International Journal of Global Science Research
Vol. 13, Issue. 2, October 2026, pp. 9263-9267
Available Online at www.ijgsr.com
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ISSN: 2348-8344 (Online)
DOI: https://doi.org/10.26540/ijgsr.v13.i2.2026.368

Research Paper

Sustainable Labels for Circular Plastic Packaging: Materials, Adhesives and Design for Recycling

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Received: 03/09/2026
Revised: 11/09/2026
Accepted:19/09/2026

Abstract: Labels are essential for product identification, branding and regulatory communication, yet their substrates, adhesives, inks and coatings can influence the recovery of plastic packaging. This review-style article outlines the principal design considerations linking label construction with sorting, washing and mechanical recycling. It discusses polymer compatibility, label coverage and optical sorting, adhesive release behaviour, printing systems, and distinctions among recyclable, bio-based, biodegradable and compostable materials. The article also describes a practical framework for evaluating label-and-container combinations against a defined recycling pathway. The central conclusion is that label sustainability cannot be determined from a single material attribute or environmental claim. It depends on the behaviour of the complete packaging system and on the collection, sorting and recycling infrastructure available at end of life. Design-for-recycling guidance and stream-specific evaluation protocols provide a basis for assessing compatibility; where performance is uncertain, testing under relevant process conditions is necessary. This article is a technical overview and does not report new experimental results.

Keywords: plastic packaging; design for recycling; label adhesives; polymer compatibility; mechanical recycling; optical sorting; circular economy

Introduction:

Packaging labels perform several functions, including product identification, communication of ingredients and instructions, traceability, and brand presentation. These functions must be maintained throughout storage, transport and use. At end of life, however, the label becomes part of a multi-component packaging system that may enter a sorting and recycling process not designed around the label alone.

Mechanical recycling commonly involves collection, sorting, size reduction, washing, drying and melt processing. Incompatible label films, persistent adhesives, pigments, coatings or paper fibres can affect sorting accuracy, washing efficiency and the quality of recovered polymer. The magnitude of these effects depends on the packaging format, material combination, contamination level and process conditions. Reviews of industrial PET recycling identify labels and adhesives as relevant contamination sources and discuss their

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effects on sorting and recyclate quality (Ragaert, et al., 2025).

This article provides a focused technical overview of sustainable labelling, with emphasis on material compatibility, adhesive separation, optical sorting, emerging design approaches and practical validation. It is not a systematic review and does not present original experimental data.

Material selection and compatibility:

A label should be assessed in relation to the primary packaging polymer and the intended recycling stream. PET, high-density polyethylene (HDPE), polypropylene (PP) and polyethylene (PE) differ in density, thermal behaviour and processing characteristics. When incompatible polymers remain in a recovered material, they may form separate phases or otherwise influence the mechanical, optical or processing properties of the recyclate.

Using a label made from a compatible polymer can reduce material-separation challenges in some systems, but polymer-family matching alone does not guarantee recyclability. Adhesives, inks, coatings, pigments and label geometry also affect performance. Design-for-recycling guidance is therefore typically specific to packaging format and polymer stream rather than universal across all plastics (https://recyclass.eu/protocols-guidelines/design-for-recycling-guidelines/packaging/ ; https://recyclass.eu/protocols-guidelines/testing-protocols/)

Where a different label substrate is required for functional or commercial reasons, designers should consider whether the label can be separated during washing or whether the label-and-adhesive combination has been shown to be compatible with the target stream. The decision should reflect actual facility capabilities and the intended application of the recovered polymer.

Adhesive performance and label separation:

Adhesives must balance in-use durability with end-of-life behaviour. A label must remain attached during handling, moisture exposure and transportation, yet some packaging systems benefit when the label detaches during recycling. Wash-off or water-releasable adhesives are formulated to release under defined process conditions; performance can depend on temperature, water chemistry, residence time, agitation and the adhesive formulation.

Relevant assessment criteria include label removal, residual adhesive on the container or flakes, contamination of the wash stream, and any downstream effect on recovered material. A water-based adhesive should not automatically be considered recycling-compatible: its formulation and behaviour under the intended process conditions must be assessed.

RecyClass provides evaluation protocols for labels and adhesives used on PET bottles and HDPE containers, illustrating the importance of testing complete label systems against specific recycling streams (https://recyclass.eu/protocols-guidelines/testing-protocols/). Such protocols can help suppliers and packaging designers move from broad material claims to evidence-based compatibility assessments.

Inks, coatings and optical sorting:

Near-infrared (NIR) sorting systems use reflected spectral signals to help identify polymers. Label colour, opacity, surface coverage and material composition may interfere with the identification of the underlying container in some configurations. Full-body sleeves and certain pigments can create challenges depending on the equipment and package design. These effects should be evaluated against the sorting technology and waste stream for which the package is intended.

Printing inks, protective coatings and metallised layers can also affect the

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appearance or quality of recovered material. Excessive material complexity may introduce additional separation challenges, although the impact depends on the specific materials and recycling process. Label design should therefore consider substrate, ink system, coating, coverage and removal behaviour together rather than treating each feature independently.

Emerging approaches to sustainable labelling:

Linerless labelling can eliminate the conventional release liner and reduce waste generated during label application. Bio-based substrates can replace some fossil-derived feedstocks, but bio-based origin does not by itself establish recyclability or biodegradability. Water-based and other lower-VOC ink systems may reduce certain emissions, depending on formulation and manufacturing conditions. Digital product information, such as QR-linked content, may supplement physical labels, although mandatory information and essential instructions must remain available as required.

Each innovation should be assessed across the complete packaging system. A compostable label is not automatically suitable for conventional mechanical plastic recycling, and a label recyclable in isolation may not be compatible with the container's recovery pathway. Claims should identify the relevant conditions and infrastructure rather than rely on broad terms such as 'green' or 'eco-friendly'.

Practical framework for design and validation:

A practical assessment can begin by documenting the packaging components: container polymer, label substrate, adhesive, inks, coatings and closure. The intended end-of-life route should then be identified, including the collection, sorting and recycling technologies likely to process the package.

Candidate label systems can be screened for polymer compatibility, label coverage, optical detectability, separation during washing and residue formation. Where needed, laboratory trials should reflect relevant process conditions, including temperature, washing chemistry, residence time and mechanical agitation. Recovered material may then be assessed for visible contamination, colour, melt-flow behaviour or mechanical properties, according to the polymer and target application.

The acceptance criteria should be defined before testing and should reflect the requirements of the intended recycling stream. This framework is a practical synthesis of design-for-recycling principles; it is not a substitute for a recognised protocol or certification where one is required.

Discussion:

Sustainable labelling is a systems-engineering challenge. A label optimised only for print quality and shelf appearance may create downstream sorting or washing difficulties. Conversely, a label designed solely for easy removal may fail during distribution or use. Packaging developers must balance durability, information delivery, product safety, manufacturing requirements and end-of-life compatibility.

The available guidance also demonstrates why universal rules should be avoided. A label feature may be acceptable in one polymer stream and problematic in another. Local collection and processing infrastructure further influence whether a theoretically recyclable design can be recovered in practice. Collaboration among brand owners, label converters, adhesive formulators, polymer suppliers and recyclers is therefore important during package development.

Future work and industry trials would benefit from transparent reporting of label composition, process conditions, separation performance and the quality of recovered material. Such data can help distinguish

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environmental claims from demonstrated technical performance.

Conclusion:

Labels should be treated as functional components of the complete packaging system rather than as an afterthought. Their polymer substrate, adhesive, inks, coatings and geometry can influence sorting, washing and the quality of recovered plastic. Improving circularity requires material choices that fit a defined recovery pathway, validation under relevant conditions and clear communication of disposal requirements. The key question is not simply whether a label is marketed as sustainable, but whether the complete labelled package can be recovered effectively within the intended recycling system.

Acknowledgments:

No external funding or specific institutional support has been taken for this draft.

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Figure 1. Conceptual circular packaging lifecycle showing label and package design, product use, collection and optical sorting, washing and label separation, and conversion of recovered plastic into material for a new product. This is an illustrative schematic, not experimental data.

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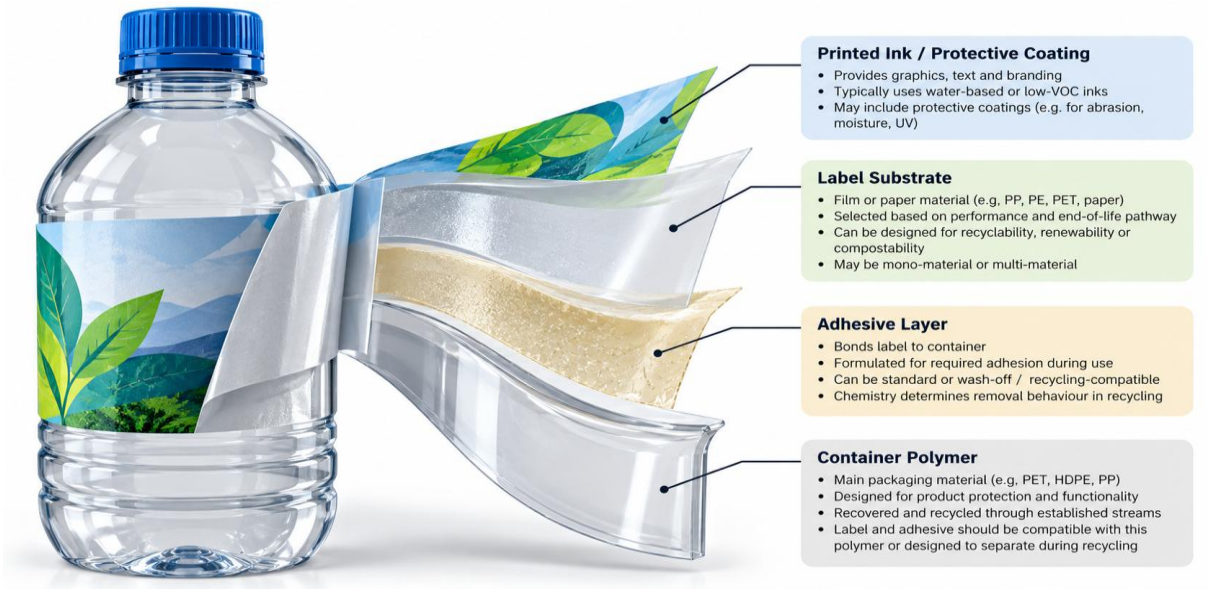

Figure 2. Schematic cross-section of a labelled plastic container showing the container polymer, adhesive interface, label substrate and printed ink or coating layers.

Figure 3. Illustrative laboratory setup for evaluating label separation in a controlled washing bath, with detached label pieces and recovered plastic flakes.