Integrated environmental management strategies for sustainable polymer production

Robert R. Papp

Department of Environmental Engineering and Protection, Faculty of Agriculture,
University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca, Cluj-Napoca,
Romania. Corresponding author: R. R. Papp, robert-raul.papp@student.usamvcluj.ro

Abstract. The rapid expansion of polymer production has generated significant environmental pressures, including resource depletion, greenhouse gas emissions, and the accumulation of persistent plastic waste. Addressing these challenges requires a transition from conventional linear production models toward integrated and sustainable polymer systems. This review critically examines the role of integrated environmental management strategies in enabling sustainable polymer production across the entire life cycle, from feedstock selection and synthesis to product design, use, and end-of-life management. Key technological and managerial approaches are analyzed, including the application of green chemistry principles, the development of renewable and biodegradable polymers, advanced mechanical and chemical recycling technologies, and the implementation of circular economy strategies. The paper further highlights the importance of life cycle assessment as a decision-support tool, resource-efficient production planning, and design for recyclability and controlled degradation. In addition, the role of policy frameworks and governance mechanisms in supporting sustainable transitions within the polymer sector is discussed. The analysis demonstrates that no single solution can ensure sustainability; rather, environmental performance improvements emerge from the coordinated integration of material innovation, process optimization, waste management, and regulatory support. Adopting a systems-oriented approach is essential for transforming polymer production into a circular, resource-efficient, and environmentally responsible industry.

Key Words: advanced recycling, circular economy, green chemistry, life cycle assessment, resource efficiency.

Introduction. The rapid growth of polymer production over the past decades has fundamentally transformed modern society, enabling technological development across sectors such as packaging, construction, medicine, electronics, transportation, and agriculture (Scholten et al 2021; Jambeck & Walker-Franklin 2023). At the same time, this growth has generated profound environmental challenges, primarily associated with resource depletion, greenhouse gas emissions, and the accumulation of persistent plastic waste (Geyer et al 2017; Mierzwa-Hersztek et al 2019; Shen et al 2020; Cabernard et al 2022). Conventional polymer systems have historically been developed within a linear economic paradigm, emphasizing performance and cost efficiency while largely neglecting end-of-life considerations (Law & Narayan 2021; Chen et al 2022; Johansen et al 2022; Highmoore et al 2024). As a result, polymer value chains have become a significant contributor to global environmental pressures (Nicholson et al 2021; Westlie et al 2022; Salah et al 2024).

Sustainable polymer production has therefore emerged as a strategic priority at the interface of materials science, chemical engineering, environmental management, and public policy (Schneiderman & Hillmyer 2017; Fagnani et al 2020; Mohanty et al 2022). Rather than focusing on isolated technological solutions, sustainability in polymer systems requires integrated environmental management strategies that address the entire life cycle of polymer materials - from feedstock selection and synthesis to product design, use, and end-of-life management (Zhu et al 2016; Zhang et al 2018; Fagnani et al 2020; Von Vacano et al 2023; Kerton 2025). This integrated perspective aligns with circular economy principles and seeks to decouple polymer functionality from environmental degradation (Wang et al 2023; Unni & Joseph 2024; Ajiola et al 2025; Peti et al 2025; Radu et al 2025).

The objective of this review is to critically examine the key technological, environmental, and managerial strategies that enable more sustainable polymer production. The paper emphasizes integration across scales and disciplines, highlighting how green chemistry, renewable materials, advanced recycling, life cycle assessment, production planning, and policy frameworks collectively contribute to reducing the environmental footprint of polymer systems.

Environmental challenges associated with conventional polymer systems. Conventional polymer production relies predominantly on fossil-based feedstocks and energy-intensive processing routes (Benavides et al 2020; Singh et al 2022; Seewoo et al 2024; Unni & Joseph 2024). Feedstock extraction, monomer synthesis, and polymerization contribute substantially to greenhouse gas emissions and fossil resource depletion (Hahladakis et al 2018; Nicholson et al 2021; Mohanty et al 2022; Seewoo et al 2024; Unni & Joseph 2024). In addition, polymer products are frequently designed for short service lives, particularly in packaging applications, resulting in high material throughput and waste generation (Heller et al 2020; Pan et al 2020; Epps et al 2021; Evode et al 2021; Lange 2021).

At the end-of-life stage, inadequate waste management infrastructure and limited recycling efficiency lead to widespread landfilling, incineration, and environmental leakage (Heller et al 2020; Pan et al 2020; Evode et al 2021; Law & Narayan 2021; Thomas et al 2023; Fayshal 2024; Seewoo et al 2024). Landfilling represents a long-term loss of material value and occupies valuable land resources, while incineration generates emissions and often recovers only a fraction of the embedded energy (Heller et al 2020; Evode et al 2021; Lange 2021; Yaroslavov et al 2022; Thomas et al 2023). Environmental leakage, including the accumulation of macro- and microplastics in terrestrial and aquatic ecosystems, has emerged as a major ecological and societal concern (Hahladakis et al 2018; Heller et al 2020; Law & Narayan 2021; Thomas et al 2023; Seewoo et al 2024; Unni & Joseph 2024; Titone et al 2025).

These challenges illustrate that sustainability issues in polymer systems are not confined to a single stage of the life cycle. Instead, they arise from systemic interactions between material design, production technologies, consumption patterns, and waste management practices (Heller et al 2020; Epps et al 2021; Mohanty et al 2022; Yaroslavov et al 2022; Thomas et al 2023; Seewoo et al 2024). Addressing these challenges therefore requires coordinated interventions rather than isolated technical improvements (Hillmyer 2017; Epps et al 2021; Law & Narayan 2021; Thomas et al 2023; Radu et al 2025).

Green chemistry principles in sustainable polymer synthesis. Green chemistry provides a foundational framework for reducing the environmental impacts associated with polymer synthesis (Schneiderman & Hillmyer 2017; Iglesias et al 2020; Kerton 2025). Its principles promote the prevention of waste, the use of safer chemicals, energy efficiency, and the substitution of hazardous substances with environmentally benign alternatives (Kharissova et al 2019; Grishin & Grishin 2025). In polymer production, these principles translate into innovations in solvents, catalysts, feedstocks, and process design (Iglesias et al 2020; Sternberg et al 2021; Apostolidis et al 2025; Grishin & Grishin 2025; Kerton 2025).

One key strategy involves minimizing or eliminating the use of organic solvents, which are often volatile, toxic, and difficult to recover (Kharissova et al 2019; Iglesias et al 2020; Apostolidis et al 2025; Kerton 2025). Solvent-free and solid-state polymerization or depolymerization processes reduce emissions, simplify downstream processing, and lower overall process mass intensity (Ohn & Kim 2018; Kharissova et al 2019; Lee et al 2021; Štrukil 2021; Anglou et al 2024; Kerton 2025). Mechanochemical approaches, which rely on mechanical energy to drive chemical transformations, represent a promising pathway for polymer modification and recycling without extensive solvent use (Lee et al 2021; Anglou et al 2024; Skala et al 2024; Hutsch et al 2025).

Catalysis plays a central role in improving reaction efficiency and selectivity (Zhang et al 2018; Borkar et al 2022; Nguyen & Lim 2024; Grishin & Grishin 2025). The development of catalysts based on earth-abundant and low-toxicity elements reduces reliance on scarce or hazardous metals while enabling polymerization under milder conditions (Borkar et al 2022; Grishin & Grishin 2025; Oza et al 2025). Advances in catalyst design also facilitate more precise control over polymer architecture, enabling the synthesis of materials tailored for recyclability or controlled degradation (Schneiderman & Hillmyer 2017; Zhang et al 2018; Iglesias et al 2020; Borkar et al 2022; Nguyen & Lim 2024; Kerton 2025).

Process intensification complements these advances by integrating multiple reaction steps, reducing energy demand, and improving heat and mass transfer (Iglesias et al 2020; Borkar et al 2022; Anglou et al 2024; Kerton 2025). Real-time monitoring and modeling tools further enhance process efficiency, allowing dynamic optimization and reducing off-specification material (Iglesias et al 2020; Anglou et al 2024; Grishin & Grishin 2025). Collectively, these green chemistry strategies reduce the environmental footprint of polymer synthesis while maintaining or improving material performance (Zhang et al 2018; Iglesias et al 2020; Sternberg et al 2021; Nguyen & Lim 2024; Grishin & Grishin 2025; Kerton 2025).

Renewable and biodegradable polymer materials. The substitution of fossil-based polymers with materials derived from renewable resources represents an important pathway toward sustainable polymer systems (Zhu et al 2016). Renewable polymers can be produced from biomass-derived feedstocks, industrial by-products, or alternative carbon sources, thereby reducing dependence on finite fossil resources and potentially lowering life-cycle greenhouse gas emissions (Benavides et al 2020; Wang et al 2020).

Bio-based polymers encompass a wide range of materials, including naturally occurring polymers and synthetically produced polymers derived from renewable monomers (Zhu et al 2016; Mohanty et al 2022). The sustainability of such materials depends not only on their renewable origin but also on feedstock availability, land-use implications, processing efficiency, and end-of-life behavior (Rosenboom et al 2022; Mohanty et al 2022). Using non-edible and waste-derived biomass is particularly important to avoid competition with food production and to minimize indirect environmental impacts (Maraveas 2020; Rosenboom et al 2022).

Biodegradable polymers are often proposed as solutions for applications where material recovery is difficult or economically unfeasible (Lim & Thian 2022; Dallaev et al 2025). However, biodegradability must be carefully evaluated in relation to specific environmental conditions and waste management systems (Lim & Thian 2022; Afshar et al 2024). Controlled biodegradation in industrial composting or managed environments can be beneficial, whereas uncontrolled degradation may result in incomplete breakdown or microplastic formation (Agarwal 2020; Afshar et al 2025). Consequently, biodegradable polymers should be viewed as complementary to, rather than substitutes for, recycling-based strategies (Mohanty et al 2022; Rosenboom et al 2022; Serrano-Aguirre & Prieto 2024).

The development of next-generation renewable polymers increasingly focuses on balancing environmental performance with functional properties such as mechanical strength, thermal stability, and processability (Wang et al 2020; Xia et al 2021; Cywar et al 2022). Achieving this balance is essential for widespread industrial adoption and for ensuring that sustainability gains are not offset by reduced product performance or increased material consumption (Zhu et al 2016; Pellis et al 2021; Cywar et al 2022).

Advanced recycling and circular economy strategies. Recycling is a cornerstone of circular polymer systems, as it enables the recovery of material value and reduces demand for virgin feedstocks (Ragaert et al 2017; Clark & Shaver 2024). Mechanical recycling remains the most established route and is generally associated with lower energy demand and environmental impact, but its effectiveness is limited by polymer degradation, contamination, and the complexity of multi-material products (Schyns & Shaver 2021).

Chemical recycling technologies expand the range of waste streams that can be valorized by converting polymers into monomers, fuels, or platform chemicals (Ragaert et al 2017; Chanda 2021). These approaches are particularly relevant for contaminated, mixed, or composite plastics that are unsuitable for mechanical recycling (Ragaert et al

2017; Clark & Shaver 2024; Liu et al 2024). While chemical recycling offers the potential for high-quality material recovery, its environmental performance depends strongly on energy sources, process efficiency, and solvent or catalyst recovery (Coates & Getzler 2020; Clark & Shaver 2024).

Upcycling strategies aim to transform polymer waste into products of higher value than the original material, including specialty chemicals, functional materials, or advanced composites (Chen et al 2021; Korley et al 2021; Jehanno et al 2022; Zhang et al 2022). Although upcycling can improve economic incentives for waste recovery, its contribution to large-scale waste reduction depends on scalability and market demand for the resulting products (Korley et al 2021; Clark & Shaver 2024).

An effective circular economy strategy integrates multiple recycling pathways and aligns them with product design, waste collection systems, and market structures (Hong & Chen 2017; Ragaert et al 2017). Digital tools, such as advanced sorting technologies and material tracking systems, can further enhance recycling efficiency and transparency across the value chain (Abbas-Abadi et al 2025; Ajiola et al 2025; Chidara et al 2025).

Life cycle assessment as a decision-support tool. Life cycle assessment (LCA) is an essential methodology for evaluating the environmental performance of polymer systems in a holistic and quantitative manner (Blanco et al 2020; Walker & Rothman 2020). By considering all stages of the life cycle, LCA helps identify environmental hotspots and assess trade-offs between alternative materials, processes, and end-of-life options (Hottle et al 2013; Ramesh & Vinodh 2020).

LCA studies consistently show that raw material production and polymer synthesis are major contributors to environmental impacts, although the relative importance of different stages varies between fossil-based and bio-based polymers (Ramesh & Vinodh 2020; Tonini et al 2021). Recycling pathways can significantly reduce impacts compared to virgin production, but the magnitude of these benefits depends on realistic assumptions regarding collection rates, process efficiency, and energy sources (Gomes et al 2019; Schwarz et al 2021).

Importantly, LCA highlights that sustainability cannot be inferred solely from material origin or single performance indicators (Tabone et al 2010; Bishop et al 2021). Bio-based or biodegradable polymers do not automatically outperform conventional plastics under all conditions (Fonsêca et al 2023; Senila et al 2024). Integrating LCA early in material and process development supports evidence-based decision-making and helps avoid unintended environmental consequences (Blanco et al 2020; Banerjee & Ray 2022; De Souza et al 2023).

Production planning and resource efficiency. Resource efficiency in polymer manufacturing is strongly influenced by production planning and process control (Abeykoon et al 2021; Costa et al 2025). Variability in operating conditions can lead to off-specification products, increased waste generation, and excessive energy consumption (Aguilar-Vásquez et al 2023; Estrada-Ramírez et al 2025). Improving process stability and control therefore contributes directly to environmental performance (Abeykoon et al 2021).

Advanced modeling, monitoring, and optimization tools enable manufacturers to adjust operating parameters in real time, reducing material losses and energy demand (Gaspar-Cunha et al 2022; Radu et al 2025). Process intensification strategies, such as improved heat management and reactor design, further enhance efficiency in large-scale polymerization systems (Mil-Martínez et al 2024; Yan & Wang 2025).

From an environmental management perspective, integrating production planning with sustainability indicators - such as material yield, energy intensity, and waste generation - supports continuous improvement and aligns operational decisions with broader sustainability objectives (Saxena et al 2020; Zarte et al 2022; De Simone et al 2023).

End-of-life management and design for sustainability. End-of-life management is a decisive factor in determining the overall sustainability of polymer products (Law & Narayan 2021; Rosenboom et al 2022). Design for recyclability and design for degradation represent complementary strategies that must be aligned with existing and anticipated waste management infrastructure (Law & Narayan 2021; Rosenboom et al 2022; Aarsen et al 2024).

Simplifying material composition, reducing the use of incompatible additives, and improving product labeling enhance sorting efficiency and recyclate quality (Alassali et al 2021; Lange 2021; Larder & Hatton 2022; Rumetshofer & Fischer 2025). For applications where recycling is impractical, controlled biodegradation or energy recovery may provide appropriate alternatives, provided that environmental trade-offs are carefully evaluated (Wojnowska-Baryła et al 2020; Law & Narayan 2021; Sikorska et al 2021; Kalita & Hakkarainen 2023; Wang et al 2024).

Integrating end-of-life considerations into product design ensures that polymers are compatible with realistic disposal or recovery pathways (Law & Narayan 2021; Aarsen et al 2024). This systems-oriented approach reduces environmental leakage and maximizes the retention of material value within the economy (Lange 2021; Jung et al 2023).

Policy, **governance**, **and future directions**. Technological innovation alone is insufficient to achieve sustainable polymer production (Schneiderman & Hillmyer 2017; Scholten et al 2021; Von Vacano et al 2023). Regulatory frameworks, economic incentives, and stakeholder collaboration play a critical role in shaping material flows and encouraging investment in sustainable solutions (Schultz et al 2021; Von Vacano et al 2023; Firoozi et al 2024). Policies such as extended producer responsibility, recycling targets, and eco-design requirements create structural conditions that support circular polymer systems (Beghetto et al 2023; Tumu et al 2023; Firoozi et al 2024).

Future progress will depend on coordinated action across disciplines and sectors (Massey-Brooker & Conway 2024; Ajiola et al 2025). Research priorities include improving the scalability and energy efficiency of advanced recycling technologies, developing polymers explicitly designed for circularity, and integrating digital tools for monitoring and optimization (Schneiderman & Hillmyer 2017; Hong & Chen 2019; Mohanty et al 2022; Unni & Joseph 2024). Coupling technological development with robust environmental assessment and coherent policy frameworks will be essential for building a resilient and sustainable polymer economy (Scholten et al 2021; Mohanty et al 2022; Von Vacano et al 2023; Firoozi et al 2024).

Conclusions. Sustainable polymer production requires an integrated environmental management approach that spans the entire polymer life cycle. Advances in green chemistry, renewable materials, recycling technologies, life cycle assessment, production planning, and policy design collectively contribute to reducing the environmental footprint of polymer systems. No single strategy provides a universal solution; instead, sustainability emerges from the alignment of material design, process efficiency, waste management, and governance. By adopting a systems perspective, polymer production can evolve from a linear, resource-intensive model toward a circular and environmentally responsible paradigm.

Conflict of interest. The authors declare that there is no conflict of interest.

References

Aarsen C. V., Liguori A., Mattsson R., Sipponen M. H., Hakkarainen M., 2024 Designed to degrade: tailoring polyesters for circularity. Chemical Reviews 124:8473-8515.

Abbas-Abadi M. S., Tomme B., Goshayeshi B., Mynko O., Wang Y., Roy S., Kumar R., Baruah B., De Clerck K., De Meester S., D’hooge D. R., Van Geem K. M., 2025 Advancing textile waste recycling: challenges and opportunities across polymer and non-polymer fiber types. Polymers 17(5):628.

Abeykoon C., McMillan A., Nguyen B. K., 2021 Energy efficiency in extrusion-related polymer processing: a review of state of the art and potential efficiency improvements. Renewable and Sustainable Energy Reviews 147:111219.

Afshar S. V., Boldrin A., Astrup T. F., Daugaard A. E., Hartmann N. B., 2024 Degradation of biodegradable plastics in waste management systems and the open environment: a critical review. Journal of Cleaner Production 434:140000.

Afshar S. V., Boldrin A., Christensen T. H., Corami F., Daugaard A. E., Rosso B., Hartmann N. B., 2025 Disintegration of commercial biodegradable plastic products under simulated industrial composting conditions. Scientific Reports 15:8569.

Agarwal S., 2020 Biodegradable polymers: present opportunities and challenges in providing a microplastic-free environment. Macromolecular Chemistry and Physics 221(6):2000017.

Aguilar-Vásquez E., Ramos-Olmos M., González-Delgado Á. D., 2023 A joint computer-aided simulation and water-energy-product (WEP) approach for technical evaluation of PVC production. Sustainability 15(10):8096.

Ajiola D. I., Osumah A. P., Ajoge E. O., Adeyera I. A., Ikedionu C., 2025 Recyclable polymers and circular material design for sustainable manufacturing. International Journal of Scientific Research and Modern Technology 4(6):66-72.

Alassali A., Picuno C., Chong Z., Guo J., Maletz R., Kuchta K., 2021 Towards higher quality of recycled plastics: limitations from the material’s perspective. Sustainability 13(23): 13266.

Anglou E., Chang Y., Bradley W., Sievers C., Boukouvala F., 2024 Modeling mechanochemical depolymerization of PET in ball-mill reactors using DEM simulations. ACS Sustainable Chemistry and Engineering 12(24):9003-9017.

Apostolidis D., Dyer W. E., Dransfeld C. A., Kumru B., 2025 Solution and precipitation based radical polymerization of renewable vinyl lactones in renewable solvents. RSC Advances 15:21659-21665.

Banerjee R., Ray S. S., 2022 Sustainability and life cycle assessment of thermoplastic polymers for packaging: a review on fundamental principles and applications. Macromolecular Materials and Engineering 307(6):2100794.

Beghetto V., Gatto V., Samiolo R., Scolaro C., Brahimi S., Facchin M., Visco A., 2023 Plastics today: key challenges and EU strategies towards carbon neutrality: a review. Environmental Pollution 334:122102.

Benavides P. T., Lee U., Zare-Mehrjerdi O., 2020 Life cycle greenhouse gas emissions and energy use of polylactic acid, bio-derived polyethylene, and fossil-derived polyethylene. Journal of Cleaner Production 277:124010.

Bishop G., Styles D., Lens P. N. L., 2021 Environmental performance comparison of bioplastics and petrochemical plastics: a review of life cycle assessment (LCA) methodological decisions. Resources, Conservation and Recycling 168:105451.

Blanco I., Ingrao C., Siracusa V., 2020 Life-cycle assessment in the polymeric sector: a comprehensive review of application experiences on the Italian scale. Polymers 12(6):1212.

Borkar S. S., Helmer R., Mahnaz F., Majzoub W., Mahmoud W., Al-Rawashdeh M., Shetty M., 2022 Enabling resource circularity through thermo-catalytic and solvent-based conversion of waste plastics. Chem Catalysis 2(12):3320-3356.

Cabernard L., Pfister S., Oberschelp C., Hellweg S., 2022 Growing environmental footprint of plastics driven by coal combustion. Nature Sustainability 5:139-148.

Chanda M., 2021 Chemical aspects of polymer recycling. Advanced Industrial and Engineering Polymer Research 4(3):133-150.

Chen B., Ray S. S., Edirisinghe M., 2022 Sustainable macromolecular materials and engineering. Macromolecular Materials and Engineering 307(6):2200242.

Chen H., Wan K., Zhang Y., Wang Y., 2021 Waste to wealth: Chemical recycling and chemical upcycling of waste plastics for a great future. ChemSusChem 14(19):4123-4136.

Chidara A., Cheng K., Gallear D., 2025 Engineering innovations for polyvinyl chloride (PVC) recycling: a systematic review of advances, challenges, and future directions in circular economy integration. Machines 13(5):362.

Clark R. A., Shaver M. P., 2024 Depolymerization within a circular plastics system. Chemical Reviews 124(5):2617-2650.

Coates G. W., Getzler Y. D. Y. L., 2020 Chemical recycling to monomer for an ideal, circular polymer economy. Nature Reviews Materials 5:501-516.

Costa I. S., De Oliveira Neto G. C., Da Silva R. N. B., Lourenço S. R., Rodrigues L. R., Amorim M., 2025 Eco-efficiency in the polymeric packaging sector: production planning and control strategies for economic and environmental gains. Polymers 17(9):1131.

Cywar R. M., Rorrer N. A., Hoyt C. B., Beckham G. T., Chen E. Y. X., 2022 Bio-based polymers with performance-advantaged properties. Nature Reviews Materials 7(2): 83-103.

Dallaev R., Papež N., Allaham M. M., Holcman V., 2025 Biodegradable polymers: properties, applications, and environmental impact. Polymers 17(14):1981.

De Simone V., Di Pasquale V., Nenni M. E., Miranda S., 2023 Sustainable production planning and control in manufacturing contexts: a bibliometric review. Sustainability 15(18):13701.

De Souza N. R. D., Matt L., Sedrik R., Vares L., Cherubini F., 2023 Integrating ex-ante and prospective life-cycle assessment for advancing the environmental impact analysis of emerging bio-based technologies. Sustainable Production and Consumption 43:319-332.

Epps T. H., Korley L. T. J., Yan T., Beers K. L., Burt T. M., 2021 Sustainability of synthetic plastics: considerations in materials life-cycle management. JACS Au 2(1):3-11.

Estrada-Ramírez O. A., Muñoz-Realpe N. A., Patiño-Murillo J. A., Chejne F., 2025 A novel set of analysis tools integrated with the energy gap method for energy accounting center diagnosis in polymer production. Resources 14(4):60.

Evode N., Qamar S. A., Bilal M., Barceló D., Iqbal H. M. N., 2021 Plastic waste and its management strategies for environmental sustainability. Case Studies in Chemical and Environmental Engineering 4:100142.

Fagnani D. E., Tami J. L., Copley G., Clemons M. N., Getzler Y. D. Y. L., McNeil A. J., 2020 100th Anniversary of macromolecular science viewpoint: redefining sustainable polymers. ACS Macro Letters 10(1):41-53.

Fayshal M., 2024 Current practices of plastic waste management, environmental impacts, and potential alternatives for reducing pollution and improving management. Heliyon 10(23):e40838.

Firoozi A. A., Firoozi A. A., Oyejobi D. O., Avudaiappan S., Flores E. S., 2024 Emerging trends in sustainable building materials: technological innovations, enhanced performance, and future directions. Results in Engineering 24:103521.

Fonsêca A., Ramalho E., Gouveia A., Figueiredo F., Nunes J., 2023 Life cycle assessment of PLA products: a systematic literature review. Sustainability 15(16):12470.

Gaspar-Cunha A., Covas J. A., Sikora J., 2022 Optimization of polymer processing: a review (part II-molding technologies). Materials 15(3):1138.

Geyer R., Jambeck J. R., Law K. L., 2017 Production, use, and fate of all plastics ever made. Science Advances 3(7):e1700782.

Gomes T. S., Visconte L. L. Y., Pacheco E. B. A. V., 2019 Life cycle assessment of polyethylene terephthalate packaging: an overview. Journal of Polymers and the Environment 27(3):533-548.

Grishin D. F., Grishin I. D., 2025 Controlled synthesis of polymers in the light of green chemistry. Russian Chemical Reviews 94(4):RCR5164.

Hahladakis J. N., Velis C. A., Weber R., Iacovidou E., Purnell P., 2018 An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. Journal of Hazardous Materials 344:179-199.

Heller M. C., Mazor M. H., Keoleian G. A., 2020 Plastics in the US: toward a material flow characterization of production, markets and end of life. Environmental Research Letters 15(9):094034.

Highmoore J. F., Kariyawasam L. S., Trenor S. R., Yang Y., 2024 Design of depolymerizable polymers toward a circular economy. Green Chemistry 26(5):2384-2420.

Hillmyer M. A., 2017 The promise of plastics from plants. Science 358(6365):868-870.

Hong M., Chen E. Y. X., 2017 Chemically recyclable polymers: a circular economy approach to sustainability. Green Chemistry 19(16):3692-3706.

Hong M., Chen E. Y. X., 2019 Future directions for sustainable polymers. Trends in Chemistry 1(2):148-151.

Hottle T. A., Bilec M. M., Landis A. E., 2013 Sustainability assessments of bio-based polymers. Polymer Degradation and Stability 98(9):1898-1907.

Hutsch S., Grätz S., Lins J., Gutmann T., Borchardt L., 2025 Solid-state polycyclotrimerization of diynes to porous organic polymers. Chemical Communications 61(80):15622-15625.

Iglesias J., Martínez-Salazar I., Maireles-Torres P., Alonso D. M., Mariscal R., Granados M. L., 2020 Advances in catalytic routes for the production of carboxylic acids from biomass: a step forward for sustainable polymers. Chemical Society Reviews 49(16):5704-5771.

Jambeck J. R., Walker-Franklin I., 2023 The impacts of plastics' life cycle. One Earth 6(6): 600-606.

Jehanno C., Alty J. W., Roosen M., De Meester S., Dove A. P., Chen E. Y. X., Leibfarth F. A., Sardón H., 2022 Critical advances and future opportunities in upcycling commodity polymers. Nature 603(7903):803-814.

Johansen M. R., Christensen T. B., Ramos T. M., Syberg K., 2022 A review of the plastic value chain from a circular economy perspective. Journal of Environmental Management 302(A):113975.

Jung H., Shin G., Kwak H., Hao L. T., Jegal J., Kim H. J., Jeon H., Park J., Oh D. X., 2023 Review of polymer technologies for improving the recycling and upcycling efficiency of plastic waste. Chemosphere 320:138089.

Kalita N. K., Hakkarainen M., 2023 Integrating biodegradable polyesters in a circular economy. Current Opinion in Green and Sustainable Chemistry 40:100751.

Kerton F. M., 2025 Applying the principles of green chemistry to achieve a more sustainable polymer life cycle. Current Opinion in Green and Sustainable Chemistry 51:100996.

Kharissova O. V., Kharisov B. I., González C. M. O., Méndez Y. P., López I., 2019 Greener synthesis of chemical compounds and materials. Royal Society Open Science 6(11): 191378.

Korley L. T. J., Epps T. H., Helms B. A., Ryan A. J., 2021 Toward polymer upcycling - adding value and tackling circularity. Science 373(6550):66-69.

Lange J. P., 2021 Managing plastic waste - sorting, recycling, disposal, and product redesign. ACS Sustainable Chemistry and Engineering 9(47):15722-15738.

Larder R. R., Hatton F. L., 2022 Enabling the polymer circular economy: innovations in photoluminescent labeling of plastic waste for enhanced sorting. ACS Polymers Au 3(2):182-201.

Law K. L., Narayan R., 2021 Reducing environmental plastic pollution by designing polymer materials for managed end-of-life. Nature Reviews Materials 7(2):104-116.

Lee J. W., Park J., Lee J., Park S., Kim J. G., Kim B. S., 2021 Cover feature: solvent-free mechanochemical post-polymerization modification of ionic polymers. ChemSusChem 14(18):3801-3805.

Lim B. K. H., Thian E. S., 2022 Biodegradation of polymers in managing plastic waste - a review. The Science of the Total Environment 813:151880.

Liu Q., Martinez-Villarreal S., Wang S., Tien N. N. T., Kammoun M., De Roover Q., Len C., Richel A., 2024 The role of plastic chemical recycling processes in a circular economy context. Chemical Engineering Journal 498:155227.

Maraveas C., 2020 Production of sustainable and biodegradable polymers from agricultural waste. Polymers 12(5):1127.

Massey-Brooker A., Conway R., 2024 Mission-oriented innovation for sustainable polymers in liquid formulation. Philosophical Transactions of The Royal Society A: Mathematical, Physical, and Engineering Sciences 382(2282):20230272.

Mierzwa-Hersztek M., Gondek K., Kopeć M., 2019 Degradation of polyethylene and biocomponent-derived polymer materials: an overview. Journal of Polymers and the Environment 27:600-611.

Mil-Martínez R., Gómez-López A., Escandón J. P., Jimenez E. M., Martínez-Suástegui L., Vargas R. O., 2024 Scale-up and control of the acrylamide polymerization process in solution. Processes 12(8):1624.

Mohanty A. K., Wu F., Mincheva R., Hakkarainen M., Raquez J. M., Mielewski D. F., Narayan R., Netravali A. N., Misra M., 2022 Sustainable Polymers. Nature Reviews Methods Primers 2(1):46.

Nguyen B. N. T., Lim J. Y. C., 2024 Emerging green approaches for valorization of plastics with saturated carbon backbones. Trends in Chemistry 6(3):100-114.

Nicholson S. R., Rorrer N. A., Carpenter A. C., Beckham G. T., 2021 Manufacturing energy and greenhouse gas emissions associated with plastics consumption. Joule 5(3):673-686.

Ohn N., Kim J. G., 2018 Mechanochemical post-polymerization modification: solvent-free solid-state synthesis of functional polymers. ACS Macro Letters 7(5):561-565.

Oza G., Olivito F., Rohokale A., Nardi M., Procopio A., Wan-Mohtar W. A. A. Q. I., Jagdale P., 2025 Advancements in catalytic depolymerization technologies. Polymers 17(12): 1614.

Pan D., Su F., Liu C., Guo Z., 2020 Research progress for plastic waste management and manufacture of value-added products. Advanced Composites and Hybrid Materials 3: 443-461.

Pellis A., Malinconico M., Guarneri A., Gardossi L., 2021 Renewable polymers and plastics: performance beyond the green. New Biotechnology 60:146-158.

Peti D., Dobránsky J., Michalík P., 2025 Recent advances in polymer recycling: a review of chemical and biological processes for sustainable solutions. Polymers 17(5):603.

Radu I. C., Vadureanu A. M., Cozorici D. E., Blanzeanu E., Zaharia C., 2025 Advancing sustainability in modern polymer processing: strategies for waste resource recovery and circular economy integration. Polymers 17(4):522.

Ragaert K., Delva L., Van Geem K., 2017 Mechanical and chemical recycling of solid plastic waste. Waste management 69:24-58.

Ramesh P., Vinodh S., 2020 State of art review on life cycle assessment of polymers. International Journal of Sustainable Engineering 13(6):411-422.

Rosenboom J. G., Langer R., Traverso G., 2022 Bioplastics for a circular economy. Nature Reviews Materials 7:117-137.

Rumetshofer T., Fischer J., 2025 Enhancement in post-consumer mechanical recycling of plastics: role of design for recycling, specifications, and efficient sorting of packaging material. Polymers 17(9):1177.

Salah C., Istrate R., Bjørn A., Tulus V., Pérez-Ramírez J., Guillén-Gosálbez G., 2024 Environmental benefits of circular ethylene production from polymer waste. ACS Sustainable Chemistry and Engineering 12(37):13897-13906.

Saxena P., Stavropoulos P., Kechagias J., Salonitis K., 2020 Sustainability assessment for manufacturing operations. Energies 13(11):2730.

Schneiderman D. K., Hillmyer M. A., 2017 50th anniversary perspective: there is a great future in sustainable polymers. Macromolecules 50(10):3733-3749.

Scholten P. B. V., Cai J., Mathers R. T., 2021 Polymers for a sustainable future. Macromolecular Rapid Communications 42(3):e2000745.

Schultz F. C., Everding S., Pies I., 2021 Circular supply chain governance: a qualitative-empirical study of the European polyurethane industry to facilitate functional circular supply chain management. Journal of Cleaner Production 317:128445.

Schwarz A. E., Ligthart T. N., Bizarro D. G., De Wild P., Vreugdenhil B., Van Harmelen T., 2021 Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. Waste Management 121:331-342.

Schyns Z. O. G., Shaver M. P., 2021 Mechanical recycling of packaging plastics: a review. Macromolecular Rapid Communications 42(3):2000415.

Seewoo B. J., Wong E. W. S., Mulders Y. R., Goodes L. M., Eroglu E., Brunner M., Gozt A., Toshniwal P., Symeonides C., Dunlop S. A., 2024 Impacts associated with the plastic polymers polycarbonate, polystyrene, polyvinyl chloride, and polybutadiene across their life cycle: a review. Heliyon 10(12):e32912.

Senila L., Kovács E., Resz M. A., Senila M., Becze A., Roman C., 2024 Life cycle assessment (LCA) of bioplastics production from lignocellulosic waste (study case: PLA and PHB). Polymers 16(23):3330.

Serrano-Aguirre L., Prieto M. A., 2024 Can bioplastics always offer a truly sustainable alternative to fossil-based plastics? Microbial Biotechnology 17(4):14458.

Shen M., Huang W., Chen M., Song B., Zeng G., Zhang Y., 2020 (Micro)plastic crisis: un-ignorable contribution to global greenhouse gas emissions and climate change. Journal of Cleaner Production 254:120138.

Sikorska W., Musioł M., Zawidlak-Węgrzyńska B., Rydz J., 2021 End-of-life options for (bio)degradable polymers in the circular economy. Advances in Polymer Technology 2021:6695140.

Singh N., Ogunseitan O. A., Wong M. H., Tang Y., 2022 Sustainable materials alternative to petrochemical plastics pollution: a review analysis. Sustainable Horizons 2:100016.

Skala M. E., Zeitler S. M., Golder M. R., 2024 Liquid-assisted grinding enables a direct mechanochemical functionalization of polystyrene waste. Chemical Science 15(28): 10900-10907.

Sternberg J., Sequerth O., Pilla S., 2021 Green chemistry design in polymers derived from lignin: review and perspective. Progress in Polymer Science 113:101344.

Štrukil V., 2021 Highly efficient solid-state hydrolysis of waste polyethylene terephthalate by mechanochemical milling and vapour-assisted aging. ChemSusChem 14(1):330-338.

Tabone M. D., Cregg J. J., Beckman E. J., Landis A. E., 2010 Sustainability metrics: life cycle assessment and green design in polymers. Environmental Science and Technology 44(21):8264-8269.

Thomas J., Patil R. S., Patil M., John J., 2023 Addressing the sustainability conundrums and challenges within the polymer value chain. Sustainability 15(22):15758.

Titone V., Botta L., La Mantia F. P., 2025 Mechanical recycling of new and challenging polymer systems: a brief overview. Macromolecular Materials and Engineering 310(1):2400275.

Tonini D., Schrijvers D., Nessi S., García-Gutiérrez P., Giuntoli J., 2021 Carbon footprint of plastic from biomass and recycled feedstock: methodological insights. The International Journal of Life Cycle Assessment 26:221-237.

Tumu K., Vorst K., Curtzwiler G., 2023 Global plastic waste recycling and extended producer responsibility laws. Journal of Environmental Management 348:119242.

Unni A. B., Joseph T. M., 2024 Enhancing polymer sustainability: eco-conscious strategies. Polymers 16(13):1769.

Von Vacano B., Mangold H., Vandermeulen G. W. M., Battagliarin G., Hofmann M., Bean J., Künkel A., 2023 Sustainable design of structural and functional polymers for a circular economy. Angewandte Chemie 62(12):e202210823.

Walker S., Rothman R., 2020 Life cycle assessment of bio-based and fossil-based plastic: a review. Journal of Cleaner Production 261:121158.

Wang X., Gao Y., Tang Y., 2023 Sustainable developments in polyolefin chemistry: progress, challenges, and outlook. Progress in Polymer Science 143:101713.

Wang Y., Van Putten R. J., Tietema A., Parsons J. R., Gruter G. J. M., 2024 Polyester biodegradability: importance and potential for optimisation. Green Chemistry 26(7): 3698-3716.

Wang Z., Ganewatta M. S., Tang C., 2020 Sustainable polymers from biomass: bridging chemistry with materials and processing. Progress in Polymer Science 101:101197.

Westlie A. H., Chen E. Y. X., Holland C. M., Stahl S. S., Doyle M., Trenor S. R., Knauer K. M., 2022 Polyolefin innovations toward circularity and sustainable alternatives. Macromolecular Rapid Communications 43(24):2200492.

Wojnowska-Baryła I., Kulikowska D., Bernat K., 2020 Effect of bio-based products on waste management. Sustainability 12(5):2088.

Xia Q., Chen C., Yao Y., Li J., He S., Zhou Y., Li T., Pan X., Yao Y., Hu L., 2021 A strong, biodegradable and recyclable lignocellulosic bioplastic. Nature Sustainability 4:627-635.

Yan C., Wang J., 2025 Conceptual modeling and performance evaluation of novel reactors for efficient synthesis of nylon-6,6. International Journal of Chemical Reactor Engineering 23(3):287-304.

Yaroslavov A. A., Arzhakov M. S., Khokhlov A. R., 2022 The life cycle of polymer materials: problems and prospects. Herald of the Russian Academy of Sciences 92(1):18-24.
Zarte M., Pechmann A., Nunes I. L., 2022 Problems, needs, and challenges of a sustainability-based production planning. Sustainability 14(7):4092.
Zhang M. Q., Wang M., Sun B., Hu C., Xiao D., Ma D., 2022 Catalytic strategies for upvaluing plastic wastes. Chem 8(11):2912-2923.
Zhang X., Fèvre M., Jones G. O., Waymouth R. M., 2018 Catalysis as an enabling science for sustainable polymers. Chemical Reviews 118(2):839-885.
Zhu Y., Romain C., Williams C. K., 2016 Sustainable polymers from renewable resources. Nature 540:354-362.

Received: 31 October 2025. Accepted: 28 November 2025. Published online: 25 December 2025.

Author:
Robert Raul Papp, Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca, 3-5 Calea Mănăştur Street, 400372 Cluj-Napoca, Romania, e-mail: robert-raul.papp@student.usamvcluj.ro

How to cite this article:
Papp R. R., 2025 Integrated environmental management strategies for sustainable polymer production. AES Bioflux 17(1):107-117.