A Data-Driven Roadmap for Cost-Effective Reductions in Emissions, Waste, and Resource Use in Plastics: A Case Study of the Packaging Economy

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Abstract:

Plastic materials present both challenges and opportunities for advancing a circular economy. Over the past few decades, plastic production and consumption have risen sharply, with packaging emerging as one of the most rapidly growing sectors. While plastics provide numerous societal benefits, their widespread adoption has resulted in substantial resource use, waste generation, and pollution that threatens both biodiversity and human health. In this work, we dynamically model the plastic packaging economy and evaluate a portfolio of cost-effective technologies to reduce emissions and waste. The analysis considers a broad range of solutions, from optical and AI-assisted sorting to multiple end-of-life pathways, including mechanical recycling (high TRL), chemical recycling (mid-TRL), and solvent-based processes (low TRL). A key novelty of this study is the explicit inclusion of macro- and microplastic pollution in the packaging sector and the evaluation of technologies to mitigate these impacts. Preliminary results highlight that no single technology is sufficient; rather, a coordinated portfolio of complementary solutions is required to enable a sustainable and profitable packaging economy. Integrating circularity with renewable feedstocks, renewable energy, and advanced mitigation technologies is shown to substantially reduce emissions and costs, offering a viable pathway toward a win–win outcome for industry and the environment.

In addition, this work introduces a generalized, open-access, multi-objective optimization framework under uncertainty, built on freely available data, for dynamically modeling the packaging economy. The framework is designed to interoperate with open-source integrated assessment models (IAMs), which are large-scale models that link energy, economic, land-use, and climate systems, to make it possible to evaluate how plastics system transitions interact with broader national and global developments. This integration allows the assessment of the impacts of changing economic policies, energy pathways, and climate conditions on plastics management strategies. By making the model open, transparent, and connected to IAMs, this work enhances reproducibility and provides a versatile decision-support tool for researchers, industry, and policymakers seeking to co-develop strategies for a circular, lower-emission plastics economy.