



System-level approaches to carbon footprint reduction in polymer manufacturing

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Abstract. The polymer manufacturing sector represents one of the most energy-intensive branches of the chemical industry and is therefore a major contributor to global greenhouse gas emissions. This article provides an in-depth, system-level analysis of carbon footprint reduction strategies in polymer manufacturing, drawing exclusively on peer-reviewed scientific literature. Life cycle assessment (LCA) is applied as the primary analytical framework to evaluate emissions associated with feedstock extraction, polymer synthesis, processing, use, and end-of-life management. Particular emphasis is placed on the interactions between material flows, energy systems, and recycling infrastructures. The study demonstrates that isolated technological interventions are insufficient to achieve climate neutrality and that integrated, system-level strategies are essential for long-term emission reductions.

Key Words: carbon capture, carbon utilization, circular economy, electrification, recycling.

Introduction. The polymer industry forms the backbone of numerous industrial sectors, including packaging, construction, automotive manufacturing, electronics, and medical devices. The versatility, low cost, and durability of polymeric materials have driven continuous growth in global production volumes. This rapid growth has, however, resulted in increasing environmental pressure. Polymer manufacturing relies heavily on fossil resources, not only as energy carriers but also as carbon feedstocks embedded in polymer chains. As a result, the sector contributes significantly to industrial greenhouse gas emissions.

Historically, mitigation efforts focused primarily on improving process efficiency. While such measures have reduced energy intensity, they have not offset the emissions associated with increasing production volumes. This has led to growing recognition that incremental improvements are insufficient. Consequently, contemporary research emphasizes the need for system-level approaches that consider the entire polymer life cycle, from raw material extraction to end-of-life management, in order to achieve meaningful carbon footprint reductions.

Life cycle assessment as the core analytical tool

Methodological basis of life cycle assessment. Life cycle assessment (LCA) is a quantitative environmental assessment methodology standardized under ISO 14040 and ISO 14044 (Finkbeiner et al 2006). It evaluates environmental impacts associated with a product system throughout its entire life cycle, including raw material extraction, production, use, and disposal (Banerjee & Ray 2022). In polymer manufacturing, LCA enables the identification of emission hotspots and allows comparison between alternative materials, processes, and end-of-life scenarios. The method provides a holistic perspective that is essential for system-level decision-making (Tan & Culaba 2009). However, LCA results are sensitive to assumptions regarding system boundaries,

functional units, and data quality. As a result, transparent reporting and critical interpretation are essential to avoid misleading conclusions (Banerjee & Ray 2022).

LCA findings for polymer production. Numerous LCA studies consistently show that upstream processes dominate the carbon footprint of polymers (Khasreen et al 2009; Fnais et al 2022; Bjørn et al 2020).

Downstream polymer processing, such as extrusion and injection molding, contributes a smaller but non-negligible fraction of emissions. The magnitude of this contribution depends strongly on the carbon intensity of electricity used (Tan & Culaba 2009).

These findings highlight that decarbonization strategies must address both material and energy systems simultaneously rather than focusing on isolated stages of the life cycle (Banerjee & Ray 2022).

In the life cycle assessment of polymers, LCA studies indicate that differences between fossil-based polymers and biopolymers are significant in terms of energy consumption and environmental impact, and that cradle-to-gate and cradle-to-grave assessments highlight production stages with varying impact footprints, emphasizing the importance of clearly defining system boundaries in sustainability evaluations (Ramesh & Vinodh 2020).

Cradle-to-gate vs. cradle-to-grave approaches. In polymer studies, cradle-to-gate LCAs are commonly used to evaluate production-related emissions up to the factory gate. While useful for comparing manufacturing routes, such studies neglect use-phase and end-of-life impacts (Tan & Culaba 2009).

Cradle-to-grave assessments provide a more complete picture by including product use and disposal. For polymers, end-of-life scenarios such as recycling, incineration, and landfill can significantly influence total emissions. The choice of system boundaries therefore has a major influence on conclusions regarding the sustainability of polymer systems (Banerjee & Ray 2022).

Limitations of LCA in polymer decarbonization. Although LCA is a powerful tool, it has limitations when applied to emerging technologies. Data uncertainty, scaling assumptions, and regional variability can introduce significant errors (Tan & Culaba 2009). Consequently, LCA should be interpreted as a decision-support tool rather than a precise predictor of future environmental performance (Banerjee & Ray 2022).

Dependence on fossil feedstocks. Even if production processes are powered by renewable energy, the fossil carbon embedded in polymers contributes to life cycle emissions when materials are incinerated or degraded at end-of-life. This structural dependence represents a fundamental barrier to decarbonization. As a result, scientific literature increasingly emphasizes the importance of transitioning away from fossil feedstocks toward renewable or circular carbon sources (Banerjee & Ray 2022).

In addition, fossil-based polymer systems are exposed to volatility in oil and gas markets, which introduces economic risks alongside environmental concerns. Transitioning away from fossil feedstocks therefore offers both climate and economic resilience benefits (Banerjee & Ray 2022).

In the material flow analysis, the chemical industry in China demonstrated a heavy reliance on fossil hydrocarbons as feedstocks, with significant proportions of coal, crude oil, and natural gas used as raw materials for chemical production, underscoring the sector's dependence on fossil feedstocks and its implications for emissions and resource demand (Jiang et al 2024).

Biobased polymer feedstocks

Overview of biobased polymers. Biobased polymers are derived from renewable biological resources such as corn, sugarcane, and lignocellulosic biomass. Common examples include polylactic acid (PLA) and polyhydroxyalkanoates (PHA), which have

attracted significant research interest as alternatives to fossil-based plastics (Jha et al 2024).

These materials offer the potential to reduce dependence on fossil carbon and, under certain conditions, to lower greenhouse gas emissions. However, their environmental performance depends strongly on agricultural practices and energy inputs used during production (Jha et al 2024).

It is important to distinguish between “biobased” and “biodegradable”, as not all biobased polymers are biodegradable and vice versa. This distinction has significant implications for end-of-life management (Jha et al 2024).

Environmental performance and limitations. LCA of biobased polymers show that emission reductions are achievable when biomass cultivation is efficient and when renewable energy sources are used in processing. Conversely, intensive fertilizer use, irrigation, and indirect land-use change can significantly reduce or even negate potential climate benefits. As a result, biobased polymers should not automatically be considered low-carbon. Instead, their sustainability must be evaluated on a case-by-case basis using system-level LCA (Banerjee & Ray 2022).

LCA suggest that biobased polymers can offer greenhouse gas emission reductions compared to fossil-based alternatives, particularly when renewable energy is used in processing. However, environmental benefits are highly context-dependent. Intensive agriculture, land-use change, and fertilizer application can significantly increase emissions, potentially offsetting gains (Banerjee & Ray 2022).

Food vs. materials debate. A major concern regarding first-generation biobased polymers is competition with food production. The diversion of agricultural land to material production can exacerbate food security challenges (Jha et al 2024).

Second-generation feedstocks derived from agricultural residues and non-food biomass offer potential solutions but are not yet widely available at industrial scale (Banerjee & Ray 2022).

Industrial scalability. Although biobased polymers are commercially available, their production volumes remain small compared to fossil-based plastics. Scaling up production requires significant investment and infrastructure development (Jha et al 2024).

Despite the development of advanced synthetic methods and the application of biofilms in smart/intelligent food packaging, construction, exclusion nets, and medicine, commercial production is limited by cost, the economics of production, useful life, and biodegradation concerns, and the availability of adequate agro-wastes, indicating challenges in scaling up industrial production of bio-based polymers (Maraveas 2020).

CO₂-derived and carbon-above-ground feedstocks. An alternative approach to reducing fossil carbon use is the utilization of captured carbon dioxide as a feedstock for polymer and chemical production. This concept, often referred to as keeping carbon 'above ground', aims to circulate carbon within the industrial system rather than extracting new fossil resources (Gruter 2023).

CO₂ can be converted into polymer precursors through catalytic and electrochemical routes, particularly when combined with renewable hydrogen. However, these processes are energy-intensive, and their climate benefit depends strongly on the availability of low-carbon electricity (Gruter 2023).

Carbon capture and utilization (CCU) aims to convert captured CO₂ into valuable chemicals and polymers, thereby reducing the need for fossil carbon extraction (Gruter 2023).

CO₂-derived polymer production typically requires renewable hydrogen and large quantities of low-carbon electricity. Without a decarbonized energy system, CCU may result in higher overall emissions (Gruter 2023). Thus, CCU must be evaluated within a system-level context that considers energy supply and competing uses of renewable resources (Banerjee & Ray 2022).

Mechanical recycling. The mechanical recycling section of the review provides an overview of current sorting technologies and highlights specific challenges such as thermo-mechanical degradation and the immiscibility of polymer blends, which affect the efficiency of mechanical recycling processes for solid plastic waste (Ragaert et al 2017).

Despite these advantages, mechanical recycling faces limitations related to material degradation, contamination, and complex multi-material product designs. These factors reduce recycling efficiency and limit the number of recycling cycles that a polymer can undergo (Banerjee & Ray 2022). However, repeated recycling leads to polymer chain degradation, reducing material properties. Contamination and complex product design further limit recycling efficiency. Design-for-recycling strategies, including material simplification and improved labeling, are therefore essential to maximize the benefits of mechanical recycling (Banerjee & Ray 2022).

Chemical recycling. Chemical recycling encompasses a range of technologies that aim to convert plastic waste into monomers, fuels, or basic chemicals through chemical or thermochemical processes. Unlike mechanical recycling, which preserves polymer chains, chemical recycling breaks them down, enabling treatment of mixed, multilayer, or contaminated waste streams (Harasymchuk et al 2024).

Among the most studied approaches is pyrolysis, where plastics are thermally decomposed in the absence of oxygen to produce liquid hydrocarbons, gases, and char. Pyrolysis oils can be further refined and used as feedstocks for new polymer production, potentially closing the material loop (Harasymchuk et al 2024).

Solvolytic processes, such as glycolysis and methanolysis, are particularly relevant for condensation polymers like PET and polyamides. These processes enable recovery of monomers with relatively high purity, supporting closed-loop recycling (Harasymchuk et al 2024).

Despite these advantages, chemical recycling is inherently energy-intensive due to high temperature and pressure requirements. LCA indicate that without low-carbon energy sources, chemical recycling may result in higher emissions than mechanical recycling (Banerjee & Ray 2022).

Furthermore, large-scale deployment of chemical recycling raises concerns regarding economic viability, process emissions, and competition for renewable energy. As a result, chemical recycling is increasingly viewed as a complementary rather than primary recycling solution (Harasymchuk et al 2024).

Energy efficiency in polymer processing. Polymer processing operations, including extrusion, injection molding, blow molding, and thermoforming, account for a significant share of total energy consumption in polymer manufacturing. Energy use is dominated by heating, melting, and mechanical work (Abeykoon et al 2021).

Improving energy efficiency can be achieved through advanced screw designs, optimized barrel heating systems, and improved insulation. Process integration and heat recovery systems further reduce energy losses (Abeykoon et al 2021).

Digitalization and real-time process monitoring enable precise control of operating conditions, reducing scrap rates and unnecessary energy use. These measures often provide rapid payback periods, making them attractive for industry (Banerjee & Ray 2022).

However, efficiency improvements face diminishing returns as systems approach thermodynamic limits. Moreover, energy efficiency does not address emissions embedded in fossil-based feedstocks. Thus, energy efficiency should be regarded as a foundational but insufficient measure within a broader decarbonization strategy (Banerjee & Ray 2022).

Electrification of polymer manufacturing. Certain polymer processes, particularly low- to medium-temperature operations such as extrusion and injection molding, are well-suited for electrification. High-temperature processes present greater technical challenges (Tan & Culaba 2009).

The carbon reduction potential of electrification depends strongly on the electricity mix. In regions with coal-dominated grids, electrification may yield limited or even negative climate benefits (Tan & Culaba 2009). Consequently, electrification must be coordinated with broader energy system transitions to maximize its environmental benefits (Banerjee & Ray 2022).

The electron-withdrawing ability and density of different functional groups on the polymer main chain determine both the polarity and density of contact-electrification-induced surface charges, clarifying how specific molecular structures influence the electrification behavior of polymers (Li et al 2020).

Carbon capture, utilization, and storage. Carbon capture, utilization, and storage (CCUS) technologies aim to mitigate industrial CO₂ emissions by capturing carbon dioxide from point sources or directly from air. In polymer manufacturing, CCU focuses on converting CO₂ into chemical intermediates and polymers (Gruter 2023).

CCU pathways often require hydrogen produced via water electrolysis, making them highly dependent on renewable electricity availability. Without low-carbon hydrogen, CCU may increase total system emissions (Gruter 2023).

Carbon storage (CCS) offers the potential for permanent emission reduction but requires extensive infrastructure for CO₂ transport and storage. Public acceptance and long-term liability remain major challenges. As a result, CCUS is best viewed as a transitional or complementary solution rather than a standalone pathway to climate neutrality (Banerjee & Ray 2022).

Integrated system-level decarbonization strategies. Integrated system-level strategies combine multiple mitigation approaches to address emissions across the entire polymer life cycle. Such strategies recognize interdependencies between material flows, energy systems, and waste management infrastructures (Banerjee & Ray 2022). For example, combining mechanical recycling with electrified processing and renewable energy supply can significantly reduce cradle-to-gate emissions. Chemical recycling can be selectively applied to waste streams unsuitable for mechanical recycling (Harasymchuk et al 2024).

System integration also reduces the risk of burden shifting, where emission reductions in one life cycle stage lead to increases elsewhere. Scenario-based modeling studies consistently show that integrated approaches outperform single-technology solutions in terms of emission reduction potential and robustness under uncertainty (Banerjee & Ray 2022).

Conclusions. This paper demonstrates that reducing the carbon footprint of polymer manufacturing requires a holistic, system-level perspective. Life cycle assessment provides the analytical foundation for identifying effective interventions, while integrated strategies addressing feedstocks, energy systems, and end-of-life management enable substantial emission reductions. Understanding these system-level interactions is essential for evaluating future technologies and contributing to the transition toward a more sustainable polymer industry.

Conflict of interest. The author declares that there is no conflict of interest.

References

- 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.
- 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.

- Bjørn A., Chandrakumar C., Boulay A. M., Dóka G., Fang K., Gondran N., Hauschild M. Z., Kerkhof A., King H., Margni M., McLaren S., Mueller C., Owsianiak M., Peters G., Roos S., Sala S., Sandin G., Sim S., Vargas-González M., Ryberg M., 2020 Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. *Environmental Research Letters* 15(8):083001.
- Finkbeiner M., Inaba A., Tan R., Christiansen K., Klüppel H. J., 2006 The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *The International Journal of Life Cycle Assessment* 11(2):80-85.
- Fnaïs A., Rezgui Y., Petri I., Beach T., Yeung J., Ghoroghi A., Kubicki S., 2022 The application of life cycle assessment in buildings: challenges, and directions for future research. *The International Journal of Life Cycle Assessment* 27:627-654.
- Gruter G. J. M., 2023 Using carbon above the ground as feedstock to produce our future polymers. *Current Opinion in Green and Sustainable Chemistry* 40:100743.
- Harasymchuk I., Kočí V., Vitvarová M., 2024 Chemical recycling: comprehensive overview of methods and technologies. *International Journal of Sustainable Engineering* 17(1):124-148.
- Jha S., Akula B., Enyioma H., Novak M., Amin V., Liang H., 2024 Biodegradable biobased polymers: a review of the state of the art, challenges, and future directions. *Polymers* 16(16):2262.
- Jiang M., Cao Y., Liu C., Chen D., Zhou W., Wen Q., Yu H., Jiang J., Ren Y., Hu S., Hertwich E., Zhu B., 2024 Tracing fossil-based plastics, chemicals and fertilizers production in China. *Nature Communications* 15:3854.
- Khasreen M. M., Banfill P. F. G., Menzies G. F., 2009 Life-cycle assessment and the environmental impact of buildings: a review. *Sustainability* 1(3):674-701.
- Li S., Nie J., Shi Y., Tao X., Wang F., Tian J., Lin S., Chen X., Wang Z., 2020 Contributions of different functional groups to contact electrification of polymers. *Advanced Materials* 32(25):2001307.
- Maraveas C., 2020 Production of sustainable and biodegradable polymers from agricultural waste. *Polymers* 12(5):1127.
- Ramesh P., Vinodh S., 2020 State of art review on life cycle assessment of polymers. *International Journal of Sustainable Engineering* 13(6):411-422.
- Ragaert K., Delva L., Van Geem K., 2017 Mechanical and chemical recycling of solid plastic waste. *Waste Management* 69:24-58 .
- Tan R. T., Culaba A. B., 2009 Estimating the carbon footprint of tuna fisheries. WWF Binary Item, 17870, 14 pp.

Received: 04 November 2025. Accepted: 30 November 2025. Published online: 23 December 2025.

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How to cite this article:

Budae A. C., 2025 System-level approaches to carbon footprint reduction in polymer manufacturing. *AES Bioflux* 17(1):94-99.