Recycling of Composite Multilayer Packaging Waste Through Solvent-Based Separation: Implications for Resource Recovery

T. Mumladze[1], Kh. Kharazishvili[1], G. Denafas[2], I. Bochoidze[1], Ts. Turkadze[1], M. Gabidzashvili[1], N. Guleishvili[1]

[1]Department of Chemical and Environmental Technologies, Akaki Tsereteli State University, Kutaisi, Imereti, 4600, Georgia
[2] Department of Environmental Technology, Kaunas Univeersity of Technology, Kaunas, LT-50254, Lithuania
Presenting author email: tamari.mumladze@atsu.edu.ge

This work was supported by Shota Rustaveli National Science Foundation of Georgia (SRNSFG) [grant number FR-24-2116 - Recycling of Combined Aluminum-Polymer Packaging Waste (APPW) Using Circular Economy and Green Chemistry Approaches]

Keywords: multilayer packaging, solvent-based separation, advanced recycling, STRAP process, resource recovery

Composite multilayer packaging materials are extensively used in food, beverage, and pharmaceutical applications due to their superior barrier performance, mechanical stability, and ability to extend product shelf life (Tamizhdurai et al., 2024; Kaiser et al., 2017). These materials typically consist of multiple polymer layers—such as polyethylene (PE), polyethylene terephthalate (PET), polyamide (PA), and ethylene vinyl alcohol (EVOH)—often combined with aluminum or paperboard. While this complex structure enhances functionality, it presents significant challenges at end of life. Conventional mechanical recycling technologies are largely ineffective for multilayer structures because of polymer incompatibility and the presence of adhesives, inks, and barrier layers, resulting in low recycling rates and extensive downcycling or disposal via landfilling and incineration (Kaiser et al., 2017; Li et al., 2022).

Solvent-based separation technologies have emerged as a promising advanced recycling route capable of selectively recovering high-purity polymers from composite multilayer packaging waste. These processes rely on differences in polymer solubility to dissolve individual layers sequentially and subsequently recover them via controlled precipitation, while preserving polymer quality (Walker et al., 2020). Among these approaches, the Solvent-Targeted Recovery and Precipitation (STRAP) process has demonstrated near-complete material recovery for multilayer films composed of PE, EVOH, and PET (Walker et al., 2020). Further development of STRAP using temperature-controlled dissolution and precipitation has significantly reduced antisolvent use and improved process economics and environmental performance (Sánchez-Rivera et al., 2021).

In parallel, alternative solvent systems have been investigated to improve sustainability and operational feasibility. Switchable hydrophilicity solvents enable reversible changes in solvent polarity through CO_2 triggering, allowing efficient delamination and solvent recovery with reduced chemical consumption (Mumladze et al., 2018; Mastroddi et al., 2025). Deep eutectic solvents have also attracted attention due to their low volatility, tunable properties, and potential for formulation from bio-based components, showing promising results for delaminating PE/Al/PET laminates (Loukodimou et al., 2024a, 2024b). Systematic screening of green solvents using computational and experimental approaches further supports the development of safer and more sustainable solvent-based recycling systems (Ikegwu et al., 2025).

Reported recovery efficiencies for solvent-based separation processes typically exceed 95%, substantially outperforming mechanical recycling of multilayer materials (Walker et al., 2020; Sánchez-Rivera et al., 2021). Importantly, recovered polymers exhibit molecular weight, thermal stability, and mechanical properties comparable to virgin resins, enabling their potential reuse in high-value applications, including packaging (Li et al., 2024; Walker et al., 2020). This capability represents a key advantage over conventional recycling, which often results in low-quality recyclates unsuitable for closed-loop applications (Kaiser et al., 2017).

Environmental implications of solvent-based separation have been assessed through life cycle assessment studies, which consistently report reduced greenhouse gas emissions, fossil resource depletion, and overall environmental impacts compared to landfilling and incineration (Munguía-López et al., 2023; Jasiński et al., 2025). When high solvent recovery rates are achieved and low-carbon energy sources are employed, solvent-based recycling can approach or even outperform virgin polymer production in key environmental impact categories (Munguía-López et al., 2023). Nevertheless, energy demand associated with heating and solvent recovery remains a critical contributor to overall impacts, underscoring the importance of process optimization and heat integration (Sánchez-Rivera et al., 2021; Munguía-López et al., 2024).

From an economic perspective, technoeconomic analyses indicate that solvent-based separation can be cost-competitive with virgin polymer production, particularly for high-value barrier polymers such as EVOH (Sánchez-Rivera et al., 2021). Process innovations that reduce solvent consumption and simplify recovery significantly improve economic viability, although large-scale implementation remains sensitive to feedstock quality, energy prices, and solvent losses (Munguía-López et al., 2024). Policy instruments such as extended producer responsibility schemes, recycled content mandates, and carbon pricing are therefore essential to support market uptake and investment in solvent-based recycling infrastructure (Jasiński et al., 2025).

Despite their promise, solvent-based separation technologies face several challenges, including the heterogeneity and contamination of post-consumer waste streams, solvent recovery at industrial scale, and regulatory constraints related to solvent handling and food-contact applications (Li et al., 2022; Tamizhdurai et al., 2024). Continued research into green solvent systems, computational process design, and integration with existing waste management infrastructure is required to overcome these barriers and enable widespread deployment.

Table 1. Indicative recovery performance and key characteristics of solvent-based separation technologies reported in recent literature.

Technology	**Typical recovered materials**	**Reported recovery efficiency (%)**	**Key advantage**
STRAP	PE, EVOH, PET	>95–99	High purity, closed-loop potential
Switchable solvents	PE, PET, Al	>90	Low solvent loss, mild conditions
Deep eutectic solvents	PE/Al/PET	>85–95	Low volatility, green solvent profile

Overall, solvent-based separation represents a technologically robust and environmentally advantageous pathway for recycling composite multilayer packaging waste. By enabling high-purity polymer recovery and supporting closed-loop material flows, these technologies can play a critical role in advancing circular economy objectives and reducing the environmental footprint of plastic packaging systems.

References

Ikegwu, C., Munguía-López, A. C., Sánchez-Rivera, K. L., Ponce-Ortega, J. M., & Zavala, V. M. (2025). *Screening green solvents for multilayer plastic film recycling processes*. ChemRxiv. https://doi.org/10.26434/chemrxiv-2025-zrmnp

Jasiński, D., Meredith, M., & Kirwan, K. (2025). Sustainability assessment of employing chemical recycling technologies on multilayer packaging waste. *Sustainability, 17*(2), 556. https://doi.org/10.3390/su17020556

Kaiser, K., Schmid, M., & Schlummer, M. (2017). Recycling of polymer-based multilayer packaging: A review. *Recycling, 3*(1), 1. https://doi.org/10.3390/recycling3010001

Li, H., Aguirre-Villegas, H. A., Allen, R. D., Bai, X., Benson, C. H., Beckham, G. T., … Zavala, V. M. (2022). Expanding plastics recycling technologies: Chemical aspects, technology status and challenges. *Green Chemistry, 24*(23), 8899–9002. https://doi.org/10.1039/d2gc02588d

Li, H., Shi, Y., Aguirre-Villegas, H. A., Bai, X., Benson, C. H., Beckham, G. T., … Zavala, V. M. (2024). Progress in solvent-based recycling of polymers from multilayer packaging. *Polymers, 16*(12), 1670. https://doi.org/10.3390/polym16121670

Loukodimou, E. E., Lambropoulou, D. A., & Bikiaris, D. N. (2024a). Formulation and characterization of deep eutectic solvents and potential application in recycling packaging laminates. *Polymers, 16*(19), 2781. https://doi.org/10.3390/polym16192781

Loukodimou, E. E., Lambropoulou, D. A., & Bikiaris, D. N. (2024b). Delamination and evaluation of multilayer PE/Al/PET packaging waste separated using a hydrophobic deep eutectic solvent. *Polymers, 16*(19), 2718. https://doi.org/10.3390/polym16192718

Mastroddi, F., Pastore, C., Samorì, C., & Mazzanti, A. (2025). Recycling of multilayer flexible packaging waste through delamination with recoverable switchable hydrophilicity solvents. *Separations, 12*(2), 45. https://doi.org/10.3390/separations12020045

Mumladze, T., Younes, R., Maric, I., Moores, M., & Jessop, P. G. (2018). Sustainable approach to recycling of multilayer flexible packaging using switchable hydrophilicity solvents. *Green Chemistry, 20*(17), 3604–3618. https://doi.org/10.1039/C8GC01062E

Munguía-López, A. C., Sánchez-Rivera, K. L., Ponce-Ortega, J. M., & Zavala, V. M. (2023). Quantifying the environmental benefits of a solvent-based separation process for multilayer plastic films. *Green Chemistry, 25*(5), 1611–1625. https://doi.org/10.1039/d2gc04262b

Munguía-López, A. C., Ikegwu, C., Sánchez-Rivera, K. L., Ponce-Ortega, J. M., & Zavala, V. M. (2024). A fast computational framework for the design of solvent-based plastic recycling processes. *Sustainable Chemistry & Technology*. https://doi.org/10.69997/sct.175924

Sánchez-Rivera, K. L., Zhou, P., Kim, M. S., González-González, L. D., & Huber, G. W. (2021). Reducing antisolvent use in the STRAP process by enabling a temperature-controlled polymer dissolution and precipitation for the recycling of multilayer plastic films. *ChemSusChem, 14*(19), 4317–4329. https://doi.org/10.1002/cssc.202101128

Tamizhdurai, P., Sakthinathan, A., Chen, S. M., Shanthi, K., Sivasanker, S., & Sangeetha, C. (2024). A state-of-the-art review of multilayer packaging recycling: Challenges, alternatives, and outlook. *Journal of Cleaner Production, 441*, 141403. https://doi.org/10.1016/j.jclepro.2024.141403

Walker, T. W., Frelka, N., Shen, Z., Chew, A. K., Banick, J., Grey, S., … Huber, G. W. (2020). Recycling of multilayer plastic packaging materials by solvent-targeted recovery and precipitation. *Science Advances, 6*(47), eaba7599. https://doi.org/10.1126/sciadv.aba7599

Wong, B., Sánchez-Rivera, K. L., Zhou, P., Kim, M. S., & Huber, G. W. (2024). Solvent-targeted recovery of all major materials in beverage carton packaging waste. *Resources, Conservation and Recycling, 201*, 107367. https://doi.org/10.1016/j.resconrec.2023.107367