

AI-AUGMENTED INSIGHTS FOR RE-X

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ABSTRACT

Designing for reuse, remanufacturing, recovery, and recycling (Re-X) increasingly hinges on early decisions that must withstand evolving policy, limited evidence, and cross-functional scrutiny. This paper proposes a capability-based, AI-augmented method that pairs retrieval-augmented generation (RAG) for citation-first evidence grounding with multi-criteria decision-making (MCDM)-ready outputs and lightweight governance artifacts to improve traceability and reproducibility.

We instantiate the method on an illustrative packaging case: evaluating barrier-film and coating alternatives for fiber-based cartons under the EU Packaging and Packaging Waste Regulation (PPWR). Task 1 translates PPWR clauses into measurable design gates (for example, PFAS thresholds, recyclability grades, plastic mass fraction, harmonized recyclability testing). Task 2 builds a normalized, citation-first evidence matrix across candidate materials to populate option reports and MCDM inputs. The combined workflow narrows the design space and identifies near-term actions without prescribing a single solution.

Directional findings indicate that chitosan/polysaccharide and Cellulose nanofibers (CNF)/lignin dispersions align with current gates and merit pilot trials; microfibrillated cellulose (MFC) bilayers and mineral-enhanced dispersions are promising for higher barrier loads with process tuning; starch/biowax dispersions suit moderate moisture demands; conventional Polyethylene/Polypropylene (PE/PP), Polylactic acid (PLA) extrusion, and Aluminium Oxide (AlOx) thin films are deprioritized for fiber formats due to paper-stream recyclability failures. The method's contribution is the coupling of citation-first retrieval with decision-ready structures and auditable artifacts, enabling faster iteration and defensible early-stage choices under regulatory uncertainty.

INTRODUCTION AND MOTIVATION

Designing for Re-X is central to the circular economy. The goal is simple yet ambitious: eliminate waste and pollution, keep products and materials circulating at their highest value, and regenerate natural systems. The Ellen MacArthur Foundation's framework has been instrumental in guiding industry and policy toward design and system choices that extend product life and maximize resource efficiency¹. Our central question is as follows: How can AI-augmented tools be turned into a reproducible research workflow that makes early Re-X decisions more defensible as circular-economy regulations evolve?

In Europe, two major legislative pillars have made circularity a design and market requirement:

1. Packaging and Packaging Waste Regulation (PPWR)²: setting recyclability performance grades by 2030 and requiring packaging to be "recycled at scale" by 2035.
2. Right to Repair Directive³: mandating repair obligations for manufacturers, creating an EU-wide repair platform, publishing indicative repair pricing, and extending warranties by one year when repair is chosen.

These measures complement Extended Producer Responsibility (EPR) schemes⁴, which adjust fees to incentivize designs that are easier to recycle and repair.

Take PPWR as an example: it introduces a unified approach that demands recyclable packaging and promotes circularity across the value chain. The ripple effects are significant:

- Resin Producers will see rising demand for recycled resins, requiring process adjustments.
- Material and Device Manufacturers must adapt offerings to meet recyclability standards.

- Brands and Retailers will need to redesign packaging and source materials with higher recycled content, which may impact costs and supply strategies.

While these regulations aim to improve environmental outcomes and spark innovation, they also create uncertainty. Many companies struggle to decide which Re-X strategies to prioritize or where to begin. Innovation depends on generating and managing ideas, yet organizations often face limited bandwidth, entrenched mental models, financial constraints, and organizational inertia. This is where the responsible use of AI-augmented systems changes the game. It introduces a new model for creative problem-solving, one that blends human expertise with AI-driven insight within a “human-in-the-loop” framework to accelerate decision-making and innovation. This paper serves as a foundational guide for innovators taking their first steps with these powerful tools, with the understanding that deeper mastery requires continuous learning in areas like advanced prompt engineering and AI model evaluation.

To harness this potential responsibly, it is crucial to understand that valuable outputs are not the result of an AI model alone, but an equation: **high-quality context + a well-structured prompt + a capable/reliable AI model**, all delivered through an intuitive software interface. We advocate for research practices that prioritize this equation, specifically through retrieval-augmented generation (RAG), an approach that grounds the AI's responses in specific, verifiable data sources, and a “citation-first” mindset.

This human-in-the-loop, citation-first approach favors tools and methods such as: (i) Answer engines that always display their sources; (ii) Academic discovery tools with sentence-level citations, while recognizing that human oversight is still required to validate outputs and guard against potential AI hallucinations; (iii) Grounded project workspaces that empower teams to bring their own relevant context to the AI; and (iv) IP analytics tools that leverage AI to scan open datasets and summarize curated abstracts.

Applied effectively, this stack has the potential to shorten the time needed to identify technologies and partners, improve visibility into IP risks, and ensure policy readiness at critical design gates. This paper introduces a capability-based, tool-agnostic method that couples citation-first RAG with a policy-to-metric translation and a MCDM schema, packaged with lightweight governance artifacts that make early circular-design decisions transparent, auditable, and rapidly re-scorable under regulatory change.

CURRENT STATE OF THE TECHNOLOGY INDUSTRY USES

Recent reviews synthesize AI-enabled decision support for sustainable manufacturing and circular supply chains, highlighting gains in evidence synthesis, predictive analytics, and waste reduction, while noting gaps in methodological integration and evaluation⁵⁻⁷. Complementary circular-economy studies emphasize Multi-Criteria Decision-Making (MCDM) for balancing environmental, economic, and technical criteria in design and supplier selection⁸⁻¹⁰. Our method suggests pairing RAG-based evidence grounding¹¹⁻¹² with MCDM-ready outputs for reproducibility.

Note: Named tools herein are illustrative examples of capabilities; the method does not prescribe specific platforms.

Live Web Answer Engines for Horizon Scanning and Policy Checks

- **Traditional Approach:** Horizon scanning and policy tracking have traditionally involved manual searches across news sites, government portals, and industry journal, a time-consuming process prone to missing key updates.
- **How AI Helps:** Live web answer engines use RAG to retrieve and synthesize real-time information from multiple online sources, providing conversational answers backed by inline citations.
- **Limitations & Human Role:** While RAG significantly reduces the risk of hallucination, it does not eliminate it. The AI can misinterpret tangential information or fail to capture a source's full context. Therefore, human oversight is essential to verify every citation before integrating findings into strategic decisions.
- **Example Tools:** This category includes tools like **Perplexity AI**, and features within larger models such as **ChatGPT** and **Gemini**.

- **Example Use Case:** Design team tracks PPWR implementation notes and PFAS thresholds; verified citations are translated into measurable gates (e.g., grade C minimum by 2030; PFAS ppb limits from a certain date in the future) and carried into the evaluation criteria.
- **Example MCDM-ready outputs:** A short, dated list of important updates with links and a one-line summary of why each update matters. The numbers in the table are converted to a common 0–1 score so options can be fairly compared and ranked.

Academic Discovery and Evidence Synthesis

- **Traditional Approach:** Conducting systematic literature reviews has been a painstaking, manual effort, requiring researchers to sift through thousands of papers to extract relevant data.
- **How AI Helps:** AI-powered academic discovery tools can automate parts of the literature review process by extracting structured data from millions of papers, identifying key themes, and generating citation-backed summaries.
- **Limitations & Human Role:** These tools accelerate evidence gathering, but they are not a substitute for deep domain expertise. The user must still critically assess the quality of the source papers, the validity of the AI's data extraction, and the nuances of the research.
- **Example Tools: Elicit, Consensus**
- **Example Use Case:** An R&D team assesses a new recycling technology to build an evidence matrix, comparing the methods and findings from dozens of relevant studies to prioritize their research direction.
- **Example MCDM-ready outputs:** A simple table that compares each material option on common facts, like recyclability grade, test results, technology readiness (TRL), cost signals, and citations. The numbers in the table are converted to a common 0–1 score so options can be fairly compared and ranked.

Grounded Project Workspaces

- **Traditional Approach:** Synthesizing knowledge from internal documents, such as proprietary research and market analyses, typically involves manual summarization, making it difficult to connect insights across disparate sources.
- **How AI Helps:** Grounded project workspaces provide a controlled environment where an AI's reasoning is restricted to user-uploaded source documents. This allows teams to "chat" with their own data and receive citation-first answers grounded in their trusted materials.
- **Limitations & Human Role:** The quality of the output depends entirely on the quality of the uploaded sources. The human role is to curate the context for the AI and probe its responses to uncover deeper insights. Users should also remain mindful of data privacy and avoid uploading sensitive information unless their organization has a secure enterprise agreement with the tool provider.
- **Example Tool: Google NotebookLM**, and similar "project" or "workspace" features in other leading AI tools.
- **Example Use Case:** A policy team uploads internal reports and new draft legislation into a grounded workspace to rapidly synthesize a briefing note, ensuring all claims are directly traceable to the source documents.
- **Example MCDM-ready outputs:** A one-page profile for each option that shows pass/fail against design gates, expected line-integration needs, any cost or risk notes, and links back to the source documents. These profiles provide the actual inputs for the model (scores and constraints) and flag any unknowns that should be tested in pilots or treated with sensitivity analysis.

Patent and IP Analytics

- **Traditional Approach:** Intellectual property management, such as prior art searches, has long relied on manual, keyword-driven searches across dense patent database, a process that could take weeks.
- **How AI Helps:** Modern IP intelligence platforms use domain-specific AI models (including semantic search and transformer-based architectures) to map technology landscapes, track competitor activity, and uncover non-obvious connections between patents and non-patent literature.
- **Limitations & Human Role:** These platforms could accelerate IP analysis, but they do not replace legal counsel. The insights they provide should be used to inform strategic discussions and guide deeper investigation by IP professionals.
- **Example Tool: PatSnap** applies domain-specific AI to connect patents with non-patent literature, supporting R&D prioritization.
- **Example Use Case:** An innovation team uses these platforms to quickly identify "white space" opportunities in a crowded technology field and assess IP risks before committing significant R&D resources.
- **Example MCDM-ready outputs:** A short summary that tells whether an option appears free to use, may need a license, or is high risk, plus a few key patent references. Freedom-to-operate becomes a simple gate (pass/fail), and IP exposure becomes a risk score that can lower the overall ranking if needed.

Job to be Done	Tool Category	Example Tools	Primary Use Case	Key Considerations
Horizon Scanning & Policy Tracking	Live Web Answer Engines	Perplexity AI, ChatGPT, Gemini	Tracking real-time updates on regulations, news, and competitors with cited sources.	Verify all citations. AI can misinterpret or hallucinate despite RAG. Human oversight is critical.
Literature Reviews & Evidence Synthesis	Academic Discovery Tools	Elicit, Consensus	Automating literature reviews by extracting structured data and summarizing academic papers.	Requires domain expertise. Assess source quality, validate AI data extraction, and interpret research nuances.
Internal Knowledge Synthesis	Grounded Project Workspaces	Google NotebookLM	Interrogating proprietary documents (reports, data) in a controlled environment for grounded insights.	Curate high-quality sources. Probe AI responses and remain mindful of data privacy.
Patent & IP Analytics	IP Intelligence Platforms	PatSnap	Mapping technology landscapes, identifying opportunities, and assessing IP risks from patent/non-patent data.	Does not replace legal counsel. Insights inform strategy and require validation by IP professionals.

Table 1. Summary of AI-Enabled Insights Tooling Stack

TECHNOLOGY APPROACH - THE PLAYBOOK: TOOLS, PROMPTS, AND OUTPUTS

To operationalize reproducible prompting, we propose incorporating a Prompt Canvas¹³ into the AI Playbook as a standard artifact. The Canvas formalizes intent (objective and audience), constraints (privacy and IP), exemplar prompts and expected output formats, and acceptance criteria; thereby improving reproducibility and lowering variance introduced by ad hoc prompt engineering. Including the Canvas in the Playbook also supports training and

cross-team review, making prompt design an auditable part of research methodology. To illustrate this playbook, we will use the following prompts across two tasks:

Persona / Role: You are a research engineer at a mid-sized European packaging manufacturer, with expertise in fiber-based carton design, barrier films, EU PPWR, and sustainability-oriented decision engineering. You combine regulatory interpretation with data-driven design and supplier evaluation, ensuring outputs are suitable for engineering gates and executive decision-making.

Target Audience: The primary audience for the output consists of: (i) Packaging R&D and materials engineers; (ii) Sustainability and regulatory compliance teams, and (iii) Procurement and supplier-selection committees.

Assume a technically competent audience that values clarity, traceability, and comparability over legal prose.

Context: The organization is a mid-sized packaging manufacturer evaluating barrier-film and coating alternatives for fiber-based cartons in light of evolving EU PPWR requirements and broader circular-economy objectives. Decisions must balance regulatory compliance, recyclability performance, fiber retention, barrier functionality, cost, scalability, and intellectual-property risk.

The decision process spans multiple stages: (i) Regulatory horizon scanning to track PPWR developments and translate legal text into measurable, engineering-relevant design gates; (ii) Evidence synthesis combining academic literature, industry testing, and supplier disclosures to compare material options on common, auditable facts; (iii) Grounded internal analysis, where proprietary test reports, supplier data, and regulatory excerpts are fused in a controlled workspace to produce traceable, option-level dossiers; (iv) Patent and IP screening to assess freedom-to-operate (FTO), potential licensing needs, and white-space opportunities before committing to scale-up or supplier agreements.

AI-augmented tools are used to accelerate evidence retrieval, synthesis, and landscape mapping, but they do not replace expert judgment. All outputs must be citation-first, transparent, and reproducible, with clear separation between evidence, assumptions, and interpretation.

Tonality: Professional, neutral, and engineering-focused; Regulatory interpretations should be cautious and explicit about uncertainty; Avoid advocacy or speculative language; prioritize decision usability and reproducibility.

Task 1
Horizon scanning and policy-to-metric translation
Objective
Track PPWR developments and related guidance, then translate relevant clauses into clear, measurable design gates for fiber-based cartons and barrier films.
Tool(s)
Perplexity AI, ChatGPT, Gemini.
Example Prompt
<p>1. Persona / Role</p> <p>2. Target Audience</p> <p>3. Task / Intent: Track PPWR developments and closely related EU guidance relevant to fiber-based cartons and barrier films, and translate them into clear, measurable design gates that can be used in MCDM for material and supplier selection. The objective is to convert regulatory text into decision-ready inputs that balance: Environmental performance; Technical feasibility; Economic and supply-chain implications.</p> <p>4. Step-by-Step: Follow these steps precisely:</p> <ol style="list-style-type: none"> 1. Identify recent and authoritative PPWR-related updates (regulation text, delegated acts, implementation guidance, or official clarifications) that affect fiber-based cartons and barrier films.

2. Filter for clauses relevant to recyclability, material composition, barrier layers, substances of concern, and future compliance timelines.
3. For each relevant update: Record the date and source; Summarize the clause in plain engineering language; Explain in one sentence why it matters for carton or barrier-film design
4. Translate each clause into a measurable design gate (e.g., minimum recyclability grade, maximum barrier-layer mass fraction, substance thresholds, or time-bound compliance requirements).
5. Normalize each gate into a 0–1 score or pass/fail constraint suitable for MCDM comparison across design or supplier options.
6. Clearly flag any assumptions, uncertainties, or areas requiring human/legal verification.

5. Context

6. References: Base your work on: Official EU PPWR texts and amendments; EU Commission guidance, FAQs, or delegated acts; Recognized regulatory or industry guidance on packaging recyclability and substances; Established principles from MCDM and decision engineering; Avoid citing unofficial commentary unless clearly labeled as interpretive.

7. Output / Format: Provide the output as:

1. A short, dated table with the following columns: Date; Source / Link; PPWR clause or guidance topic; One-line “why this matters” summary; Translated design gate; MCDM-ready metric (0–1 score or pass/fail).
2. A brief explanatory note (3–5 bullets) describing: (i) How scores should be interpreted, (ii) How they feed into broader environmental, economic, and technical criteria.

Keep the output concise, structured, and suitable for direct inclusion in a decision model.

8. Tonality

Task 2
Evidence-First Literature Scan and Benchmarking
Objective
Build a citation-first evidence matrix comparing barrier-film and coating alternatives on recyclability behavior, fiber retention, performance, PFAS status, TRL, cost signals, and references.
Tool(s)
Consensus for synthesis; Elicit for data tables
Example Prompt
<p>1. Persona / Role</p> <p>2. Target Audience</p> <p>3. Task / Intent: Construct a citation-first evidence matrix that compares barrier-film and coating alternatives for fiber-based cartons across environmental, technical, and economic dimensions, and translate the evidence into MCDM-ready inputs. The intent is to ground all claims in verifiable sources, enable side-by-side comparison of material options, and produce normalized (0–1) scores that can be directly ranked or weighted in an MCDM model.</p> <p>4. Step-by-Step: Follow these steps rigorously:</p> <ol style="list-style-type: none"> 1. Identify relevant material options (e.g., polymer films, dispersion coatings, bio-based or mineral systems) used as barriers on fiber-based cartons. 2. For each material option, retrieve citation-backed evidence on: <ul style="list-style-type: none"> ○ Recyclability behavior in paper streams ○ Fiber retention or yield impact ○ Barrier performance (e.g., moisture, grease, oxygen—qualitative or quantitative)

- PFAS status (intentionally added, non-added, unknown)
 - Technology Readiness Level (TRL)
 - Cost signals (relative cost, maturity, supply constraints)
3. Extract only explicitly stated facts or test results from sources; avoid unsupported inference.
 4. Record each fact with an inline citation (academic, industry, or authoritative guidance).
 5. Translate qualitative or heterogeneous data into comparable indicators, noting assumptions.
 6. Normalize each indicator to a 0–1 scale (or pass/fail where appropriate) to support MCDM ranking.
 7. Flag gaps, conflicting evidence, or low-confidence data for human review or sensitivity analysis.

5. Context

6. References: Use and cite: (i) Peer-reviewed literature on paper recycling and barrier-coated board; (ii) Industry recyclability testing protocols and public position papers; (iii) Regulatory or NGO guidance on PFAS and paper-based packaging, and (iv) Technology assessments or credible pilot-scale reports. All entries in the matrix must be citation-first; rows without sources should be explicitly marked as “evidence gap.”

7. Output / Format: Provide the output as:

A. Evidence Matrix Table: A single table with rows for each material option and columns including (i) Material / Barrier Type; (ii) Recyclability Grade or Behavior; (iii) Fiber Retention / Yield Impact; (iv) Barrier Performance Summary; (v) PFAS Status; (vi) TRL; (vii) Cost Signal (qualitative or indexed); (viii) Key Citations

B. MCDM-Ready Scoring Table: A companion table that (i) Converts each criterion into a 0–1 normalized score; (ii) Clearly states scoring logic and thresholds; (iii) Identifies pass/fail gates versus weighted criteria

C. Notes: Brief bullet notes explaining (i) Scoring assumptions; (ii) Data limitations; (iii) Recommended sensitivity checks

8. Tonality

DISCUSSION

This section illustrates how PPWR requirements can be translated into early R&D decisions for fiber-based cartons using two capability-based tasks: horizon scanning and policy-to-metric translation (Task 1) and evidence-first literature benchmarking (Task 2). The goal is to show how citation-first regulatory gates, and a normalized evidence matrix combine to narrow the option set and define near-term actions without making unverified prescriptions.

How the workflow operates:

1. Task 1 expresses PPWR clauses as design gates with units and pass/fail thresholds. In the current phase these include PFAS limits for food-contact packs from August 12, 2026, a recyclability grade target of at least C by 2030 with a trajectory toward B/A by 2038, a plastic mass-fraction threshold to retain paper/cardboard classification, and harmonized recyclability testing^{2,14,15}.
2. Task 2 compiles a citation-first evidence matrix for barrier and coating candidates, capturing recyclability behavior and fiber yield, barrier sufficiency at use-relevant conditions where reported, PFAS status, indicative TRL, and cost signals.
3. The two outputs interlock in option reports that list gate status, key evidence, and open items to resolve in pilots. These dossiers are MCDM-ready and preserve a traceable audit trail.

Illustrative synthesis from Tasks 1–2

The following synthesis is directional and intended to demonstrate the method, not to mandate selection.

- Chitosan and other polysaccharide dispersions, along with CNF and lignin-based coatings, align with current gates and show strong recyclability and fiber retention. Evidence indicates adequate oxygen and grease barrier for several applications and pilot-to-industrial readiness. These look suitable for near-term pilots, with focus on confirming Water vapor transmission rate (WVTR) at-use humidity and line speed¹⁶⁻²¹.
- Microfibrillated cellulose (MFC) bilayer composites and mineral-enhanced dispersions provide multi-barrier uplift with minor process penalties. They warrant targeted pilots for higher-demand SKUs, with attention to recyclability testing and process tuning²²⁻²⁵.
- Starch and biowax dispersions are attractive where barrier loads are moderate and cost is critical; for moisture-sensitive SKUs, blends or mineral boosters may be explored²⁶⁻²⁹.
- Conventional PE/PP or PLA extrusion coatings and AIOx thin films fail the paper-stream recyclability gate for fiber formats despite strong barrier properties; they are not prioritized for PPWR-aligned fiber packs without major redesign³⁰⁻³¹.

Near-term actions (illustrative)

- **Confirm gates early.** Schedule targeted PFAS plus total-fluorine testing; run recyclability trials using the referenced protocol and record fiber yield, stickies, and residues.
- **Close performance gaps via time-boxed pilots.** For CNF/MFC systems, optimize coat weight, drying, and run speed; for starch/biowax systems, validate barrier at SKU humidity and temperature and evaluate mineral boosters.
- **Engage suppliers on documentation.** Request recyclability and PFAS attestations aligned to the gate definitions and archive all certificates and test reports.
- **Prepare the MCDM model.** Treat PFAS, plastic fraction, and heavy-metal limits as hard gates; weight recyclability highly in early phases; include sensitivity scenarios for delegated-act updates and for raw-material cost swings.

Lifecycle and MCDM implications: In early selection, scores are most sensitive to recyclability grade and PFAS status; as pilots progress, cost per unit and barrier sufficiency at application conditions drive the trade-offs. The workbook should preserve criteria, weights, normalization rules, and scenario runs so re-scoring is rapid and auditable as new evidence arrives.

Limitations: This illustration relies solely on Task 1 design gates and Task 2 literature-based matrices. Several candidates have limited industrial data; therefore, the posture per option is provisional. Quantitative validation should include accredited PFAS testing, mill-like recyclability trials, and barrier measurements under SKU-specific conditions.

CONCLUSIONS & RECOMMENDATIONS

This work demonstrates a practical way to turn diffuse regulatory text and heterogeneous technical literature into defensible early-stage decisions for circular design. Using PPWR as the anchor regulation, we show how a citation first RAG process can be formalized into design gates. In the packaging illustration, this approach (1) clarified hard constraints and near-term targets, (2) surfaced a shortlist of directionally viable options for pilot trials, and (3) specified time boxed experiments and documentation to reduce uncertainty and preserve an audit trail

The evidence to action posture emerging from Tasks 1–2 is as follows: chitosan/polysaccharide and CNF/lignin dispersions appear aligned to present gates and are suitable for pilots that confirm barrier performance at use conditions and mill like recyclability; MFC bilayers and mineral enhanced dispersions warrant targeted trials for higher barrier demands with process optimization; starch/biowax dispersions fit moisture moderate SKUs; PE/PP, PLA extrusion, and AIOx thin films are deprioritized for PPWR aligned fiber formats due to paper stream recyclability failure. These positions are illustrative and conditioned on further testing.

Methodologically, the key contribution is not tool choice, but the pairing of RAG grounded, citation first retrieval with MCDM ready structures and governance artifacts. This pairing improves traceability, accelerates scoring as evidence evolves, and makes sensitivity analysis routine rather than exceptional. Future work should broaden cases beyond fiber-based cartons, integrate cost and supply risk data streams in real time, and report cross site pilot results to benchmark robustness.

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The authors thank colleagues and reviewers RTI International who contributed ideas and examples used to refine the AI Playbook for Re-X. The authors also certify they are not sponsored by nor endorsing any of the tools or platform owners mentioned. This paper is intended for informational purposes only. AI tools evolve rapidly, and features such as privacy controls, data handling, and compliance mechanisms may change over time. It is the responsibility of each user or organization to stay up to date with these changes and ensure that tool usage aligns with internal policies and regulatory requirements.

REFERENCES

1. Ellen MacArthur Foundation (EMF), The Circular Economy—Definition & Model Explained.
2. EUR Lex, Regulation (EU) 2025/40 on Packaging and Packaging Waste (PPWR).
3. EUR Lex, Directive (EU) 2024/1799 on common rules promoting the repair of goods (Right to Repair), <https://eur-lex.europa.eu/eli/dir/2024/1799/oj/eng>, 2024.
4. OECD, Extended Producer Responsibility: Updated Guidance for Efficient Waste Management, [https://one.oecd.org/document/ENV/EPOC/WPRPW\(2015\)16/final/en/pdf](https://one.oecd.org/document/ENV/EPOC/WPRPW(2015)16/final/en/pdf), 2016.
5. Bitzenis, A.; Koutsoupias, N.; Nosios, M. 2025. Artificial intelligence and machine learning in production efficiency enhancement and sustainable development: a comprehensive bibliometric review. *Frontiers in Sustainability*, 5: 1508647.
6. Patalas-Maliszewska, J.; Szmolda, M.; Łosyk, H. 2024. Integrating Artificial Intelligence into the Supply Chain in Order to Enhance Sustainable Production — A Systematic Literature Review. *Sustainability*, 16(16): 7110.
7. Deveci, M.; Delen, D.; Ding, W. 2024. AI-based Decision Support Systems for Sustainable Business Management under Circular Economy. *Annals of Operations Research*, 342(1): 1–3.
8. Tighnavard Balasbaneh, A.; Aldrovandi, S.; Sher, W. 2025. A Systematic Review of Implementing Multi-Criteria Decision-Making (MCDM) Approaches for the Circular Economy and Cost Assessment. *Sustainability*, 17(11): 5007.
9. Gonçalves, P. V. S.; Campos, L. M. S. 2022. A systemic review for measuring circular economy with multi-criteria methods. *Environmental Science and Pollution Research*, 29: 31597–31611.
10. Tramarico, C.; Petrillo, A.; Andrade, H.; Salomon, V. 2025. Advancing Circular Supplier Selection: Multi-Criteria Perspectives on Risk and Sustainability. *Sustainability*, 17(15): 6814.
11. Gupta, S.; Ranjan, R.; Singh, S. N. 2024. A Comprehensive Survey of Retrieval-Augmented Generation (RAG): Evolution, Current Landscape and Future Directions. *arXiv:2410.12837*.
12. Brown, A.; Roman, M.; Devereux, B. 2025. A Systematic Literature Review of Retrieval-Augmented Generation: Techniques, Metrics, and Challenges. *Big Data and Cognitive Computing*, 9(12): 320.
13. Hewing, M., The Prompt Canvas, licensed under CC BY 4.0, <https://www.thepromptcanvas.com/#section2>, 2025.
14. 4evergreen Alliance, Recyclability Evaluation Protocol for Fiber-based Packaging, v2.0, 2025.
15. Confederation of European Paper Industries (CEPI), EN 643 European List of Standard Grades of Paper and Board for Recycling, 2014.
16. Chi, K., He, J., Lin, W., Bokhari, S., & Catchmark, J. (2023). Electrostatically Complexed Natural Polysaccharides as Aqueous Barrier Coatings for Sustainable and Recyclable Fiber-Based Packaging. *ACS Applied Materials & Interfaces*.
17. Vinitaskaia, N., Lindstad, A., Lev, R., Kvikant, M., Xu, C., Leminen, V., Li, K., Pettersen, M., & Grönman, K. (2024). Environmental Sustainability, Food Quality and Convertibility of Bio-Based Barrier Coatings for Fibre-Based Food Packaging: A Semisystematic Review. *Packaging Technology and Science*, 38.
18. Hu, L., Wang, L., Xu, W., Wang, X., Toivakka, M., Gustafsson, J., & Xu, C. (2025). In situ polymerization of lignin in cellulose nanofibrils aqueous dispersion for fully bio-based barrier coating in packaging. *Cellulose*, 32, 5389–5405.

19. Wang, W., Gu, F., Deng, Z., Zhu, Y., Zhu, J., Guo, T., Song, J., & Xiao, H. (2021). Multilayer surface construction for enhancing barrier properties of cellulose-based packaging. *Carbohydrate Polymers*, 255, 117431.
20. Kumar, V., Elfving, A., Koivula, H., Bousfield, D., & Toivakka, M. (2016). Roll-to-Roll Processed Cellulose Nanofiber Coatings. *Industrial & Engineering Chemistry Research*, 55, 3603–3613.
21. Kopacic, S., Walzl, A., Hirn, U., Zankel, A., Kniely, R., Leitner, E., & Bauer, W. (2018). Application of Industrially Produced Chitosan in the Surface Treatment of Fibre-Based Material: Effect of Drying Method and Number of Coating Layers on Mechanical and Barrier Properties. *Polymers*, 10.
22. Upadhyay, A., Lucia, L., & Pal, L. (2025). Functional barrier and recyclable packaging materials through microfibrillated cellulose bilayer composite coatings. *Carbohydrate Polymers*, 359, 123592.
23. Hult, E., Iotti, M., & Lenés, M. (2010). Efficient approach to high barrier packaging using microfibrillar cellulose and shellac. *Cellulose*, 17, 575–586.
24. Mascarenhas, A., Scatolino, M., Dias, M., Martins, M., Melo, R., Mendonça, M., & Tonoli, G. (2022). Association of cellulose micro/nanofibrils and silicates for cardboard coating: Technological aspects for packaging. *Industrial Crops and Products*.
25. Tayeb, A., & Tajvidi, M. (2018). Sustainable Barrier System via Self-Assembly of Colloidal Montmorillonite and Cross-linking Resins on Nanocellulose Interfaces. *ACS Applied Materials & Interfaces*, 11(1), 1604–1615.
26. Chi, K., Wang, H., & Catchmark, J. (2020). Sustainable starch-based barrier coatings for packaging applications. *Food Hydrocolloids*, 103, 105696.
27. Koivula, H., Jalkanen, L., Saukkonen, E., Ovaska, S., Lahti, J., Christophliemk, H., & Mikkonen, K. (2016). Machine-coated starch-based dispersion coatings prevent mineral oil migration from paperboard. *Progress in Organic Coatings*, 99, 173–181.
28. Li, S., Svedström, K., & Lepo, A. (2024). Biowaxes Used as a Barrier Formulation Material in Coating Fibre-Based Substrates. *Packaging Technology and Science*, 37.
29. Li, S., Lepo, A., & Svedström, K. (2025). Towards optimized barrier performance using biowaxes and inorganic pigments in coating formulations on fiber-based substrates. *Journal of Coatings Technology and Research*.
30. Hirvikorpi, T., Vähä-Nissi, M., Harlin, A., & Karppinen, M. (2010). Comparison of some coating techniques to fabricate barrier layers on packaging materials. *Thin Solid Films*, 518, 5463–5466.
31. Lindstad, A., Hansen, A., Li, K., & Pettersen, M. (2025). Material Properties of Paperboard With Biodegradable and Nonbiodegradable Coatings Affected by Storage Conditions and Contact With Selected Food Products. *Packaging Technology and Science*, 38.

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