing enforcement gaps, integrating the informal sector, and building collection and recycling infrastructure at scale.

6. Future Outlook: Innovations on the Horizon

Plastic recovery is changing quickly with new tech, greater concern for our planet, and alongside efforts to reuse materials, this is driving it.

6.1.AI-Powered Sorting and Robotics

A major hurdle in plastic recycling is the accurate sorting of materials. Fortunately, machine learning and computer vision systems now identify plastic type, colour, and sometimes contamination in real time, using RGB cameras, NIR/IR spectroscopy, and deep neural networks [82]. AI-based sorting robots are already operating in MRFs, learning from accumulated data to improve picking decisions and reduce human exposure to hazardous waste [83]. Cost analyses suggest higher upfront investment but lower operating costs and labour requirements for medium to high-volume plants [84].

6.2. Bio-Based and Recyclable Plastics

More people are turning to bioplastics sourced from renewable materials such as lignocellulose, starch, and vegetable oils [85]These innovative materials can be engineered for closed-loop recycling; however, simply creating new materials isn't enough, as they pose challenges if misdirected to mechanical recycling pathways or if they fail to decompose properly in natural composting environments [86]

7. Recycling within a Multi-Pronged Net-Zero Strategy: a holistic perspective

Zero or near-zero emissions from plastics can be achieved through strategies that companies and governments can implement. They can design better product packaging, substitute materials, reduce demand, promote reuse, and adopt carbon management technologies, such as recycling and carbon capture. Recycling is especially crucial because it captures carbon in plastic, preventing its release if disposed of, and also reducing the need for new plastic production from virgin oil. Its impact is maximised when paired with improved design and repeated reuse, delivering greater environmental benefits than relying on it alone [87, 88].

Recycling can become more impactful when waste is viewed as a valuable resource rather than a disposal problem. Innovations such as improved sorting techniques, compatibilisers, advanced depolymerisation processes, and upcycling contribute to the production of higher-grade polymers. Turning plastic waste into useful stuff boosts recycling profits while helping the planet. Instead of just processing tons of poor-grade material, we can now create fewer yet better recycled goods, so what's good for companies is also good for Earth.

Still, the contribution of recycling to net-zero goals is limited by real-world challenges, such as material degradation, energy demands, insufficient infrastructure, and the fact that new plastics are often cheaper without policy support.

8. Summary

Plastic recycling is vital for reusing materials, but it won't solve the climate crisis on its own. Though better methods now lower the carbon footprint compared to making

new plastic, some material inevitably gets lost, requires considerable power, or weakens over time, stopping a truly closed loop. Because of ongoing pollution, limited facilities, alongside dependence on oil, recycling isn't enough to reach zero emissions.

To get to zero plastic waste, we need change on every front. Combining better recycling with options like reusing containers, switching to plant-based plastics, and reducing the amount of plastic made in the first place through smarter design will significantly cut pollution. To truly help the environment, rules such as making companies responsible for their products' end-of-life, requiring a certain amount of recycled material, likewise putting a price on carbon emissions need to encourage businesses to do better. Moreover, using consistent methods to evaluate a product's entire lifespan from creation to disposal will offer clearer comparisons between areas, guaranteeing we can track if efforts to reach zero emissions are working.

Smart sorting powered by artificial intelligence, recycling fuelled by clean energy, and new plastics designed to be reused are the new tech that show real potential for better resource management. Nevertheless, scaling this up requires strong systems, funding, alongside worldwide teamwork. To get plastics to zero emissions isn't just about better recycling; it demands a complete overhaul, rethinking plastic from its creation through disposal. Shifting away from today's make-use-discard pattern toward one where materials continually loop back around will change plastics from a problem for our climate to a useful component of an enduring, carbon-balanced future.

References

[1] Zheng, J., Suh, S.: Strategies to reduce the global carbon footprint of plastics. Nature Climate Change 2019 9:5. 9, 374–378 (2019). https://doi.org/10.1038/s41558-019-0459-z

[2] Global plastic production| Statista, https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/

[3] Minderoo Foundation. (2023)

[4] Global Plastics Outlook. OECD Publishing (2022)

[5] Rhodes, C.J.: Plastic pollution and potential solutions. Sci. Prog. 101, 207–260 (2018). https://doi.org/10.3184/003685018X15294876706211

[6] Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., Thompson, R.C., Jankowska, E., Castillo, A.C., Pilditch, T.D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., Baulch, S., Atreya, M.E., Fischer, D., He, K.K., Petit, M.M., Sumaila, U.R., Neil, E., Bernhofen, M. V., Lawrence, K., Palardy, J.E.: Evaluating scenarios toward zero plastic pollution. Science. 369, (2020). https://doi.org/10.1126/SCIENCE.ABA9475

[7] Ragaert, K., Delva, L., Van Geem, K.: Mechanical and chemical recycling of solid plastic waste. Waste Management. 69, 24–58 (2017). https://doi.org/10.1016/j.wasman.2017.07.044

[8] Rahimi, A.R., Garciá, J.M.: Chemical recycling of waste plastics for new materials production. Nature Reviews Chemistry 2017 1:6. 1, 0046- (2017). https://doi.org/10.1038/s41570-017-0046

[9] Geueke, B., Groh, K., Muncke, J.: Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials. J. Clean. Prod. 193, 491–505 (2018). https://doi.org/10.1016/j.jclepro.2018.05.005
[10] Schyns, Z.O.G., Shaver, M.P.: Mechanical Recycling of Packaging Plastics: A Review. Macromol. Rapid Commun. 42, (2021). https://doi.org/10.1002/marc.202000415
[11] Ragaert, K., Delva, L., Van Geem, K.: Mechanical and chemical recycling of solid plastic waste. Waste Management. 69, 24–58 (2017). https://doi.org/10.1016/j.wasman.2017.07.044
[12] Larrain, M., Van Passel, S., Thomassen, G., Van Gorp, B., Nhu, T.T., Huysveld, S., Van Geem, K.M., De Meester, S., Billen, P.: Techno-economic assessment of mechanical recycling of challenging post-consumer plastic packaging waste. Resour. Conserv. Recycl. 170, (2021). https://doi.org/10.1016/j.resconrec.2021.105607
[13] Gu, F., Guo, J., Zhang, W., Summers, P.A., Hall, P.: From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study. Science of the Total Environment. 601–602, 1192–1207 (2017). https://doi.org/10.1016/j.scitotenv.2017.05.278
[14] Ruggeri, M., Savastano, M., Rizzi, A., Veronesi, A., Vinci, G.: Life cycle assessment of post-industrial plastics mechanical recycling. A case study from Italy. Science of the Total Environment. 998, (2025). https://doi.org/10.1016/j.scitotenv.2025.180246
[15] Chen, J., Wang, W., Zou, C., Chen, C.: Mechanical Recycling of Mixed Plastics by Supramolecular Dynamic Cross-Linking Strategy. J. Am. Chem. Soc. 147, 24747–24758 (2025). https://doi.org/10.1021/jacs.5c06330
[16] Liu, Q., Martinez-Villarreal, S., Wang, S., Ngoc Thanh Tien, N., Kammoun, M., De Roover, Q., Len, C., Richel, A.: The role of plastic chemical recycling processes in a circular economy context. Chemical Engineering Journal. 498, (2024). https://doi.org/10.1016/j.cej.2024.155227
[17] Qureshi, M.S., Oasmaa, A., Pihkola, H., Deviatkin, I., Tenhunen, A., Mannila, J., Minkkinen, H., Pohjakallio, M., Laine-Ylijoki, J.: Pyrolysis of plastic waste: Opportunities and challenges. J. Anal. Appl. Pyrolysis. 152, (2020). https://doi.org/10.1016/j.jaap.2020.104804
[18] Payne, J., Jones, M.D.: The Chemical Recycling of Polyesters for a Circular Plastics Economy: Challenges and Emerging Opportunities. ChemSusChem. 14, 4041–4070 (2021). https://doi.org/10.1002/cssc.202100400.
[19] Huang, J., Veksha, A., Chan, W.P., Giannis, A., Lisak, G.: Chemical recycling of plastic waste for sustainable material management: A prospective review on catalysts and processes. Renewable and Sustainable Energy Reviews. 154, (2022). https://doi.org/10.1016/j.rser.2021.111866
[20] Martínez-Narro, G., Hassan, S., Phan, A.N.: Chemical recycling of plastic waste for sustainable polymer manufacturing – A critical review. J. Environ. Chem. Eng. 12, (2024). https://doi.org/10.1016/j.jece.2024.112323

[21] Nixon, K.D., Schyns, Z.O.G., Luo, Y., Ierapetritou, M.G., Vlachos, D.G., Korley, L.T.J., Epps, I.T.H.: Analyses of circular solutions for advanced plastics waste recycling. Nature Chemical Engineering

[22] Ragaert, K., Delva, L., Van Geem, K.: Mechanical and chemical recycling of solid plastic waste. Waste Management. 69, 24–58 (2017). https://doi.org/10.1016/j.wasman.2017.07.044

[23] Akram, M.A., Savitha, R., Kinsella, G.K., Nolan, K., Ryan, B.J., Henehan, G.T.: Microbial and Enzymatic Biodegradation of Plastic Waste for a Circular Economy. Applied Sciences 2024, Vol. 14,. 14, (2024). https://doi.org/10.3390/app142411942

[24] Mohanan, N., Montazer, Z., Sharma, P.K., Levin, D.B.: Microbial and Enzymatic Degradation of Synthetic Plastics. Front. Microbiol. 11, 580709 (2020). https://doi.org/10.3389/fmicb.2020.580709

[25] Rikhter, P., Dinc, I., Zhang, Y., Jiang, T., Miyashiro, B., Walsh, S., Wang, R., Dinh, Y., Suh, S., Kneifel, J.D., Rikhter, P., Dinc, I., Zhang, Y., Jiang, T., Miyashiro, B., Walsh, S., Wang, R., Dinh, Y., Suh, S., Kneifel, J.D.: Life Cycle Environmental Impacts of Plastics: A Review. (2022). https://doi.org/10.6028/NIST.GCR.22-032

[26] Alhazmi, H., Almansour, F.H., Aldhafeeri, Z.: Plastic Waste Management: A Review of Existing Life Cycle Assessment Studies. Sustainability 2021, Vol. 13,. 13, (2021). https://doi.org/10.3390/su13105340

[27] Jeswani, H., Krüger, C., Russ, M., Horlacher, M., Antony, F., Hann, S., Azapagic, A.: Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. Science of the Total Environment. 769, (2021). https://doi.org/10.1016/j.scitotenv.2020.144483

[28] Tenhunen-Lunkka, A., Rommens, T., Vanderreydt, I., Mortensen, L.: Greenhouse Gas Emission Reduction Potential of European Union's Circularity Related Targets for Plastics. Circular economy and sustainability. 3, 475–510 (2023). https://doi.org/10.1007/s43615-022-00192-8

[29] Amadei, A.M., Rigamonti, L., Tosches, D., Sala, S.: Combining MFA and LCA models to unveil the EU plastic value chain impacts. Resour. Conserv. Recycl. 219, (2025). https://doi.org/10.1016/j.resconrec.2025.108279

[30] Nessi, Simone., Sinkko, Taija., Bulgheroni, Claudia., Garbarino, Elena., Garcia-Gutierrez, Pelayo., Giuntoli, Jacopo., Konti, Aikaterini., Orveillon, Glenn., Sanye-Mengual, Esther., Tonini, Davide., Pant, Rana., Marelli, Luisa., Ardente, Fulvio.: Life Cycle Assessment (LCA) of alternative feedstocks for plastics production. (2022). https://doi.org/10.2760/655230

[31] Arumdani, I.S., Puspita, A.S., Budihardjo, M.A.: MSW handling of top 5 leading waste-producing countries in Southeast Asia. IOP Conf. Ser. Earth Environ. Sci. 896, 114760 (2021). https://doi.org/10.1088/1755-1315/896/1/012003

[32] Alsabri, A., Tahir, F., Al-Ghamdi, S.G.: Decarbonising the plastic industry: A review of carbon emissions in the lifecycle of plastics production. Science of

The Total Environment. 999, 180337 (2025). https://doi.org/10.1016/j.matpr.2021.11.574

[33] Cabernard, L., Pfister, S., Oberschelp, C., Hellweg, S.: Growing environmental footprint of plastics driven by coal combustion. Nature Sustainability 2021 5:2. 5, 139–148 (2021). https://doi.org/10.1038/s41893-021-00807-2

[34] Plastic leakage and greenhouse gas emissions are increasing, https://www.oecd.org/en/data/insights/data-explainers/2022/08/plastic-leakage-and-greenhouse-gas-emissions-are-increasing.html

[35] Bauer, F., Nielsen, T.D., Nilsson, L.J., Palm, E., Ericsson, K., Fråne, A., Cullen, J.: Plastics and climate change breaking carbon lock-ins through three mitigation pathways. One Earth. 5, 361–376 (2022). https://doi.org/10.1016/j.oneear.2022.03.007

[36] Zheng, J., Suh, S.: Strategies to reduce the global carbon footprint of plastics. Nat. Clim. Chang. 9, 374–378 (2019). https://doi.org/10.1038/s41558-019-0459-z

[37] Recycling of Plastics in the United States: Plastic Material Flows and Polyethylene Terephthalate (PET) Recycling Processes. https://doi.org/10.1021/acssuschemeng.1c06845.s001

[38] Jiao, H., Ali, S.S., Alsharbaty, M.H.M., Elsamahy, T., Abdelkarim, E., Schagerl, M., Al-Tohamy, R., Sun, J.: A critical review on plastic waste life cycle assessment and management: Challenges, research gaps, and future perspectives. Ecotoxicol. Environ. Saf. 271, (2024). https://doi.org/10.1016/j.ecoenv.2024.115942

[39] Costamagna, M., Massaccesi, B.M., Mazzucco, D., Baricco, M., Rizzi, P.: Environmental assessment of the recycling process for polyamides - Polyethylene multilayer packaging films. Sustainable Materials and Technologies. 35, (2023). https://doi.org/10.1016/j.susmat.2022.e00562

[40] Silva, C.O., Casagrande, N., Candeias, C., Sobral, P., Martinho, G.: Assessing ecotoxicity of plastic additives to apply in effect factors for Life Cycle Impact Assessment. Science of the Total Environment. 967, (2025). https://doi.org/10.1016/j.scitotenv.2025.178836

[41] Morici, E., Dintcheva, N.T.: Recycling of Thermoset Materials and Thermoset-Based Composites: Challenge and Opportunity. Polymers 2022, Vol. 14,. 14, (2022). https://doi.org/10.3390/polym14194153

[42] Alhazmi, H., Almansour, F.H., Aldhafeeri, Z.: Plastic waste management: A review of existing life cycle assessment studies. Sustainability (Switzerland). 13, (2021). https://doi.org/10.3390/su13105340

[43] Antelava, A., Damilos, S., Hafeez, S., Manos, G., Al-Salem, S.M., Sharma, B.K., Kohli, K., Constantinou, A.: Plastic Solid Waste (PSW) in the Context of Life Cycle Assessment (LCA) and Sustainable Management. Environ. Manage. 64, 230–244 (2019). https://doi.org/10.1007/s00267-019-01178-3

[44] Kalverkamp, M., Helmers, E., Pehlken, A.: Impacts of life cycle inventory databases on life cycle assessments: A review by means of a drivetrain case study. J. Clean. Prod. 269, (2020). https://doi.org/10.1016/j.jclepro.2020.121329

[45] Volk, R., Stallkamp, C., Steins, J.J., Yogish, S.P., Müller, R.C., Stapf, D., Schultmann, F.: Techno-economic assessment and comparison of different plastic recycling pathways: A German case study. J. Ind. Ecol. 25, 1318–1337 (2021). https://doi.org/10.1111/jiec.13145

[46] Schwarz, A.E., Ligthart, T.N., Godoi Bizarro, D., De Wild, P., Vreugdenhil, B., van Harmelen, T.: Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. Waste Management. 121, 331–342 (2021). https://doi.org/10.1016/j.wasman.2020.12.020

[47] Gabisa, E.W., Ratanatamskul, C., Gheewala, S.H.: Recycling of Plastics as a Strategy to Reduce Life Cycle GHG Emission, Microplastics and Resource Depletion. Sustainability (Switzerland). 15, (2023). https://doi.org/10.3390/su151511529

[48] Meys, R., Kätelhön, A., Bachmann, M., Winter, B., Zibunas, C., Suh, S., Bardow, A.: Achieving net-zero greenhouse gas emission plastics by a circular carbon economy. Science (1979). 374, 71–76 (2021). https://doi.org/10.1126/science.abg9853

[49] Brouwer, M.T., van Velzen, E.U.T., Ragaert, K., Klooster, R. Ten: Technical Limits in Circularity for Plastic Packages. Sustainability 2020, Vol. 12,. 12, 1–29 (2020). https://doi.org/10.3390/su122310021

[50] Antonopoulos, I., Faraca, G., Tonini, D.: Recycling of post-consumer plastic packaging waste in EU: Process efficiencies, material flows, and barriers. Waste Management. 126, 694–705 (2021). https://doi.org/10.1016/j.wasman.2021.04.002

[51] Hidiroglu, K., Ruzzenenti, F., Merciai, S., Wang, D., Hubacek, K.: The extent and fate of fossil carbon accumulation in our technosphere. Cell Reports Sustainability. 1, (2024). https://doi.org/10.1016/j.crsus.2024.100265

[52] Lahl, U., Zeschmar-Lahl, B.: Material Recycling of Plastics—A Challenge for Sustainability. Sustainability (Switzerland). 16, (2024). https://doi.org/10.3390/su16156630

[53] Muñoz Meneses, R.A., Cabrera-Papamija, G., Machuca-Martínez, F., Rodríguez, L.A., Diosa, J.E., Mosquera-Vargas, E.: Plastic recycling and their use as raw material for the synthesis of carbonaceous materials. Heliyon. 8, (2022). https://doi.org/10.1016/j.heliyon.2022.e09028

[54] Jiang, X., Bateer, B.: A systematic review of plastic recycling: technology, environmental impact and economic evaluation. Waste Management and Research. 43, 1159–1178 (2025). https://doi.org/10.1177/0734242X241310658

[55] Sola, A., Rosa, R., Ferrari, A.M.: Green Hydrogen and Its Supply Chain. A Critical Assessment of the Environmental Impacts. Adv. Sustain. Syst. 9, (2025). https://doi.org/10.1002/adsu.202400708

[56] Maniscalco, M.P., Longo, S., Cellura, M., Miccichè, G., Ferraro, M.: Critical Review of Life Cycle Assessment of Hydrogen Production Pathways. Environments - MDPI. 11, (2024). https://doi.org/10.3390/environments11060108

[57] Greenwood, S.C., Walker, S., Baird, H.M., Parsons, R., Mehl, S., Webb, T.L., Slark, A.T., Ryan, A.J., Rothman, R.H.: Many Happy Returns: Combining insights from the environmental and behavioural sciences to understand what is required to make reusable packaging mainstream. Sustain. Prod. Consum. 27, 1688–1702 (2021). https://doi.org/10.1016/j.spc.2021.03.022

[58] Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., Thompson, R.C., Jankowska, E., Castillo, A.C., Pilditch, T.D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., Baulch, S., Atreya, M.E., Fischer, D., He, K.K., Petit, M.M., Sumaila, U.R., Neil, E., Bernhofen, M. V., Lawrence, K., Palardy, J.E.: Evaluating scenarios toward zero plastic pollution. Science (1979). 369, (2020). https://doi.org/10.1126/SCIENCE.ABA9475

[59] Rosenboom, J.G., Langer, R., Traverso, G.: Bioplastics for a circular economy. Nat. Rev. Mater. 7, 117–137 (2022). https://doi.org/10.1038/s41578-021-00407-8

[60] Islam, M., Xayachak, T., Haque, N., Lau, D., Bhuiyan, M., Pramanik, B.K.: Impact of bioplastics on environment from its production to end-of-life. Process Safety and Environmental Protection. 188, 151–166 (2024). https://doi.org/10.1016/j.psep.2024.05.113

[61] Yadav, K., Nikalje, G.C.: Comprehensive analysis of bioplastics: life cycle assessment, waste management, biodiversity impact, and sustainable mitigation strategies. PeerJ. 12, (2024). https://doi.org/10.7717/peerj.18013

[62] Singh, N., Ogunseitan, O.A., Wong, M.H., Tang, Y.: Sustainable materials alternative to petrochemical plastics pollution: A review analysis. Sustainable Horizons. 2, (2022). https://doi.org/10.1016/j.horiz.2022.100016

[63] Benavides, P.T., Lee, U., Zarè-Mehrjerdi, O.: Life cycle greenhouse gas emissions and energy use of polylactic acid, bio-derived polyethylene, and fossil-derived polyethylene. J. Clean. Prod. 277, (2020). https://doi.org/10.1016/j.jclepro.2020.124010

[64] Ahsan, W.A., Hussain, A., Lin, C., Nguyen, M.K.: Biodegradation of Different Types of Bioplastics through Composting—A Recent Trend in Green Recycling. Catalysts. 13, (2023). https://doi.org/10.3390/catal13020294

[65] Filiciotto, L., Rothenberg, G.: Biodegradable Plastics: Standards, Policies, and Impacts. ChemSusChem. 14, 56–72 (2021). https://doi.org/10.1002/cssc.202002044

[66] Costa, A., Encarnação, T., Tavares, R., Todo Bom, T., Mateus, A.: Bioplastics: Innovation for Green Transition. Polymers (Basel). 15, (2023). https://doi.org/10.3390/polym15030517

[67] Serrano-Aguirre, L., Prieto, M.A.: Can bioplastics always offer a truly sustainable alternative to fossil-based plastics? Microb. Biotechnol. 17, (2024). https://doi.org/10.1111/1751-7915.14458

[68] Ding, Q., Zhu, H.: The Key to Solving Plastic Packaging Wastes: Design for Recycling and Recycling Technology. Polymers (Basel). 15, (2023). https://doi.org/10.3390/polym15061485

[69] Nazarko, J., Chodakowska, E., Nazarko, Ł.: Evaluating the Transition of the European Union Member States towards a Circular Economy. Energies (Basel). 15, (2022). https://doi.org/10.3390/en15113924
[70] Willis, K.A., Richards, M., Hardesty, B.D.: Focusing plastic solutions up the waste hierarchy: Pathways for a more circular economy. iScience. 28, 113217 (2025). https://doi.org/10.1016/j.isci.2025.113217
[71] Vidal, F., van der Marel, E.R., Kerr, R.W.F., McElroy, C., Schroeder, N., Mitchell, C., Rosetto, G., Chen, T.T.D., Bailey, R.M., Hepburn, C., Redgwell, C., Williams, C.K.: Designing a circular carbon and plastics economy for a sustainable future. Nature 2024 626:7997. 626, 45–57 (2024). https://doi.org/10.1038/s41586-023-06939-z
[72] Tumu, K., Vorst, K., Curtzwiler, G.: Global plastic waste recycling and extended producer responsibility laws. J. Environ. Manage. 348, (2023). https://doi.org/10.1016/j.jenvman.2023.119242
[73] Georgescu, L.P., Barbuta Misu, N., Antohi, V.M., Fortea, C., Zlati, M.L.: Approaches and perspectives on the transition to the circular economy in the European Union. Front. Environ. Sci. 13, (2025). https://doi.org/10.3389/fenvs.2025.1533776
[74] De Pascale, A., Di Vita, G., Giannetto, C., Ioppolo, G., Lanfranchi, M., Limosani, M., Szopik-Depczyńska, K.: The circular economy implementation at the European Union level. Past, present and future. J. Clean. Prod. 423, (2023). https://doi.org/10.1016/j.jclepro.2023.138658
[75] Chioatto, E., Sospiro, P.: Transition from waste management to circular economy: the European Union roadmap. Environ. Dev. Sustain. 25, 249–276 (2023). https://doi.org/10.1007/s10668-021-02050-3
[76] Mhatre, P., Panchal, R., Singh, A., Bibyan, S.: A systematic literature review on the circular economy initiatives in the European Union. Sustain. Prod. Consum. 26, 187–202 (2021). https://doi.org/10.1016/j.spc.2020.09.008
[77] Leigh Krietsch Boerner: US singles out plastic pollution. C&EN Global Enterprise. 102, 6–6 (2024). https://doi.org/10.1021/cen-10223-leadcon
[78] Chen, Y., Awasthi, A.K., Wei, F., Tan, Q., Li, J.: Single-use plastics: Production, usage, disposal, and adverse impacts. Science of the Total Environment. 752, (2021). https://doi.org/10.1016/j.scitotenv.2020.141772
[79] Sorensen, R.M., Kanwar, R.S., Jovanovi, B.: Past, present, and possible future policies on plastic use in the United States, particularly microplastics and nanoplastics: A review. Integr. Environ. Assess. Manag. 19, 474–488 (2023). https://doi.org/10.1002/ieam.4678
[80] Kalauni, K., Vedrtnam, A., Sharma, S.P., Sharma, A., Chaturvedi, S.: A comprehensive review of recycling and reusing methods for plastic waste focusing Indian scenario. Waste Management and Research. 43, 1378–1399 (2025). https://doi.org/10.1177/0734242X241308499
[81] Hossain, R., Islam, M.T., Shanker, R., Khan, D., Locock, K.E.S., Ghose, A., Schandl, H., Dhodapkar, R., Sahajwalla, V.: Plastic Waste Management in India: Challenges, Opportunities, and Roadmap for Circular Economy. Sustainability (Switzerland). 14, (2022). https://doi.org/10.3390/su14084425

[82] Lubongo, C., Bin Daej, M.A.A., Alexandridis, P.: Recent Developments in Technology for Sorting Plastic for Recycling: The Emergence of Artificial Intelligence and the Rise of the Robots. Recycling. 9, (2024). https://doi.org/10.3390/recycling9040059

[83] Lubongo, C., Alexandridis, P.: Assessment of Performance and Challenges in Use of Commercial Automated Sorting Technology for Plastic Waste. Recycling. 7, (2022). https://doi.org/10.3390/recycling7020011

[84] Pučnik, R., Dokl, M., Fan, Y. Van, Vujanović, A., Novak Pintarič, Z., Aviso, K.B., Tan, R.R., Pahor, B., Kravanja, Z., Čuček, L.: A waste separation system based on sensor technology and deep learning: A simple approach applied to a case study of plastic packaging waste. J. Clean. Prod. 450, (2024). https://doi.org/10.1016/j.jclepro.2024.141762

[85] Bartolucci, L., Cordiner, S., De Maina, E., Kumar, G., Mele, P., Mulone, V., Igliński, B., Piechota, G.: Sustainable Valorization of Bioplastic Waste: A Review on Effective Recycling Routes for the Most Widely Used Biopolymers. Int. J. Mol. Sci. 24, (2023). https://doi.org/10.3390/ijms24097696

[86] Kumar, R., Sadeghi, K., Jang, J., Seo, J.: Mechanical, chemical, and bio-recycling of biodegradable plastics: A review. Science of the Total Environment. 882, (2023). https://doi.org/10.1016/j.scitotenv.2023.163446

[87] von Vacano, B., Reich, O., Huber, G., Türkoglu, G.: Elucidating pathways of polypropylene chain cleavage and stabilization for multiple loop mechanical recycling. Journal of Polymer Science. 61, 1849–1858 (2023). https://doi.org/10.1002/pol.20230121

[88] Mangold, H., von Vacano, B.: The Frontier of Plastics Recycling: Rethinking Waste as a Resource for High-Value Applications. Macromol. Chem. Phys. 223, (2022). https://doi.org/10.1002/macp.202100488