

Review

Beyond the Label: Rethinking the Industrial Recyclability of Paper-Based Packaging for Sustainable Circularity

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Abstract

Paper-based packaging is widely promoted as a sustainable alternative to plastic; however, functional coatings can reduce fibre integrity and lead to burden shifting in industrial recycling systems. This review examines how these effects undermine the environmental benefits expected from fibre-based packaging and weaken progress towards high-quality circularity, as required by current EU sustainability policy. By comparing leading assessment schemes (PTS, CEPI, 4evergreen) with industrial evidence, we identify a systemic gap: laboratory-focused recyclability tests often overlook fibre-quality degradation and the resulting limitations for circular material loops. To close this gap, we propose a sustainability-oriented extension module based on three measurable ISO-anchored indicators—fibre length, fines fraction and WRV—that prevent “recyclable-only-on-paper” claims and support genuinely sustainable recycling performance. Case studies demonstrate how high laboratory yields can mask low industrial recyclability and thus hinder circular economy objectives. This study contributes to sustainability science by operationalising recyclability in a manner consistent with EU circularity goals and by providing a transparent method to protect fibre value in multiple loop cycles.

Keywords: paper-based packaging; industrial recyclability; sustainable circularity; fibre integrity; recyclability assessment; barrier coatings; sustainable packaging design



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1. Introduction

Paper-based packaging is widely perceived as an environmentally preferable option due to its renewable origin and mature collection and recycling systems [1–4]. In parallel, packaging design is rapidly changing: polymer layers (e.g., PE/PP), water-based barrier coatings (WBBC), silicone systems and other functional additives are increasingly used to deliver performance in contact with moist, fatty or oxygen-sensitive products [5,6]. This evolution challenges recyclability assessment because a package may be rated as recyclable under a laboratory protocol while, in industrial practice, it generates disproportionate rejects, dispersed contamination and a recovered fibre fraction with low papermaking potential.

Such mismatches matter scientifically and economically [7,8]. They can encourage “recyclable-only-on-paper” outcomes in which apparent laboratory yield is improved by stronger disintegration, shifting burdens from coarse rejects to fines and process circuits, while undermining fibre integrity, process stability and the quality of material loops.

Ensuring that recyclability claims reflect industrial reality is increasingly important in the context of EU policy and standardisation drivers that link packaging claims with verified performance and high-quality recycling.

A key methodological tension is that many schemes prioritise repulpability and separability metrics that can be improved by increasing disintegration severity. Longer pulping time or higher shear may fragment coatings and reduce visible rejects, raising apparent fibre yield; however, the same actions can shorten fibres, increase the mass fraction of fines, and exacerbate hornification-related loss of swelling and bonding potential. Without explicit fibre-quality safeguards, a protocol-compliant “recyclable” result may mask the low papermaking value of the recovered fibre and increased contamination loads.

Aim and contribution: This study (i) critically analyses leading recyclability assessment methodologies used for fibre-based packaging in the context of EU regulatory and standardisation developments and (ii) proposes a compatible extension module that complements existing schemes with fibre-quality indicators. The module is implemented as a transparent decision tree using three measurable indicators anchored in ISO methods: length-weighted mean fibre length (ISO 16065-2) [9], mass fraction of fines below 200 µm (adapted from ISO 10376) [10], and water retention value (WRV; ISO 23714) [11].

The manuscript is structured as follows. Section 2 describes the materials and methods used to identify and analyse leading recyclability assessment methodologies (a PRISMA-inspired scoping review) and to derive the proposed extension module. Section 3 summarises the regulatory and standardisation context that increasingly connects recyclability claims with verified performance. Section 4 reviews leading assessment methodologies and their decision outputs. Section 5 identifies cross-cutting gaps relevant to coated and functionalised fibre packaging. Section 6 presents the proposed extension module and describes how it can be integrated into existing schemes. Section 7 provides illustrative case vignettes, and Section 8 concludes with implications for industry, standardisation and future research.

2. Materials and Methods

2.1. Literature Identification and Selection

A PRISMA-inspired scoping review was conducted to identify leading recyclability assessment methodologies for fibre-based packaging and to map how these schemes operationalise recyclability (e.g., repulpability, separability, yield-based scoring, and translation to labels). Searches were performed in Scopus and Web of Science, complemented by targeted searches of standardisation and industry sources (e.g., CEPI, 4evergreen, PTS, Aticelca, EcoPaperLoop, APCO/PREP and FBA). The search strings combined terms related to fibre-based packaging, recyclability testing, barrier coatings, and recycling performance. Records were screened by title/abstract and then by full text against inclusion criteria: (i) explicit description of a recyclability assessment protocol, scoring system or decision framework for paper-based packaging; (ii) relevance to coated or functionalised fibre packaging; and (iii) sufficient methodological detail to enable critical appraisal.

2.2. Analytical Approach and Derivation of the Extension Module

For each included methodology, the system boundary, test conditions, decision outputs and explicit treatment of fibre integrity were extracted and compared. Cross-cutting gaps were identified through thematic synthesis, with particular attention to failure modes that can produce false-positive outcomes for coated and functionalised papers (e.g., increased disintegration severity that raises yield while shortening fibres and increasing fines). The proposed extension module was derived by linking these gaps to measurable indicators of papermaking potential that are widely used in pulp and paper science: length-weighted

mean fibre length (ISO 16065-2), mass fraction of fines (ISO 10376, with a 200 µm cut-off adapted for the present purpose), and water retention value WRV (ISO 23714).

The analysed methodologies/protocols comprised:

- PTS-RH 021 (Category II)
- EcoPaperLoop framework
- Aticelca 501:2019 scoring system
- CEPI Recyclability Test Method (Version 3, 2025) and harmonised laboratory method (Part I)
- 4evergreen Fibre-based Packaging Recyclability Evaluation Protocol (2025)
- APCO/ARL and PREP decision portal
- FBA Voluntary Standard for Repulping and Recycling of Fibre-based Packaging

2.3. Industrial Evidence Base

Indicative threshold bands and the practical decision logic of the module were informed by pilot-scale recycling trials and full-scale mill observations obtained within an R&D project at one Polish recovered-paper mill, covering 12 recovered-paper grades (unpublished industrial observations obtained within an R&D project). These observations were used to define plausible cut-offs for flagging pulp streams with low papermaking potential; the manuscript explicitly treats these thresholds as illustrative and subject to broader multi-mill validation.

3. Regulatory and Standardisation Context

EU policy increasingly requires that recyclability claims reflect actual recycling performance rather than marketing narratives. The Packaging and Packaging Waste Regulation (PPWR) establishes harmonised requirements for packaging design, waste prevention and recyclability across the EU, replacing the earlier directive-based approach [12,13]. It operates alongside the Waste Framework Directive and the Circular Economy amendments, which emphasise the waste hierarchy, high-quality recycling and extended producer responsibility [14–16]. Recycling targets for packaging materials further strengthen the need for robust, comparable recyclability assessments [12–18].

For paper-based packaging that contains polymer layers or functional coatings, additional legal interfaces become relevant. The Single-Use Plastics Directive affects certain packaging formats and can influence how polymer-coated paper is treated in waste and labelling systems [17]. For food packaging, materials and articles intended for food contact must comply with EU food-contact legislation and good manufacturing practice requirements; when plastic layers are present, plastic-specific rules also apply [19–21]. Substance-related obligations and restrictions, including those potentially affecting hydrophobic and oleophobic treatments (e.g., PFAS), arise under REACH and related regulatory processes [17,22–27].

Standardisation complements legislation. Harmonised European standards historically supported the essential requirements of packaging law (EN 13427–EN 13432) [28–33], while sector guidance documents translate recyclability expectations into practical design and testing approaches [34,35]. In the fibre-based packaging sector, 4evergreen and CEPI provide influential protocols and guidelines that are increasingly used as reference points for what “recyclable” should mean in practice [36–38]. In this regulatory and standardisation landscape, a key challenge is ensuring that recyclability assessments do not reward strategies that merely shift environmental burdens from visible rejects to dispersed contamination and degraded fibre quality.

In the European Union, packaging policy is evolving from general recyclability aspirations towards enforceable requirements linked to measurability, harmonisation and verified performance. The Packaging and Packaging Waste Regulation (PPWR) establishes

a directly applicable framework for packaging placed on the EU market and progressively replaces the earlier directive-based regime. Although the detailed operational definitions of recyclability depend on implementing and delegated acts, as well as harmonised standards, the policy direction is clear: recyclability claims are expected to align with actual recycling performance and to support high-quality material loops.

This direction is reinforced by the Waste Framework Directive and its circular economy amendments, which promote waste prevention, high-quality recycling, and protection of the environment and human health. In this policy setting, a packaging design that yields large volumes of difficult-to-process contamination or produces a recovered fibre fraction with limited papermaking potential can undermine circularity objectives even if it appears compliant under a laboratory scheme. The issue is therefore not only technical but also regulatory and market-relevant: transparent criteria are needed to ensure that recyclability ratings do not obscure burden shifting or downcycling [14,15].

Composite and coated paper packaging also interfaces with other regulatory domains. The Single-Use Plastic (SUP) directive is relevant for paper-based articles that include polymer layers or coatings, because the presence of plastic can trigger specific requirements and influence classification and labelling. Food-contact packaging introduces additional constraints: barrier systems for meat, dairy and other high-fat or high-moisture products must comply with food-contact material frameworks and good manufacturing practice requirements, and polymer layers may fall under specific plastics regulations. These constraints can shape coating choices and may accelerate substitution towards new chemistries [19–21].

Chemical policy under REACH and restriction procedures for specific substance families, including historically used PFAS in hydrophobic or oleophobic treatments, further influence which coatings and additives are used. Such substitution can change how coatings interact with fibres during recycling and how contamination behaves in process water circuits. Consequently, recyclability assessment approaches must remain adaptive and must include parameters that capture functional impacts on fibre quality and processability, not only coarse separability.

Standardisation and industry guidance have been evolving in parallel. European standards frameworks historically linked harmonised standards to essential requirements for packaging, and industry-driven protocols such as 4evergreen provide structured recyclability evaluation for fibre-based packaging, explicitly including coated and barrier structures. CEPI guidance similarly promotes design-for-recycling considerations and harmonised test methods. These documents converge on the principle that recyclability should be evaluated under conditions representative of industrial recycling and should consider not only separation but also the quality and usability of the recovered fibre fraction [34–39].

In this context, the proposed extension module supports regulatory and standardisation goals by introducing a measurable fibre-quality gate compatible with existing methodologies. The module is designed to improve transparency for multiple stakeholders and to reduce the risk that recyclability ratings reward disintegration strategies that inflate yield at the expense of fibre integrity.

4. Overview of Leading Recyclability Assessment Methodologies

Multiple recyclability assessment schemes are currently used worldwide for fibre-based packaging, differing in scope, laboratory protocols and the way outcomes are translated into a recyclability claim (see Table 1).

PTS-RH 021 (Category II). A laboratory recyclability test focused on repulpability and separation behaviour under defined conditions.

Table 1. Summary of leading recyclability assessment methodologies and their sensitivity to fibre-quality degradation.

Common Blind Spot Addressed Here	Strengths (for Fibre-Based Packaging)	Typical Decision Output	Methodology/ Initiative
High yield can be achieved by stronger disintegration; fibre shortening/fines not explicitly gated	Established repulpability and separation protocol; widely recognised in Europe	Lab test; pass/fail or graded outcome depending on application	PTS-RH 021 (Cat. II)
Fibre integrity after the test is not consistently constrained by quantitative pulp-quality indicators	Improves comparability across laboratories; supports European alignment	Harmonised laboratory recyclability assessment	CEPI test methods (v3; harmonised Part I)
May benefit from an explicit, simple pulp-quality gate robust to over-disintegration effects	Strong relevance for coated/barrier papers; design-for-recycling focus	Graded recyclability evaluation for fibre-based packaging	4evergreen protocol (4EG)
Yield/separation-driven scoring may overlook degraded papermaking potential in the recovered fibre	Practical classification used by industry; clear communication	Score/class for cellulosic packaging	Aticelca 501:2019
Limited explicit thresholds that protect fibre length, fines generation and swelling loss	Circularity-oriented; connects design choices to recyclability logic	Framework linking guidance and testing	EcoPaperLoop
Simplification can obscure fibre-quality constraints; not designed to detect over-disintegration-driven false positives	Bridges technical assessment and consumer labelling	Label-oriented guidance derived from technical evaluation	APCO/ARL + PREP
Similar to other schemes: limited explicit quantitative gating of fibre length/fines/WRV	Operational relevance for fibre-based packaging	Repulping and recycling performance guidance	FBA voluntary standard

Strength: established lab protocol.

Limitation: does not explicitly protect against fibre-quality degradation caused by aggressive disintegration [40].

EcoPaperLoop. A framework that links design-for-recycling guidance with testing and decision criteria for fibre-based packaging.

Strength: circularity-oriented perspective.

Limitation: limited explicit thresholds tied to fibre integrity after pulping [41].

Aticelca 501:2019. A scoring system for cellulosic packaging based on repulpability and the behaviour of non-paper components.

Strength: practical classification used by industry.

Limitation: recyclability scoring can remain high even when fibre quality is impaired, because the system primarily addresses separation and rejects [42].

CEPI test methods and harmonised laboratory protocols. A suite of methods aiming at harmonisation of recyclability testing in Europe.

Strength: comparability and alignment across labs.

Limitation: the focus is typically on processability and separation, while post-process papermaking potential is not consistently safeguarded [43,44].

4evergreen recyclability evaluation protocol. A sector-wide protocol dedicated to fibre-based packaging, explicitly considering packaging components and design-for-recycling.

Strength: strong relevance for coated and barrier papers.

Limitation: implementation still depends on test boundaries and may benefit from additional pulp-quality indicators for over-disintegration cases [36–38].

APCO/ARL and PREP. A labelling programme and an evaluation portal translating technical recyclability into consumer-facing labels.

Strength: system-level linkage to labels.

Limitation: the translation step can obscure industrial quality constraints, and fibre-quality safeguards are not explicit in the label logic [45,46].

FBA Voluntary Standard for Repulping and Recycling. An industry standard focusing on repulpability and recycling outcomes for fibre-based packaging.

Strength: operational relevance.

Limitation: similar to other schemes, it may not capture papermaking-potential losses associated with fibre shortening, fines and hornification [47,48].

The methodologies used to assess the recyclability of fibre-based packaging vary in purpose and in how directly they are linked to regulatory claims, market labels or internal design decisions. Some approaches are primarily laboratory protocols designed to quantify repulpability and separation behaviour. Others are scoring systems that map observations to classes or grades. Consumer-facing programmes translate technical evaluations into labelling guidance. Despite these differences, a common pattern is reliance on repulpability and separability outcomes, with relatively limited explicit measurement of recovered fibre quality in terms directly relevant to papermaking.

For consistent discussion, leading approaches can be described by four attributes: (i) system boundary (which stages are covered, from collection and sorting through recycling); (ii) test severity and operating conditions (time, consistency, shear, screening configuration, and cleaning steps); (iii) decision output (binary pass/fail versus graded classes); and (iv) whether fibre integrity, fine formation, fibre swelling and bonding potential are explicitly measured and used as decision criteria.

PTS-RH 021 is a laboratory recyclability test focused on repulpability and separation behaviour under defined conditions. It can provide actionable information on disintegration behaviour and the removability of non-paper components. However, like many repulpability-centred approaches, the outcome can be sensitive to disintegration severity. If a coated structure is subjected to strong mechanical action, coarse rejects can be reduced by fragmentation, potentially improving apparent recyclability while simultaneously shortening fibres and increasing fines. Unless fibre-quality criteria are applied, such outcomes can remain undetected.

EcoPaperLoop provides a broader framework linking design guidance, testing and decision criteria for fibre-based packaging. Its strength lies in connecting laboratory evaluation with design recommendations and in supporting harmonisation across stakeholders. Nevertheless, the degree to which fibre integrity and fine formation are explicitly constrained depends on implementation. In the absence of standardised fibre-quality indicators, the framework can still be vulnerable to false-positive outcomes for structures that fragment coatings and fibres into fine fractions.

Aticelca 501:2019 is a scoring system for cellulosic packaging based on repulpability and the behaviour of non-paper components. It offers a structured output that is convenient

for design guidance and market communication. Similarly to other scoring systems, its robustness depends on how it penalises fine-scale contamination and whether it accounts for degradation of recovered fibre. If the score is primarily driven by yield and coarse separation, the system can assign favourable outcomes to structures that produce a high-yield but low-quality recovered fibre fraction.

CEPI has developed recyclability test methods and harmonised laboratory protocols aiming at comparability across laboratories. Harmonisation is a prerequisite for credible decision-making and provides an important platform for methodological improvements. However, comparability alone does not guarantee sensitivity to all failure modes. Without explicit fibre-quality metrics, harmonised methods may still allow favourable ratings when high yield is achieved through over-disintegration and when coating fragments pass into fines and process circuits.

The 4evergreen fibre-based packaging recyclability evaluation protocol is particularly relevant because it explicitly addresses coated and barrier structures and connects evaluation to industrial reality. It recognises several mechanisms by which coatings and additives can impair recycling, including the formation of stickies, deposition and impacts on water circuits, and it promotes design-for-recycling guidance. Even within such an advanced protocol, however, a practical and standardised quality gate for the recovered fibre fraction remains desirable, especially for capturing fibre shortening, fine formation and swelling loss in an interpretable manner.

Consumer-facing programmes such as APCO/ARL and the PREP evaluation portal translate technical assessments into label guidance. Their strength lies in bridging technical evaluation and consumer understanding, but this necessarily requires simplification. Robustness therefore depends on the underlying technical evaluation being resistant to manipulation through test severity and being transparent about its boundaries. Similarly, the Fibre Box Association (FBA) voluntary standard provides industry guidance for repulping and recycling outcomes and can support consistent practice, but its effectiveness for coated and functionalised papers depends on the indicators used to define acceptable outcomes.

Across these approaches, fibre shortening, fines mass fraction and hornification-related loss of bonding potential are often not measured directly or are treated indirectly. When fibre quality is considered, it may be inferred from qualitative sheet formation observations or broad processability indicators. This motivates the extension module proposed in Section 6, which introduces standardised and measurable indicators of fibre integrity and papermaking potential that can be applied as a quality gate alongside existing methodologies [49–56].

5. Cross-Cutting Gaps in Current Assessment Practice

Across the reviewed schemes, several recurring limitations become apparent for paper-based packaging with functional coatings and additives [57,58]:

1. Yield- and reject-focused metrics can incentivise over-disintegration. Increasing mechanical intensity can reduce coarse rejects and increase apparent fibre yield while simultaneously degrading fibre length distribution and raising fines content—effects that are not penalised in many scoring systems [49–51,56].
2. Limited sensitivity to fibre hornification and loss of bonding potential. Many protocols do not include direct indicators of fibre swelling/flexibility (e.g., WRV), despite their central role in papermaking strength [49,59,60].
3. Fragmentation of coatings shifts burdens from rejects to process circuits. Coatings fragmented to sub-millimetre or sub-200 μm sizes may escape screening and appear as “recycled content” in pulp yield while creating dispersed contamination, higher treatment loads in water circuits, and quality defects [54,55,61–64].

4. Insufficient alignment with a multi-stakeholder definition of recyclability. A packaging design can be rated as recyclable under a laboratory protocol yet impose disproportionate costs and environmental burdens on recyclers, contradicting circular-economy goals of the EU waste hierarchy and PPWR implementation [12].

The synthesis of leading methodologies and protocols reveals several cross-cutting gaps that are particularly relevant for coated and functionalised fibre packaging [22,62,64–67].

First, recyclability is frequently operationalised as a one-dimensional concept centred on fibre liberation and coarse separability. Pulp yield and reduction in coarse rejects can dominate decision-making, while recovered fibre quality is not explicitly constrained. As a result, a structure can be classified as recyclable even if the recovered fibre is severely degraded and offers limited papermaking potential, leading to downcycling or rejection in practice.

Second, many outcomes remain sensitive to disintegration severity. Increased pulping time and shear can reduce rejects and increase yield, which is favourable within yield-oriented criteria. Yet, such conditions shorten fibres and increase fines. In industrial recycling, excessive disintegration may be undesirable due to energy consumption and operational impacts, including poorer drainage, increased sludge formation, higher load on cleaning stages and reduced product quality. Therefore, an assessment result obtained under high severity can be poorly representative of industrial operation and can incentivise unrealistic processing pathways [50,51,54,55].

Third, fragmentation of coatings and additives can shift the contamination burden. When polymer layers, silicone coatings or barrier systems are fragmented into particles that bypass coarse screening, they may enter acceptors, circulate in process water, or become part of sludge and fine rejects. This can reduce visible rejects and improve apparent yield, but it can increase microplastic loads, deposition risks, and water-circuit contamination. From an environmental perspective, such burden shifting is critical because it moves the problem from a controlled reject stream to dispersed fines and process residues [54,55].

Fourth, multi-stakeholder consistency is often limited. Recyclers focus on process stability, contaminant management, and recovered fibre quality; packaging developers require actionable design rules; policymakers require transparency and enforceability; consumers require simple and credible labels. When methodologies omit key quality and contamination dimensions, interpretations of “recyclable” diverge by stakeholder, undermining trust and weakening market signals.

Fifth, the pace of innovation in coatings and additives outstrips the pace of scheme adaptation. Substitution driven by functional requirements and chemical restrictions can introduce new interactions between fibres, coatings and process circuits. In the absence of robust quality gates, schemes can label novel structures as recyclable based on repulpability alone, even when the recovered fibre fraction is of low papermaking value or when fines and water-circuit impacts increase [22,62,65–67].

These gaps suggest that recyclability assessment for functionalised fibre packaging should include a fibre-quality dimension that is robust to disintegration severity and that captures papermaking potential in a transparent and measurable way. The extension module proposed in Section 6 is designed to complement existing repulpability and separability criteria by detecting outcome patterns consistent with over-disintegration and by penalising recovered fibre streams that are unlikely to be usable in industrial papermaking.

6. Proposed Extension Module: Fibre Integrity and Papermaking Potential

Existing recyclability schemes can be strengthened through a lightweight extension module designed to detect over-disintegration strategies and fibre-quality degradation caused by functional additives, coatings and repeated recycling. The module is intended

as an add-on (“seal”) rather than a replacement: it can be applied after the standard repulping/screening stage of any scheme and interpreted using a transparent decision tree [49–53,59,60]. Figure 1 illustrates how the module overlays existing procedures.

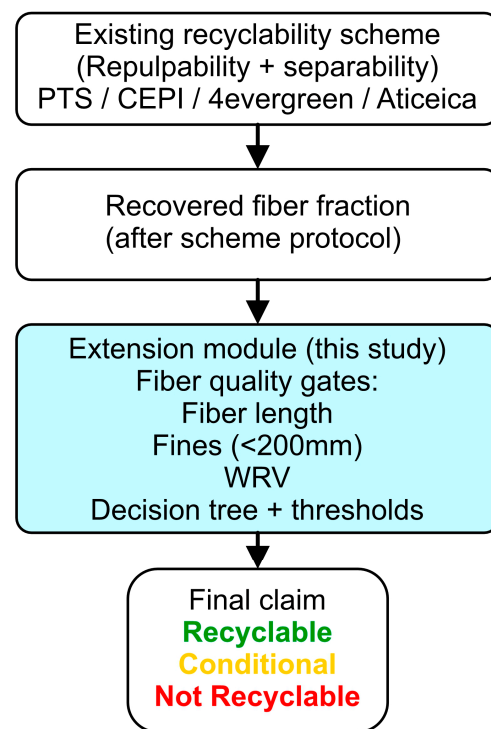


Figure 1. Conceptual integration of the proposed fibre-quality extension module as an overlay on existing recyclability assessment procedures.

The module relies on three indicators measured on the final prepared pulp (after stock preparation), selected because they directly reflect papermaking potential and are sensitive to fibre damage and hornification observed in pilot-scale recycling trials and in full-scale mill practice (12 recovered paper grades assessed in an R&D project; unpublished industrial observations).

Decision rule (overlay). Apply the three measurements to the prepared pulp obtained after the baseline protocol of the chosen scheme. If any indicator falls in the “not recyclable” range, classify the packaging as *not recyclable*. Otherwise, if one or more indicators fall in the “conditionally recyclable” range, classify it as *conditionally recyclable* (subject to additional constraints such as end-use grade, mixing ratio and recycler capability). Only if all three indicators are in the “recyclable” range are they classified as *recyclable* [49–53,59,60].

This overlay is designed to prevent false-positive outcomes in which high fibre yield is achieved through over-disintegration that creates dispersed contamination and a pulp with low papermaking potential.

The extension module is designed to be applied after the repulping, cleaning and screening steps defined by a given assessment scheme. Its purpose is to evaluate the recovered fibre fraction with a small set of standardised indicators that capture fibre integrity and papermaking potential and that discourage strategies that inflate apparent recyclability through over-disintegration.

Evidence base and scope. Threshold bands and decision logic are informed by pilot-scale recycling trials and full-scale mill observations obtained within an R&D project in a Polish recovered-paper mill. Twelve recovered-paper grades were evaluated, including representative coated and functionalised structures relevant to food and general packaging.

These observations are interpreted in light of established physical relationships linking fibre length distribution, fine content and fibre swelling to sheet strength and processability.

Indicator 1: length-weighted mean fibre length. Fibre length is determined by automated optical analysis according to ISO 16065-2. A length-weighted mean is used because longer fibres contribute disproportionately to bonding networks and strength-related properties. The length-weighted mean fibre length is evaluated on the final recovered fibre fraction after the full preparation sequence specified by the underlying scheme. Based on industrial observations, a reduction below approximately 600 micrometres is associated with a marked decline in strength potential. For the module, values above 600 micrometres indicate recyclable fibre quality, values between 600 and 400 micrometres indicate conditional recyclability, and values below 400 micrometres indicate nonrecyclability from a papermaking potential perspective [9,49–53,59,60].

Indicator 2: mass fraction of fines below 200 micrometres. The mass fraction of fines is determined gravimetrically using ISO 10376 as the base method, with an adapted screen size of 200 micrometres (rather than 76 micrometres) to capture the fraction most relevant to brittleness and processability in the intended application. The indicator reflects both fibre fragmentation and the generation of small particles originating from coatings or additives. It is evaluated on the final recovered fibre fraction. For the module, a fine fraction below 30% by mass supports recyclability, 30–50% indicates conditional recyclability, and values above 50% indicate nonrecyclability because the fibre stream is dominated by fines and microfragments that reduce sheet robustness and processing stability [10].

Indicator 3: water retention value (WRV). WRV is determined according to ISO 23714. WRV reflects fibre swelling and flexibility and is sensitive to hornification as well as to surface modification that reduces water uptake. Flexible, well-swollen fibres tend to form dense and strong paper structures, whereas stiff, hornified or hydrophobised fibres show reduced bonding and poorer sheet formation. In the module, WRV above 100% supports recyclability, WRV between 100% and 80% indicates conditional recyclability, and WRV below 80% indicates nonrecyclability from a bonding potential perspective [11].

Decision tree. The extension module is implemented as a decision tree applied after the underlying scheme provides its repulpability and separability result. The decision logic is intentionally transparent and conservative. **Step 1:** If any indicator falls in the “not recyclable” band (fibre length below 400 micrometres, fines above 50% by mass, or WRV below 80%), the structure fails the fibre-quality gate and the overall assessment should not communicate an unqualified recyclability claim. **Step 2:** If one or more indicators fall in the conditional bands, the structure is classified as conditionally recyclable and additional scrutiny is required. This may include repeating the evaluation under less severe disintegration conditions to test whether the favourable yield depends on over-disintegration, or applying additional mill-relevant indicators where available. **Step 3:** If all three indicators are in the recyclable bands, the structure passes the fibre-quality gate, and the overall recyclability outcome can be confirmed, subject to the underlying scheme’s separability criteria.

Threshold table. For clarity and reproducibility, the indicators and threshold bands are summarised in Table 2. The table is designed to be directly inserted into reports generated by existing schemes so that stakeholders can understand how the fibre-quality gate outcome was obtained.

Integration with existing schemes. The module is designed to be applied as an add-on rather than a replacement. Existing methodologies can be used unchanged to generate the recovered fibre fraction and to evaluate separability of non-paper components. The extension module is then applied to the recovered fibre fraction. If a scheme indicates recyclability but the fibre-quality gate fails, the overall conclusion becomes “not recyclable

under industrial reality” or “recyclable only under conditions that preserve fibre integrity”, depending on the language of the scheme. This addresses a key loophole: an assessment should not reward an approach that reduces rejects by converting them into fines while degrading fibre quality.

Table 2. Fibre-quality indicators and threshold bands used in the proposed extension module.

Indicator	Measurement Standard/Operationalisation	Threshold Values	Decision (Fibre-Quality Gate Output)
Length-weighted mean fibre length, L_w (μm)	ISO 16065-2:2014 (automated optical analysis; unpolarised light). Evaluate the recovered fibre fraction after the full laboratory recycling protocol (post-pulping/cleaning).	>600; 600–400; <400	Recyclable; Conditionally recyclable; Not recyclable
Mass fraction of fines <200 μm (wt.%)	ISO 10376:2011 adapted for a 200 μm cut-off (screen size adjusted from the standard 76 μm). Report mass fraction of particles/fines passing 200 μm after fibre preparation.	<30%; 30–50%; >50%	Recyclable; Conditionally recyclable; Not recyclable
Water retention value (WRV, %)	ISO 23714:2014. Determine WRV on recovered fibres after the full recycling protocol; interpret as bonding/hornification proxy.	>100%; 80–100%; <80%	Recyclable; Conditionally recyclable; Not recyclable

Note: The threshold values presented in Table 2 are indicative and are provided for illustrative purposes only. They were derived from pilot-scale recycling trials and full-scale mill observations obtained within an R&D project covering 12 recovered-paper grades evaluated at a single Polish paper mill. Therefore, these cut-off values should not be treated as universally applicable; they require broader validation across multiple mills, process configurations, and recovered-paper streams and should be further refined before any standardisation or regulatory use.

Practical implementation considerations. The indicators are measurable with standard laboratory equipment commonly available in pulp and paper laboratories. Laboratories should document disintegration intensity (time, consistency, shear conditions) and avoid additional mechanical actions not defined in the underlying scheme. Sampling should be performed after the scheme’s screening and cleaning stages on the final recovered fibre fraction. The module is compatible with different underlying schemes because it evaluates an output stream rather than prescribing a specific repulping recipe. Where laboratories lack one of the measurements, the module can be applied with two indicators as a preliminary gate, but full implementation is recommended for transparency [54,55].

Limitations and future development. The module focuses on fibre integrity and papermaking potential and does not fully quantify chemical contamination, deposition propensity or microplastic content in process circuits. It should therefore be considered complementary to indicators addressing stickies, deposits and water-circuit contamination. Future work should validate and refine threshold values across a broader range of mills, recovered-paper grades and coating chemistries and should explore additional indicators where standardised methods are available [39,50,51,54,55].

Strengths and limitations of the module. The proposed thresholds operationalise fibre integrity in a simple, scheme-agnostic manner and are based on ISO-anchored measurements that can be implemented in standard pulp and paper laboratories. However, the module does not yet quantify all relevant industrial impacts (e.g., deposit/stickies propensity, microplastic loads, or specific water-circuit effects) and its cut-offs are sensitive to mill configuration, recovered-paper mix and coating chemistry. Therefore, the module

should be used as a conservative quality gate and refined through multi-mill validation and round-robin testing before any harmonised or regulatory adoption.

7. Illustrative Case Vignettes

Case vignette 1: PE-coated hot-cup stock. A paper cup with a PE coating can achieve high formal recyclability when the test protocol employs intensive disintegration that breaks the coating into very small fragments, thereby increasing apparent fibre yield and reducing coarse rejects. However, the same operating mode can induce severe fibre shortening and generate a high mass fraction of fines, while fragmented polymer contributes to low apparent WRV and to dispersed microplastic-like contamination. Under the proposed module, such a pulp would be classified as not recyclable (or, at best, conditionally recyclable) because the papermaking potential is compromised despite a high formal yield [22,54,62,64].

Case vignette 2: Low-grammage WBBC food wrap. A low-grammage paper ($<40 \text{ g m}^{-2}$) coated with a water-based barrier coating may pass repulpability-based schemes with high fibre yield. In industrial practice, barrier components can become strongly associated with fibres, reducing WRV and promoting hornification, such that fibres no longer form strong inter-fibre bonds in re-made paper. This divergence explains why materials can be rated as recyclable under several schemes yet remain unattractive for recyclers due to quality loss and process risks [22,54,62,65–67].

The vignettes highlight a general methodological requirement: recyclability assessment should discourage “gaming” through increased test severity. When high yield is obtained by aggressive disintegration, the assessment should explicitly verify that the recovered fibre remains fit for papermaking and that fines and hornification-related effects remain within acceptable ranges [50,51,54,55].

Under the extension module, the same recovered fibre fraction is evaluated using length-weighted mean fibre length, fine mass fraction below 200 micrometres, and WRV. This additional layer converts the vignettes from anecdotal observations into an auditable decision logic: scenarios that rely on fibre over-fragmentation or that produce low-WRV fibres are flagged as conditionally recyclable or not recyclable, even if repulpability-based schemes would otherwise report a high formal yield.

8. Conclusions

This paper argues that the current notion of “recyclable” for paper-based packaging is often reduced to laboratory repulpability and fibre yield, while industrial recyclability depends on whether the resulting pulp retains sufficient papermaking potential and does not externalise contamination to rejects and process circuits. A structured review of leading assessment schemes and the EU regulatory/standardisation landscape shows a systemic gap: the absence of fibre-quality safeguards that prevent aggressive disintegration from masking poor recyclability of coated and functionally modified papers [39,49–53,57,59,60].

To close this gap without replacing existing schemes, an extension module was proposed based on three measurable indicators—length-weighted mean fibre length, fines fraction ($<200 \mu\text{m}$) and WRV—anchored in ISO methods. The resulting decision tree provides a transparent, stakeholder-readable “seal” against recyclable-only-on-paper packaging. Future work should validate and refine thresholds across additional mills, recovered paper grades and coating chemistries, and explore how the module can be integrated into 4evergreen, CEPI and national lab protocols supporting PPWR implementation [12,36–39,43,44,49–53,57,59,60].

From a sustainability perspective, the findings highlight that recyclability assessments must not only quantify fibre separation but also ensure that recovered fibres maintain

sufficient quality to remain within high-value circular material loops. Without this fibre-quality safeguard, packaging may meet laboratory recyclability criteria yet fail to deliver the environmental benefits expected under EU circular economy policy. The proposed module strengthens the alignment between recyclability testing and sustainability outcomes by preventing burden shifting to process water circuits, reducing downcycling, and supporting multi-loop fibre retention.

By integrating quantitative fibre-quality indicators with existing protocols, this work operationalises sustainability principles—resource efficiency, pollution prevention and preservation of material value—within recyclability assessment frameworks. This approach supports policymakers, recyclers and packaging developers in meeting emerging PPWR requirements and advancing genuinely sustainable packaging systems.

This paper has argued that recyclability assessment of paper-based packaging should not be reduced to repulpability and coarse separability, especially for modern functionalised structures containing polymer layers, barrier coatings or other functional additives. Under many current approaches, favourable ratings can be achieved by increasing disintegration severity to minimise rejects and increase fibre yield. Such pathways can create recovered fibre streams with severely shortened fibres, elevated fine content and reduced swelling and bonding potential, leading to low papermaking value, downcycling or operational burdens in industrial recycling [22,62,64–67].

To address this gap without discarding existing schemes, an extension module has been proposed as a fibre-quality gate. The module is based on three standardised indicators: length-weighted mean fibre length (ISO 16065-2), mass fraction of fines below 200 micrometres (adapted from ISO 10376), and WRV (ISO 23714). Explicit threshold bands are provided and implemented as a decision tree that classifies recovered fibre quality as recyclable, conditionally recyclable or not recyclable from an industrial papermaking perspective. The evidence base includes pilot-scale recycling trials and full-scale mill observations from an industrial R&D project covering twelve recovered paper mills.

The proposed approach is designed to be compatible with existing methodologies. Repulpability and separability criteria remain in place, while the fibre-quality gate prevents favourable outcomes driven by over-disintegration and helps identify cases where coatings and additives degrade fibre integrity or shift contamination into fines and process circuits. This supports recyclers by aligning assessment results with process stability and recovered fibre usability, supports packaging developers by providing clearer design signals, and supports policymakers and standardisation bodies by adding transparency to recyclability communication.

Further work is recommended to validate and refine threshold bands across a wider range of mills, recovered-paper grades and coating chemistries and to complement fibre-quality gates with indicators for water-circuit impacts, deposition propensity and microplastic loads. Nevertheless, even in its conservative form, the extension module can immediately reduce false-positive recyclability classifications and contribute to more credible and environmentally meaningful recyclability claims for fibre-based packaging.

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