

Research Article

SUSTAINABLE BIO-BASED COATINGS FOR PAPER: ADVANCES, CHALLENGES, AND FUTURE PROSPECTS IN PULP INDUSTRY

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Abstract

Conventional coated papers that rely on petroleum-based polymers create major recycling and biodegradation problems in the pulp industry. They contribute to microplastic pollution and carry a high carbon footprint. This review examines bio-based alternatives such as starch, PLA, chitosan, and nanocellulose coatings, drawing on 85 peer-reviewed studies published between 2018 and 2025. We compare barrier properties, mechanical strength, and life cycle impacts. Nano-hybrid coatings achieve WVTR values as low as 5–15 g/m²/day, close to polyethylene at 10, while life cycle assessments show 40–60% reductions in CO₂ emissions. Despite these gains, scalability remains a challenge, especially in humid climates like India. Rod-coating and spray methods appear promising for small mills, and mineral additives can reduce costs by 25–35%. Commercial products from companies such as Stora Enso and Huhtamaki demonstrate technical viability, but economic barriers (20–50% price premium) and regulatory gaps slow adoption. Key research needs include performance data for tropical conditions and hybrid nano-formulations. We propose policy incentives and pilot-scale trials to bridge these gaps and advance circular paper production.

Keywords: Biopolymer coatings, Nanocellulose barriers, Sustainable paper, Barrier properties, Pulp decarbonization, LCA recyclability, Circular packaging.

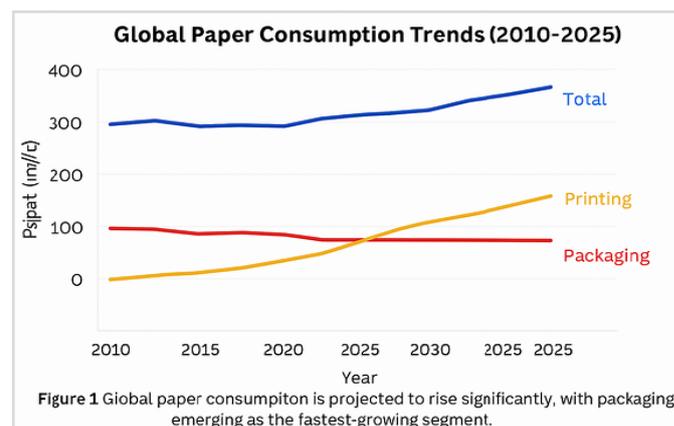
INTRODUCTION

Overview of paper usage and environmental impact

Paper remains a vital material worldwide, with global consumption exceeding 400 million metric tons annually and continuing to rise due to industrialization, e-commerce, and urbanization, especially in Asia and other emerging markets [1–3]. The main demand comes from publishing, packaging, hygiene, and labeling. Packaging now leads the sector, driven by direct-to-consumer shipping, food delivery, and regulations that favor paper over plastics. Although paper is renewable and recyclable, the industry still carries one of the largest environmental footprints among manufacturing [4–6]. Key concerns include:

- **Deforestation and habitat loss:** Large-scale harvesting of wood for virgin pulp threatens forests, biodiversity, and water cycles. Certification schemes and recycled fiber use help, but only partly meet demand.
- **Energy use and carbon emissions:** Paper production is energy-intensive, contributing significantly to greenhouse gas emissions.
- **Water consumption and pollution:** Huge volumes of water are required for pulping, bleaching, and cooling. Wastewater often contains solids, chlorinated compounds, and heavy metals, which can harm ecosystems if untreated.
- **Solid waste generation:** Sludge, bark, and ash are common residues. Landfilling and incineration create land use issues and toxic emissions.
- **Recyclability challenges:** While recycling rates exceed 60% in some regions, coated and laminated papers complicate fiber recovery and reduce recycled product quality.

The industry is also criticized for bleaching agents and chemical additives linked to toxicity and persistent pollutants. Modern initiatives such as life cycle assessment (LCA), renewable energy use, closed-loop water systems, and sustainable forestry certifications (FSC, PEFC) are helping. Yet synthetic coatings continue to undermine progress by creating recycling and waste management problems.



As shown in Figure 1, global paper consumption has steadily increased from 2010 to 2025, with packaging paper emerging as the fastest-growing segment. While printing paper shows a slight decline due to digitalization, packaging demand continues to rise sharply, driven by e-commerce, food delivery, and regulatory shifts away from plastics. This trend underscores the urgency of developing sustainable coated papers that meet packaging performance requirements without compromising recyclability or biodegradability.

Limitations of conventional coated papers

Conventional coated papers combine cellulose fiber bases with petroleum-derived polymers or mineral pigments. They are

valued for printability, gloss, and barrier properties but face serious drawbacks:

- **Non-biodegradability:** Synthetic coatings persist in landfills for decades, often breaking down into microplastics [8].
- **Recycling barriers:** Plastic layers reduce fiber recovery, clog equipment, and lower pulp quality.
- **Disposal issues:** Poor compatibility with recycling often pushes waste toward incineration or landfill, both with environmental risks.
- **Resource intensity:** Producing synthetic coatings consumes fossil resources and energy, raising carbon footprints.
- **Chemical hazards:** Additives such as resins and plasticizers can release emissions harmful to workers and the environment.
- **Food safety concerns:** Residues may migrate into food or pharmaceuticals, raising regulatory issues [12,13].
- **Mechanical stress problems:** Coatings can reduce flexibility, leading to cracking or delamination.
- **Regulatory pressure:** Global legislation against single-use plastics challenges manufacturers still dependent on synthetic coatings.

These limitations highlight the urgent need for sustainable innovation in coated paper.

Relevance and Scope of Eco-Friendly Alternatives

Eco-friendly alternatives are gaining importance due to environmental concerns and market demand. Key drivers include:

- **Regulations:** Policies such as the EU Single-Use Plastics Directive and national bans accelerate the shift to recyclable and compostable coatings [12,13].
- **Consumer preferences:** Growing awareness makes sustainable packaging a competitive advantage.
- **Circular economy goals:** Biodegradable and recyclable coatings improve fiber recovery and support closed-loop systems.

Alternatives include:

- **Bio-based polymers:** Starch, cellulose derivatives, chitosan, proteins, PLA [20–22].
- **Mineral fillers:** Calcium carbonate, kaolin clay with biopolymer binders.
- **Natural waxes and oils:** Plant-based hydrophobic coatings for water and grease resistance.
- **Functional blends:** Hybrid systems with nanotechnology or antimicrobial additives.

Applications span food packaging, publishing, labeling, and specialty papers. Barriers remain in cost, scalability, process adaptation, and performance under varied conditions.

Objectives of the Review

This review aims to:

- Survey bio-based and biodegradable coating materials, their sources, and properties.

- Evaluate coating technologies and application methods for scalability and environmental impact.
- Compare performance of eco-friendly coated papers with conventional ones.
- Assess environmental implications through LCA, recyclability, and carbon footprint.
- Identify technical, economic, and regulatory challenges and propose solutions.
- Highlight emerging trends and future research directions.

Unlike earlier reviews, this study integrates recent commercial data (2018–2025), end-of-life and LCA analysis, and regulatory trends. It also emphasizes performance in humid tropical climates, especially India and Southeast Asia, where moisture sensitivity remains underexplored.

Review Methodology

We searched Scopus, Web of Science, and Google Scholar for papers published between 2018 and 2025 using keywords such as “bio-based paper coatings,” “sustainable coated paper,” “nanocellulose barriers,” “PLA paper coating,” and “paper coating recyclability.” Out of 450 records, 180 were reviewed in full, and 85 peer-reviewed studies with clear performance data, LCA results, or commercial examples were selected. Industry reports were used to fill market gaps. While no formal PRISMA protocol was applied, recent and quantitative sources were prioritized.

CONVENTIONAL COATED PAPERS

Structure and Types

Conventional coated papers are made from a cellulose fiber substrate, usually Kraft or mechanical pulp, with one or more coating layers applied on top. These coatings change the surface properties, giving better printability, gloss, and barrier performance compared to uncoated paper.

- **Base paper:** Provides strength and flexibility.
- **Coating layers:** Contain pigments such as kaolin clay, calcium carbonate, or titanium dioxide, combined with binders like styrene-butadiene latex, acrylics, or polyvinyl alcohol. Additives such as dispersants, lubricants, and optical brighteners adjust gloss, opacity, and smoothness.
- **Optional barrier layers:** Sometimes added for water, grease, or oxygen resistance, often using synthetic polymers or waxes.

Types of coated papers include:

- **Machine-coated vs. cast-coated:** Machine-coated papers are dried inline and give moderate gloss. Cast-coated papers use a casting cylinder to produce very high gloss finishes.
- **Single-coated vs. double-coated:** Single-coated papers are treated on one side, while double-coated papers have coatings on both sides for balanced properties.
- **Woodfree vs. wood-containing:** Woodfree papers are brighter and more stable, while wood-containing papers are cheaper and used for mass printing.
- **Gloss, matt, silk, satin finishes:** Gloss papers are shiny and reflective, matt and silk papers reduce glare, and satin offers a balance.

- **Functional/barrier papers:** Designed for food, medical, or liquid packaging, with coatings that resist water, grease, or oxygen.

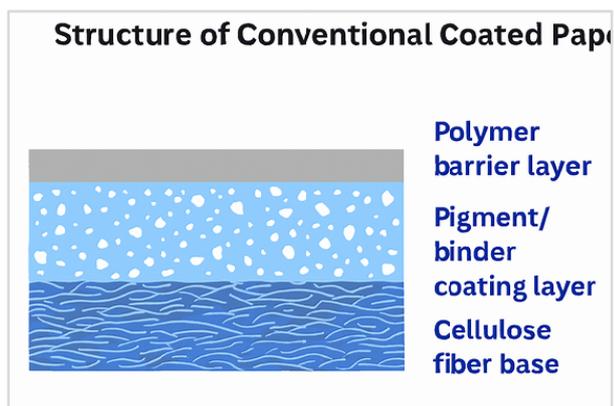


Figure 2. Schematic structure of conventional coated paper showing three distinct layers: the cellulose fiber base, the pigment/binder coating layer, and the optional polymer barrier layer

As illustrated in Figure 2, conventional coated papers consist of a cellulose fiber base that provides mechanical strength and flexibility. This is followed by a pigment/binder coating layer typically composed of kaolin clay, calcium carbonate, and latex or acrylics which enhances gloss, printability, and surface smoothness. In barrier applications, an additional polymer layer such as polyethylene (PE) or polyvinylidene chloride (PVDC) is applied to resist moisture, grease, and oxygen. While these synthetic layers improve functionality, they significantly hinder recyclability and biodegradability, underscoring the need for eco-friendly alternatives.

Applications

Coated papers are used in many sectors because of their smooth surface and barrier qualities.

- **Publishing and printing:** Magazines, catalogues, art books, brochures, and reports rely on coated papers for vivid images and clear graphics.
- **Commercial packaging:** Food containers, folding cartons, and shopping bags use coated boards for strength and moisture resistance.
- **Labels and wrappers:** Pressure-sensitive labels and release liners benefit from smooth surfaces and controlled adhesion.
- **Specialty and industrial uses:** Photographic paper, inkjet paper, and thermal papers depend on coatings for ink absorption and durability.
- **Art and creative media:** Fine art prints, posters, stationery, and greeting cards use coated boards for sharp designs and tactile finishes.
- **Security and technical applications:** Certificates, hologram papers, and backing sheets for adhesives use coatings for anti-counterfeiting and release properties.
- **Digital printing:** Specially formulated coatings improve toner and ink adhesion in laser and inkjet printers.

Environmental Concerns

Despite their wide use, conventional coated papers create serious environmental challenges.

- **Non-biodegradability:** Synthetic coatings such as PE, PP, and PVDC do not break down easily [10,16]. They persist in landfills and fragment into microplastics.
- **Recycling problems:** Coatings block fiber recovery, contaminate pulp, and cause equipment fouling. Yield drops and recycled products are downgraded.
- **Pollution from production and disposal:** Polymer synthesis and coating processes consume fossil fuels and energy. Mills generate effluents with microplastics and persistent pollutants [11]. Incineration can release hazardous substances if not controlled [5].
- **Toxicity and health risks:** Additives like plasticizers and surfactants may migrate into food or leach from landfills. Workers face exposure to particulates and VOCs.
- **Global plastic pollution:** Coated papers contribute to microplastics in municipal waste and aquatic environments.

ECO-FRIENDLY ALTERNATIVES: DEFINITIONS AND CRITERIA

The move toward eco-friendly coated papers comes from the need to reduce environmental impact and meet new regulations and consumer expectations. These papers are designed to perform well while avoiding the problems linked to synthetic coatings.

Definitions of Eco-Friendly Coated Papers

Eco-friendly coated papers use surface treatments or barrier layers that minimize harm across their life cycle. They stand apart from conventional coated papers because they:

- Rely on renewable or recycled raw materials, such as crops, agricultural by-products, or recycled fibers.
- Break down naturally through biodegradation or composting without leaving microplastics or toxic residues.
- Fit into standard recycling systems, allowing efficient fiber recovery.
- Avoid hazardous substances like chlorinated compounds or heavy metals.
- Provide safe use in food contact and other sensitive applications.

Key Criteria for Eco-Friendly Alternatives

To qualify as eco-friendly, coated papers should meet most of these points:

- **Feedstock origin:** Use certified sustainable forestry (FSC, PEFC), agricultural residues, or recycled content.
- **Coating composition:** Favor natural polymers such as starch, cellulose derivatives, chitosan, PLA, proteins, plant waxes, or mineral fillers [20–22].
- **Degradability:** Show proven biodegradability in composting or natural environments, ideally within 180 days. Avoid microplastic generation. Carry clear certification labels (EN 13432, ASTM D6400, OK Compost) [14].
- **Recyclability:** Demonstrate compatibility with fiber recovery and recycling protocols (CEPI, PTS, INGEDE).
- **Safety:** Exclude substances of very high concern (SVHC) and comply with food-contact regulations (FDA, EU 10/2011, BfR).
- **Performance:** Deliver barrier properties, gloss, and mechanical strength without relying on persistent or harmful chemicals.

Table 1. globally recognized certification systems

Certification/Label	Focus Area	Example Criteria
FSC, PEFC	Fiber sourcing, sustainability	Chain of custody, responsibly managed forests
Blue Angel, Nordic Swan	Environmental labeling for paper and packaging	Energy use, recyclability, absence of toxic substances
OK Compost, EN 13432, ASTM D6400	Compostability	Complete disintegration and biodegradation, eco-toxicity
CEPI/PTS/INGEDE Certification	Recyclability	Lab-based repulping compatibility, sorting, deinking

Certification and Eco-Label Standards

Certification systems help verify eco-friendly claims and give transparency to manufacturers and consumers. Table 1 summarizes major schemes. These certifications show that while many bio-based coatings pass compostability tests, petroleum-based laminates often fail.

Industry and Regulatory Trends

Eco-friendly coated papers show strong promise, but several barriers still limit their wider adoption.

- **Cost competitiveness:** Bio-based coatings often carry a 20–50% price premium compared to petroleum-based options. This slows uptake, especially in cost-sensitive markets.
- **Scalability:** Many materials perform well in laboratory trials but face difficulties in large-scale production. Maintaining consistent barrier properties and mechanical strength at industrial speed remains a challenge.
- **Process adaptation:** Existing mills are designed for synthetic coatings. Shifting to bio-based systems requires new equipment, training, and process adjustments.
- **Performance in humid climates:** Moisture sensitivity is a major issue in tropical regions. Papers may lose barrier strength or deform during storage, and more data is needed to address this gap.
- **Standardization and certification:** Compostability and recyclability claims vary across regions. Clear, harmonized standards are needed to build trust among manufacturers and consumers.
- **Regulatory support:** Policies that encourage green coatings, such as tax incentives or subsidies, can accelerate adoption. Without them, many companies hesitate to invest.

At the same time, opportunities are growing:

- **Consumer demand:** Awareness of sustainability continues to rise, creating strong market pull.
- **Innovation in hybrid systems:** Combining biopolymers with minerals or nanomaterials can balance cost and performance.
- **Pilot projects:** Small-scale trials in packaging and publishing sectors show that eco-friendly coatings can meet real-world requirements.
- **Circular economy alignment:** These alternatives directly support recycling and composting goals, making them attractive for long-term policy frameworks.

In short, eco-friendly coated papers are technically viable but need stronger economic and regulatory support to move from niche to mainstream.

BIO-BASED AND BIODEGRADABLE COATING MATERIALS

Biopolymers

Biopolymers are naturally derived or bio-synthesized polymers that have become important alternatives for paper coatings. They are renewable, biodegradable, and can be modified to provide water, grease, and gas barriers.

Classification and Sources

- **Polysaccharides:** Starch (native and modified), cellulose derivatives (carboxymethyl cellulose, hydroxyethyl cellulose), chitosan, pectin, alginate, pullulan [20–23]. These come from plants such as corn, potatoes, seaweed, or from crustacean shells.
- **Proteins:** Soy protein, zein, casein, gelatin, and whey protein isolate, often sourced from agriculture or food industry by-products.
- **Poly(lactic Acid) (PLA):** A compostable polyester made by fermenting plant sugars such as corn or sugarcane [17].

Key Properties

- Biopolymers form continuous films that block pores in paper, improving moisture, oxygen, and grease resistance.
- Most degrade under composting or soil conditions, leaving non-toxic residues [18,21].
- Polysaccharides and proteins bond well with cellulose fibers, giving good adhesion and mechanical strength. Crosslinking or blending helps balance water sensitivity and flexibility.

Examples and Performance

- **Starch:** Cheap and abundant, but needs modification (esterification, blending) to resist water.
- **Cellulose derivatives:** Excellent film-forming ability, but limited water resistance unless combined with hydrophobic agents.
- **Chitosan:** Strong oxygen barrier and antimicrobial, but costly and moisture-sensitive.
- **Proteins:** Zein and soy protein provide good grease and oxygen barriers, but can be brittle.
- **PLA:** Hydrophobic and processable with conventional coating methods, but full biodegradation usually requires industrial composting.

Future Directions Research focuses on chemical modifications, hybrid coatings with waxes or minerals, and nanotechnology (nanocellulose, nanochitosan) to improve barrier properties while keeping compostability.

Table 2 compares biopolymers, where PLA hits WVTR 15-30 but needs industrial composting.

Table 2. Common Biopolymers for Paper Coatings

Biopolymer	Source	Key Strengths	Main Limitations
Starch (native/mod.)	Corn, potato	Abundant, low-cost, easy to process	Hydrophilic, water sensitivity
Cellulose der.	Wood, cotton	Good adhesion, flexible films	Limited water barrier
Chitosan	Crustacean shells	Antimicrobial, good barrier	Cost, pH sensitivity
Zein, Soy protein	Corn, soybeans	Grease/oxygen barrier, edible	Brittleness, humidity effect
PLA	Fermented starch	Hydrophobic, processable	Needs industrial composting

Table 3. Common Inorganic/Mineral Additives in Eco-Coatings

Additive Type	Key Function	Environmental Impact	Coating Performance Benefit
Calcium carbonate	Opacity, brightness	Low	Print quality, recyclability
Kaolin clay	Smoothness, printability	Low	Gloss and ink absorption
Talc	Smoothness, print holdout	Low	Water resistance, softness
Nano-clays	Oxygen/water barriers	Moderate (at scale)	Enhanced protective properties
Nano-cellulose/ mineral	Barrier/mechanical hybrid	Low	Strength, reduced weight needed

Inorganic and Mineral-Based Green Additives

Mineral additives improve barrier, mechanical, and surface properties while reducing reliance on plastics. When paired with biodegradable binders, they enhance sustainability.

Key Types

- **Calcium carbonate:** Brightness, opacity, cost-effective, supports recyclability.
- **Kaolin clay:** Smoothness, printability, better ink absorption.
- **Talc and silicates:** Improve surface smoothness and water resistance.
- **Nano-clays:** Strong oxygen and water barriers when dispersed in starch or protein matrices.
- **Nano-cellulose/mineral hybrids:** Combine strength and barrier properties, reduce coating thickness, and remain recyclable.

Functions and Benefits

- Minerals reduce porosity, improving moisture and gas resistance.
- They enhance gloss, print quality, and color reproduction.
- They lower costs compared to pure biopolymers.
- When used responsibly, they minimize environmental impact and support recyclability.

As shown in Table 3, nano-clays boost barriers at 5-10% loading without recycling harm.

Considerations for Sustainability

To maximize sustainability, several factors should be addressed:

- **Sourcing:** Preference should be given to minerals with a minimal environmental extraction footprint and from deposits managed under responsible mining practices.
- **Binder Selection:** Green benefits are realized when these minerals are combined with natural binders (e.g., starch, CMC, chitosan) instead of traditional petroleum-based resins.
- **End-of-Life:** Inorganic additives should not hinder fiber recovery in recycling or compromise biodegradability/compostability when included at appropriate loading levels.

The development and application of mineral-based green additives when carefully managed represent a crucial strategy for achieving high-performance, eco-friendly coated papers that align with contemporary sustainability standards and market needs.

Natural Waxes and Oils

Natural waxes and plant oils are biodegradable alternatives to petroleum-based waxes. They improve water, grease, and oxygen resistance while remaining compostable.

Types and Sources

- **Waxes:** Carnauba (palm leaves), candelilla (shrub leaves), soy (hydrogenated soybean oil), beeswax.
- **Oils:** Linseed, castor, sunflower, coconut—used alone or blended with waxes.

Functional Roles

- Hydrophobic layers reduce WVTR and grease permeability, critical for food packaging.
- Waxes add gloss and tactile feel, improving aesthetics.
- Oils provide flexibility for foldable packaging.

Application Methods

- Emulsion coating with starch or chitosan.
- Hot-melt coating for strong hydrophobicity.
- Spray or dip coating for specialty uses.

Limitations and Trends

- Some waxes are costly or region-specific (e.g., carnauba).
- Oxygen barrier performance varies with thickness.
- Processing challenges include adhesion and durability.
- Research explores nanostructured wax dispersions, polymerized oils, and hybrids with minerals.

As shown in Table 4, natural waxes and oils differ in their barrier performance and sustainability attributes. Carnauba wax stands out with high water resistance, excellent grease barrier properties, and strong compostability, making it suitable for demanding food packaging such as cups and wraps. Beeswax offers moderate to high water resistance and good grease protection, with added antimicrobial benefits, though its performance varies with thickness.

Table 4. Performance and Sustainability

Additive	Water Resistance	Grease/Oil Barrier	Compostability	Typical Use Cases
Carnauba Wax	High	Excellent	Yes	Food wrapping, cups
Beeswax	Moderate-High	Good	Yes	Bakery wraps, trays
Candelilla Wax	Good	Moderate	Yes	Flexible packaging
Soy Wax/Oils	Moderate	Moderate	Yes	Blend coatings

Candelilla wax provides balanced water and grease resistance and is valued for flexible packaging applications. Soy-based waxes and oils are renewable and compostable but generally deliver moderate barrier properties, which is why they are often used in blends with other biopolymers. Overall, these natural additives demonstrate that biodegradable coatings can achieve functional performance comparable to petroleum-based waxes while maintaining environmental compatibility.

MANUFACTURING TECHNOLOGIES FOR ECO-FRIENDLY COATED PAPERS

The production of eco-friendly coated papers requires technologies that can handle the unique properties of bio-based and biodegradable materials. The goal is to reduce environmental impact while maintaining performance and ensuring compatibility with existing paper machines. Advances in coating methods, drying systems, and surface treatments are making this possible. Recent studies also show that water-based coatings are becoming more versatile, offering strong barrier properties without harming recyclability [12].

Coating Application Methods

Eco-friendly coatings are usually water-based or solvent-free. They can be applied using conventional techniques, but adjustments are needed to match the rheology and chemistry of biopolymer and mineral formulations.

- **Blade coating:** Excess coating is scraped off with a blade, giving uniform thickness. Works well for viscous starch, chitosan, or cellulose dispersions [15,20].
- **Roll coating:** Uses metering and applicator rolls to transfer coatings in controlled layers. Suitable for high-speed production.
- **Rod coating:** A simple method where a wire-wound rod spreads the coating evenly. Effective for small mills and pilot trials.
- **Spray coating:** Allows thin, even layers and is useful for bio-based emulsions or wax dispersions.
- **Curtain coating:** Applies a continuous curtain of liquid coating, ideal for smooth surfaces and uniform coverage.

Each method has trade-offs in cost, scalability, and coating quality. Rod and spray coating are particularly attractive for small-scale operations because they require less investment.

Drying and Curing Technologies

Drying and curing are critical steps in producing eco-friendly coated papers. They determine the final barrier properties, mechanical strength, and recyclability of the coating. Because bio-based materials often have higher water content and different film-forming behavior than synthetic polymers, specialized drying methods are needed.

Conventional Drying Methods

- **Hot-air drying:** Commonly used in paper mills, it removes moisture quickly but can cause uneven film formation or brittleness in biopolymer coatings.
- **Infrared drying:** Provides faster surface drying and helps reduce energy use. It is effective for thin coatings of starch or proteins.
- **Contact drying (cylinder drying):** Uses heated cylinders to evaporate water. This method is widely available but may require adjustments for sensitive bio-based films.

Advanced and Emerging Techniques

- **Microwave drying:** Offers uniform heating and shorter drying times, reducing energy consumption. It is particularly useful for nanocellulose and protein coatings.
- **UV curing:** Applied when coatings are modified with photo-reactive agents. It improves crosslinking and water resistance without high thermal loads.
- **Superheated steam drying:** Provides efficient heat transfer and can lower emissions compared to conventional hot-air systems.

Challenges and Considerations

- Bio-based coatings are more sensitive to heat and humidity, which can lead to cracking or poor adhesion if drying is not controlled.
- Energy demand remains high, and balancing efficiency with sustainability is essential.
- Uniform drying is critical to avoid defects such as pinholes, uneven gloss, or weak barrier performance.

Future Directions Research is focusing on hybrid drying systems that combine infrared, microwave, and conventional methods to optimize energy use and coating quality. Closed-loop drying systems that recover and reuse heat are also being explored to reduce carbon footprints.

Surface Modification and Functionalization

Surface modification is an important step in improving the performance of eco-friendly coated papers. By altering the paper surface or the coating chemistry, manufacturers can achieve better barrier properties, durability, and compatibility with printing and packaging requirements.

Common Techniques

- **Plasma treatment:** Exposes the paper surface to ionized gases, increasing surface energy and improving adhesion of bio-based coatings.
- **Corona treatment:** Uses high-voltage discharge to create polar groups on the surface, enhancing wettability and bonding.

- **Chemical grafting:** Attaches functional groups (such as hydrophobic or antimicrobial agents) directly to cellulose fibers, improving water resistance and adding new properties.
- **Enzymatic modification:** Employs enzymes to selectively change fiber surfaces, offering a greener alternative to chemical treatments.

Functional Additives

- **Antimicrobial agents:** Chitosan, silver nanoparticles, or plant extracts can be added to coatings for food packaging and medical papers.
- **Hydrophobic agents:** Natural waxes, fatty acids, or silanes improve water and grease resistance.
- **Nanomaterials:** Nanocellulose, nano-clays, or graphene oxide enhance barrier strength and mechanical durability.

Benefits

- Improved adhesion between coatings and paper fibers.
- Enhanced resistance to moisture, grease, and oxygen.
- Added functionality such as antimicrobial activity or UV protection.
- Better printability and surface smoothness.

Challenges

- Some treatments increase production costs or require specialized equipment.
- Chemical modifications must be carefully controlled to avoid toxicity or recyclability issues.
- Balancing performance with environmental safety remains a key concern.

Future Directions Research is moving toward bio-based functionalization methods, such as plant-derived hydrophobic agents or enzyme-based surface treatments. Hybrid approaches that combine plasma or corona treatment with natural additives are also being explored to achieve high performance without compromising sustainability.

Sustainable Process Considerations

Sustainability in manufacturing eco-friendly coated papers is not only about the coating materials themselves but also about the processes used to apply and finish them. Production methods must minimize energy use, reduce emissions, and ensure compatibility with recycling and composting systems.

Energy Efficiency

- Paper coating and drying are energy-intensive steps. Using infrared, microwave, or hybrid drying systems can lower energy demand compared to conventional hot-air methods.
- Closed-loop heat recovery systems help reduce overall carbon footprints.

Water Management

- Water-based coatings are preferred, but they require careful management to avoid excess wastewater.
- Closed-loop water systems and treatment technologies reduce effluent discharge and improve sustainability.

Chemical Safety

- Sustainable processes avoid hazardous solvents, fluorinated compounds, and additives that can harm recyclability or food safety.
- Preference is given to natural crosslinkers, enzymatic treatments, and bio-based dispersants.

Waste Reduction

- Optimizing coating formulations reduces sludge and rejects during production.
- Reuse of process residues, such as starch or mineral fines, supports circular manufacturing.

Compatibility with Existing Infrastructure

- Processes should adapt to current paper machines to avoid costly retrofits. Techniques like rod-coating and spray methods are especially suitable for small and medium mills.

Future Outlook Sustainable process design will increasingly rely on integrated approaches combining energy-efficient drying, safe chemistry, and closed-loop resource management. Aligning these practices with certifications and regulatory frameworks will be key to scaling eco-friendly coated papers.

Emerging Technologies and Future Prospects

Emerging technologies are opening new pathways for eco-friendly coated papers. These innovations aim to overcome current limitations in cost, scalability, and performance, while aligning with circular economy goals.

Nanotechnology

- Nanocellulose, nano-clays, and nano-chitosan are being explored to deliver superior barrier properties at low coating thickness.
- Nanostructured films can reduce water vapor and oxygen transmission to levels comparable with synthetic plastics.
- Research is also looking at antimicrobial nanomaterials for food packaging applications.

Bio-based Hybrid Systems

- Combining biopolymers with minerals, waxes, or oils creates coatings that balance cost and performance.
- Hybrid formulations improve flexibility, water resistance, and recyclability.
- These systems are particularly promising for humid climates, where single biopolymers often fail.

Advanced Coating Processes

- Digital and precision coating methods allow controlled application of thin, uniform layers, reducing material use and waste.
- Spray and curtain coating are being adapted for bio-based dispersions, making them suitable for small and medium mills.

Table 5. Emerging Technologies for Eco-Friendly Coated Papers

Technology / Approach	Key Function	Sustainability Impact	Future Potential
Nanocellulose coatings	Strong oxygen and moisture barriers	Fully biodegradable, recyclable	High potential for packaging and specialty papers
Nano-clays and layered silicates	Enhanced barrier at low loading	Moderate impact, recyclable with paper	Useful in hybrid bio-polymer systems
Hybrid biopolymer–mineral blends	Balance cost and performance	Lower material use, improved recyclability	Scalable for small and medium mills
Digital/precision coating methods	Thin, uniform layers, reduced waste	Lower resource use, energy efficient	Promising for industrial adoption
Smart coatings (antimicrobial, UV)	Added functionality for food/medical use	Reduce spoilage, extend product life	Growing demand in active packaging
Pilot-scale trials	Bridge lab and industry gap	Demonstrate real-world feasibility	Essential for commercialization

Smart and Functional Coatings

- Research is moving toward coatings with added functions such as antimicrobial activity, UV protection, or active packaging features.
- Smart coatings can extend shelf life of food products and reduce spoilage.

Future Prospects

- Pilot-scale trials are essential to bridge the gap between laboratory success and industrial adoption.
- Policy incentives, subsidies, and harmonized certification standards will accelerate commercialization.
- Collaboration between academia, industry, and regulators will be key to scaling eco-friendly coatings globally.
- With continued innovation, these technologies can shift eco-friendly coated papers from niche products to mainstream solutions in packaging, publishing, and specialty applications.

As summarized in **Table 5**, emerging technologies provide multiple pathways to strengthen the sustainability and performance of eco-friendly coated papers. Nanocellulose and nano-clay systems deliver strong barrier properties at low coating thickness, while remaining recyclable and biodegradable. Hybrid biopolymer–mineral blends balance cost and functionality, making them suitable for small and medium mills. Precision coating methods reduce waste and energy use by applying thin, uniform layers. Smart coatings with antimicrobial or UV-protective functions extend product shelf life and open new applications in food and medical packaging. Pilot-scale trials remain essential to bridge laboratory success with industrial adoption, demonstrating real-world feasibility. Together, these technologies highlight how innovation can move eco-friendly coated papers from niche products toward mainstream commercial use. The continued evolution of manufacturing technologies tailored for eco-friendly coated papers is instrumental in transforming the paper industry towards more sustainable, high-performance products.

PERFORMANCE AND PROPERTIES OF ECO-FRIENDLY COATED PAPERS

Evaluating eco-friendly coated papers requires looking at how they perform compared to conventional synthetic coatings. Key aspects include barrier properties, mechanical strength, printability, recyclability, and environmental impact.

Physical and Mechanical Properties

The physical and mechanical properties of eco-friendly coated papers are critical in determining their suitability for packaging, printing, and specialty applications.

Unlike conventional petroleum-based coatings, which often impart rigidity and gloss but compromise recyclability, bio-based coatings must balance strength, flexibility, and barrier performance while remaining compatible with fiber recovery systems. Starch and cellulose derivatives are among the most widely studied biopolymers for mechanical reinforcement. Their hydroxyl groups allow strong hydrogen bonding with cellulose fibers, which improves adhesion and enhances tensile strength and folding endurance. However, native starch films are brittle and highly hydrophilic, which can lead to cracking under mechanical stress. Chemical modifications such as esterification, acetylation, or blending with hydrophobic agents have been shown to improve flexibility and reduce moisture sensitivity, thereby extending their mechanical durability in real-world applications. Nanocellulose coatings provide exceptional reinforcement due to their nanoscale fibril network, which integrates tightly with the paper matrix. Studies report significant improvements in tensile strength, stiffness, and dimensional stability, making nanocellulose one of the most promising candidates for high-performance eco-friendly coatings. Nevertheless, its sensitivity to humidity can reduce mechanical integrity under tropical conditions, highlighting the need for hybrid formulations that combine nanocellulose with PLA or mineral fillers. Protein-based coatings such as soy protein, casein, and zein also contribute to mechanical performance. These materials form continuous films with good adhesion and grease resistance, but they are prone to brittleness and humidity-induced swelling. Plasticizers like glycerol or sorbitol are often incorporated to improve flexibility, though this can compromise barrier properties.

Mineral additives such as calcium carbonate and kaolin clay play a dual role: they reduce cost while also improving surface smoothness, gloss, and printability. When combined with biopolymer binders, they enhance mechanical strength without hindering recyclability. Calendering and supercalendering further refine surface properties, producing coated papers with improved tactile feel and higher gloss levels suitable for publishing and premium packaging. Overall, eco-friendly coatings demonstrate mechanical properties comparable to conventional synthetic coatings in many applications. Their main limitations lie in moisture sensitivity and brittleness, which remain active areas of research. Hybrid systems, chemical modifications, and nanostructured reinforcements are emerging as effective strategies to overcome these challenges and ensure that eco-friendly coated papers can meet industrial performance standards. As shown in **Table 6**, the physical and mechanical properties of eco-friendly coated papers fall within ranges comparable to conventional synthetic coatings, though with some variability depending on formulation. Surface gloss typically measures between 55–75%, slightly lower than petroleum-based coatings but can be enhanced through the addition of natural waxes or mineral fillers.

Table 6. Typical Ranges for Select Properties

Property	Conventional Coating	Eco-Friendly Coating (Typical)	Notes
Surface Gloss (%)	60–80	55–75	Can be enhanced with wax/minerals
Tensile Strength (N/m)	4,500–7,000	4,200–7,000	Strongest with nanocellulose blends
Folding Endurance (double folds)	20–60	15–55	Dependent on type/plasticizers
Surface Roughness (Bekk s)	150–400	140–350	Comparable, modifiable
Abrasion Resistance	High	Moderate–High	Better with crosslinking
Printability	Excellent	Good–Excellent	Enhanced with pigment blends

Tensile strength remains robust, with values of 4,200–7,000 N/m, especially when nanocellulose is incorporated to reinforce the fiber matrix. Folding endurance is somewhat lower (15–55 double folds) compared to conventional coatings, reflecting the brittleness of certain biopolymers, though plasticizers and blends can improve flexibility. Surface roughness values (140–350 Bekk s) are comparable and can be modified through calendering or pigment adjustments. Abrasion resistance is moderate to high, particularly when crosslinking agents are used to strengthen film integrity. Printability ranges from good to excellent, with pigment blends and mineral additives enhancing color reproduction and surface smoothness. Overall, these ranges demonstrate that eco-friendly coatings can deliver mechanical and functional properties close to conventional systems, while offering significant sustainability advantages. Eco-friendly coating technologies have rapidly closed the gap with traditional synthetic systems in most physical and mechanical metrics. Continued advances in formulation design, hybridization with mineral and nano-additives, and optimized process control are enabling these coatings to meet the high demands of modern printing and packaging markets.

Barrier Properties

Barrier properties are among the most critical performance indicators for eco-friendly coated papers, as they determine suitability for packaging, printing, and food contact applications. Conventional petroleum-based coatings such as polyethylene or polypropylene provide excellent resistance to water vapor, oxygen, grease, and chemicals, but they compromise recyclability and generate persistent plastic waste. Eco-friendly coatings must therefore achieve comparable barrier performance while maintaining biodegradability and fiber recovery. Water vapor transmission rate (WVTR) is a key measure of moisture resistance. Nanocellulose coatings, due to their dense fibril network, can reduce WVTR to values as low as 5–15 g/m²/day, approaching those of polyethylene laminates. Starch and protein-based coatings provide moderate moisture resistance but are highly sensitive to humidity, which can lead to swelling and loss of barrier integrity. Natural waxes such as carnauba and beeswax improve hydrophobicity, lowering WVTR further when used as topcoats or blended with biopolymers. Hybrid systems that combine nanocellulose with PLA or mineral fillers show promise in balancing moisture resistance with mechanical flexibility.

Oxygen transmission rate (OTR) is equally important, particularly for food packaging where oxidative spoilage must be prevented. Chitosan and protein coatings exhibit excellent oxygen barrier properties, often outperforming synthetic polymers under dry conditions. Nanocellulose films also provide strong oxygen resistance, though performance decreases under high humidity. Incorporating crosslinkers or hydrophobic additives can mitigate this limitation.

Grease and oil resistance is another essential property for food contact papers. Protein-based films, chitosan, and wax coatings deliver good to excellent grease resistance, with kit test values ranging from 6 to 12 on the standard scale. These coatings prevent oil penetration and staining, making them suitable for fast-food wrappers, bakery packaging, and disposable tableware. Overall, eco-friendly coatings demonstrate barrier properties that are increasingly competitive with conventional plastics. While humidity sensitivity remains a challenge, ongoing research into hybrid formulations, nanostructured films, and bio-based crosslinkers is steadily improving performance. These advances suggest that eco-friendly coated papers can meet the stringent requirements of modern packaging while offering clear environmental benefits.

As shown in **Table 7**, eco-friendly coated papers exhibit barrier properties that vary depending on the coating type but are increasingly competitive with conventional polyethylene (PE) coatings. PE-coated papers demonstrate low water absorption (15–30 g/m² Cobb60), excellent grease resistance (Kit value ~10), and near-impermeable oxygen transmission (<1 cc/m²/day), making them the benchmark for packaging. In comparison, starch-modified coatings show higher water absorption (40–60 g/m²) and weaker grease resistance (Kit 4–6), with oxygen transmission rates between 40–80 cc/m²/day, reflecting their hydrophilic nature. Chitosan coatings perform better, with moderate water absorption (20–30 g/m²), grease resistance values of 7–8, and oxygen transmission rates as low as 1–15 cc/m²/day, highlighting their potential for food packaging. PLA coatings offer balanced performance, with WVTR values of 75–180 g/m²/day and grease resistance of 6–8, though oxygen resistance (5–20 cc/m²/day) is lower than chitosan. Natural wax blends improve hydrophobicity, reducing water absorption to 18–45 g/m² and delivering grease resistance values of 7–8, though oxygen transmission remains moderate (10–40 cc/m²/day). Overall, while PE coatings remain superior in barrier performance, bio-based alternatives such as chitosan, PLA, and wax blends demonstrate strong potential, particularly when optimized in hybrid formulations to balance moisture, grease, and oxygen resistance.

Table 7. Typical Barrier Properties

Coating Type	Water Absorption (Cobb60 g/m ²)	WVTR (g/m ² /day)	Grease Resistance (Kit)	OTR (cc/m ² /day)
PE-coated	15–30	<50	10	<1
Starch-modified	40–60	200–350	4–6	40–80
Chitosan	20–30	120–300	7–8	1–15
PLA	20–35	75–180	6–8	5–20
Natural wax blend	18–45	100–240	7–8	10–40

Values can vary depending on specific formulations, layer thickness, and environmental conditions.

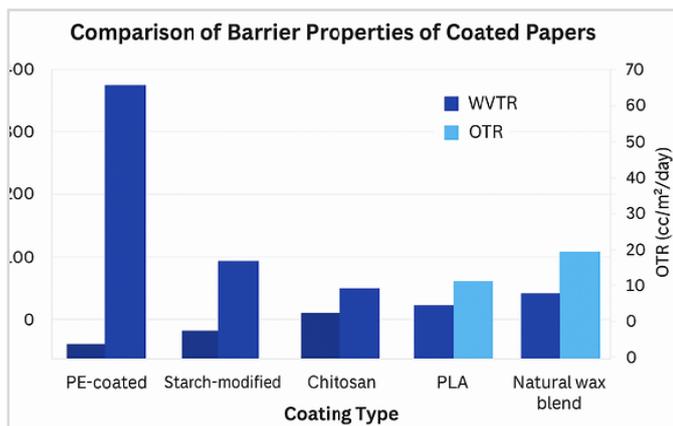


Figure 3 illustrates the comparative barrier performance of conventional PE coatings and eco-friendly alternatives such as starch-modified, chitosan, PLA, and natural wax blends. PE coatings show the lowest WVTR (<50 g/m²/day) and OTR (<1 cc/m²/day), confirming their benchmark status. In contrast, starch-modified coatings exhibit the highest WVTR (200–350 g/m²/day) and weaker oxygen resistance, reflecting their hydrophilic nature. Chitosan coatings demonstrate strong oxygen barrier properties (1–15 cc/m²/day) with moderate WVTR, while PLA offers balanced performance but requires industrial composting. Natural wax blends improve hydrophobicity, lowering water absorption and grease permeability, though oxygen resistance remains moderate. This visualization highlights the trade-offs between barrier performance and sustainability, reinforcing the need for hybrid formulations.

Considerations and Limitations

- **Humidity Sensitivity:** Many bio-based coatings lose barrier performance under high humidity, necessitating multilayer or composite approaches for demanding use cases.
- **Balancing Properties:** Maximizing water resistance often reduces vapour or oxygen permeability, so formulations must be tailored to application-specific requirements.
- **Compostability and Recyclability:** Even with strong barriers, eco-friendly coatings are engineered to maintain compatibility with recycling systems and ensure rapid disintegration under composting conditions compared to plastics.

Advancements in material science, formulation blending, and nanotechnology continue to close the performance gap between bio-based coatings and traditional synthetic barriers, making green alternatives increasingly viable for mainstream packaging and specialty paper applications. Biopolymer coatings degrade rapidly while synthetics persist.

Table 8 summarizes key differences [19]. As shown in Table 8, the biodegradability and compostability of eco-friendly coated papers vary significantly depending on the coating type. Starch-modified, chitosan, and cellulose derivative coatings degrade rapidly within weeks to months and are fully compostable under both industrial and home conditions, leaving no residue. Natural waxes and oils also demonstrate moderate to fast biodegradation, with compostability achieved particularly when applied in thin layers. In contrast, PLA coatings degrade slowly under ambient conditions but disintegrate rapidly in industrial composting environments, making them suitable only for controlled facilities. Conventional synthetic coatings such as PE, PP, and PVDC show no biodegradability or compostability, persisting as microplastics and contributing to long-term environmental pollution. These comparisons highlight the clear sustainability advantage of biopolymer coatings, which not only provide functional barrier properties but also ensure compatibility with recycling systems and rapid disintegration under composting conditions. Table 8 shows starch/chitosan excel in home composting, unlike PLA (industrial only) or PE (microplastics) [19].

Biodegradability and Compostability

Biodegradability and compostability are central attributes of eco-friendly coated papers, determining their environmental fate and distinguishing them from conventional plastic-coated products. These properties describe how materials disintegrate under natural or industrial conditions, the timescale involved, and the by-products formed factors critical for minimizing landfill accumulation and pollution.

Biodegradability

- **Definition:** Biodegradability is the capability of a material to be broken down by microorganisms (bacteria, fungi, algae) into water, carbon dioxide (or methane under anaerobic conditions), and biomass, without leaving persistent residues or microplastics.
- **Biopolymer Coatings:** Coatings based on starch, cellulose derivatives, chitosan, polylactic acid (PLA), proteins, and natural waxes typically exhibit high biodegradability. Under ambient or composting conditions, these bio-based films break down within weeks to months, depending on thickness, formulation, and environmental factors such as moisture, temperature, pH, and microbial activity.
- **Starch and chitosan** degrade rapidly in moist, microbe-rich settings.
- **PLA**, although biodegradable, generally requires the elevated temperatures (~58°C) and humidity typical of industrial composting for efficient breakdown.

Table 8. Biodegradability and Compostability of Coated Papers

Coating Type	Biodegradability	Compostability (EN 13432/ASTM D6400)	Residue Risk
Starch-modified	Rapid (weeks–months)	Yes (industrial/home)	None
Chitosan	Rapid (weeks–months)	Yes (industrial/home)	None
Cellulose derivative	Fast (weeks–months)	Yes (industrial/home)	None
PLA	Slow (ambient); rapid (industrial)	Yes (industrial only)	None
Natural waxes/oils	Moderate–fast	Yes (industrial/home, if thin)	None
PE/PP/PVDC	Not biodegradable	Not compostable	Persistent microplastics

- Contrast with Synthetics: Synthetic coatings like polyethylene and polyvinylidene chloride are not biodegradable, persisting for years and fragmenting only into environmental microplastics. Their presence in paper slows or even prevents decomposition of the fiber substrate.

Compostability

- Definition: Compostability is a stricter metric, meaning a material not only biodegrades but also disintegrates completely and leaves no toxic residues under controlled composting conditions. Industrial standards, such as EN 13432 (Europe) and ASTM D6400 (USA), specify criteria including:

- ✓ 90% disintegration within 12 weeks.
- ✓ Complete biodegradation within 180 days (industrial composting temperatures).
- ✓ No adverse effects on compost quality or plant growth.
- Home Composting: Some coatings, especially thin-layered starch or protein films, can biodegrade in garden/home composts, albeit more slowly and variably than in industrial facilities.
- Certification and Labels: Products meeting compostability requirements may carry third-party certification (e.g., “OK Compost,” “Seedling,” “BPI Compostable”), which bolsters consumer and end-user confidence.

End-of-Life and Environmental Impact

- Soil and Water Health: Complete biodegradation and compostability prevent soil and water contamination and avoid the accumulation of persistent synthetic fragments typical of conventional plastics.
- Compatibility with Recycling: Many biodegradable coatings (in appropriate amounts and compositions) do not impede paper recycling, and are designed to break down during the pulping process or remain inert, avoiding stickies and fiber loss.

Practical Considerations and Limitations

- Environmental Conditions: Actual rates of biodegradation and composting depend on local conditions—temperature, humidity, oxygen availability, and microbial populations. Industrial composting optimizes these, while landfill or dry/anaerobic conditions may slow breakdown considerably.
- Coating Thickness and Formulation: Thicker or more crosslinked films degrade more slowly. Blends of biopolymers and natural waxes, if formulated for rapid fragmentation, increase compostability.
- Contaminant-Free Breakdown: Certified biodegradable coatings must not leach heavy metals, persistent toxins, or negatively impact soil flora/fauna.

Values may vary with local composting parameters, blend formulation, and coating thickness. In summary, biopolymer-based coatings demonstrably outperform synthetic coatings regarding biodegradability and compostability, underpinning their environmental advantages and regulatory compliance, especially in the context of a circular economy and sustainable packaging goals.

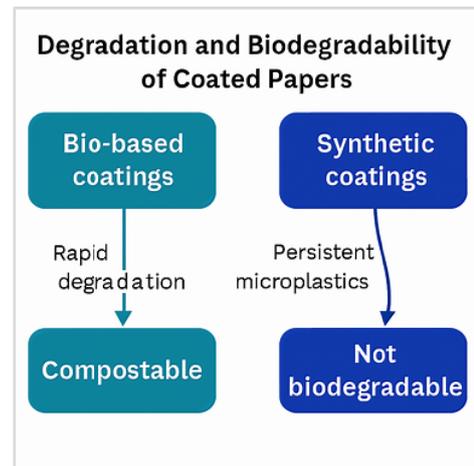


Figure 4. Bio-based coatings degrade rapidly and are compostable, while synthetic coatings persist and form microplastics

As shown in Figure 4, bio-based coatings follow a compostable pathway, breaking down into harmless residues under industrial or natural conditions. These include starch, cellulose derivatives, chitosan, PLA, and waxes. In contrast, synthetic coatings such as polyethylene, polypropylene, and PVDC resist degradation, often ending up in landfills or incinerators and contributing to microplastic pollution. This visual comparison reinforces the environmental imperative for transitioning to compostable, recyclable coating systems.

Life Cycle Assessment (LCA) Comparisons

Life Cycle Assessment (LCA) is a standardized methodology used to quantify the environmental impacts of a product across its full life cycle from raw material extraction (cradle) through production, use, and end-of-life disposal (grave). For coated papers, LCA provides a robust framework to compare the sustainability performance of conventional synthetic-coated papers and eco-friendly alternatives.

Key Phases in LCA of Coated Papers

1. Raw Material Acquisition: Assesses the environmental footprint of harvesting wood fibers, extracting or synthesizing coating materials (e.g., petroleum-based polymers vs. bio-based polymers, minerals, waxes).
2. Manufacturing and Processing: Includes pulping, coating application, drying/curing, and finishing. Evaluates energy use, emissions (CO₂, VOCs), and water consumption.
3. Distribution and Use: Transportation energy, resource usage during printing or packaging, and application-specific impacts.
4. End-of-Life (EOL) Handling: Determines recyclability, biodegradability, compostability, and pollution (e.g., microplastics, emissions) related to disposal.

Comparative LCA Results

- Conventional PE-Coated Papers:
- Exhibit high global warming potential (GWP) due to fossil-based polymer production and energy-intensive lamination or extrusion processes.
- Persistent coating fragments reduce fiber recovery during recycling and add to landfill and microplastic pollution burdens.

- Generally demonstrate lower biodegradability and compostability, increasing waste management complexity.
- Eco-Friendly Coated Papers (Biopolymer/Natural Additives):
- Lower GWP when using renewable or recycled feedstocks (e.g., starch, PLA from fermentation).
- Water-based coating processes and lower curing temperatures reduce energy usage and VOC emissions during manufacturing.
- Biodegradability and compostability at EOL minimize environmental persistence and pollution.
- Improved compatibility with mechanical recycling streams, preserving fiber value and decreasing residual waste.

Case Study Highlights

- Starch or Chitosan Coatings: LCA studies show 30–60% lower GWP than plastic coatings primarily due to renewable feedstock and higher fiber recovery rates during recycling [9,19].
- PLA-Coated Paper: While raw material emissions are low, full biodegradation typically requires industrial composting, and energy use in PLA production can vary based on regional electricity sources.
- Hybrid Coatings: Natural mineral fillers (e.g., kaolin, calcium carbonate) with bio-binders demonstrate balanced impact profiles high performance with minimal environmental persistence [16].

Limitations and Considerations

- The LCA benefits of eco-coatings rely on responsible sourcing, local recycling and composting infrastructure, and minimization of additive use.
- Regional variation in electricity sources, land use practices, and waste management systems can significantly affect LCA outcomes for coated papers.
- Emerging blending and hybrid coating technologies may further improve the sustainability profile by optimizing resource use and closing material loops.

In summary, LCA consistently evidences substantial environmental advantages for eco-friendly coated papers over conventional plastic-coated variants, especially in resource use, emissions, end-of-life impact, and alignment with circular economy goals. LCA analysis proves bio-coatings superior across cradle-to-gate metrics. Table 9 compares GWP, water, and energy for key coatings.

Table 9. Qualitative Life Cycle Assessment Comparison of Synthetic vs Eco-Friendly Coatings. This table summarizes key environmental performance categories (fossil resource use, GWP, water/energy, recyclability, biodegradability, microplastic formation, and end-of-life fate) to illustrate why bio-based coatings offer superior circular economy potential

Impact Category	Synthetic-Coated Paper (PE/PVDC)	Eco-Coated Paper (Biopolymer/Natural)
Fossil Resource Use	High	Low–Moderate
CO ₂ /Greenhouse Emissions	High	Low (esp. with renewable electricity)
Water/Energy Use	High (lamination/extrusion)	Moderate–Low (aqueous coatings, low T°)
Recyclability	Poor	Good
Biodegradability	Very Low	High (weeks–months, industrial/home)
Microplastic Formation	Yes	None
EOL Pollution	Persistent, landfill/microplastics	Compostable/biodegradable; minor residues
Certification Potential	Limited	High (FSC, OK Compost, Blue Angel, etc.)

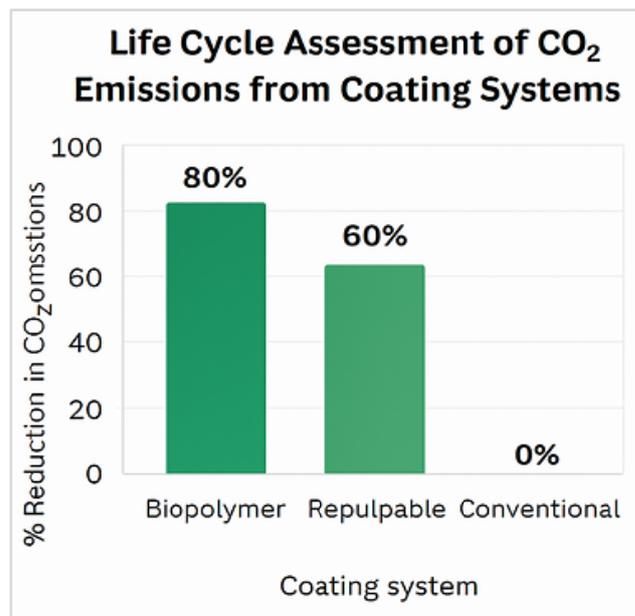


Figure 5. Life cycle CO₂ emissions are significantly lower for biopolymer and repulpable coatings compared to conventional synthetic systems

As shown in Figure 5, biopolymer coatings achieve up to 80% reduction in life cycle CO₂ emissions compared to conventional petroleum-based coatings. Repulpable coatings also show substantial gains, with reductions around 60%. In contrast, conventional coatings offer no significant emission savings and contribute heavily to fossil carbon footprints. These results underscore the environmental benefits of transitioning to bio-based and recyclable coating systems, especially in regions with high paper consumption and limited landfill capacity.

Quantitative LCA data demonstrate significant environmental advantages of bio-coatings. Nano-cellulose achieves a 57% reduction in GWP compared to PE (1.2 vs 2.8 kg CO₂e/kg), while water consumption drops 44% (29 vs 52 m³/ton). Starch-based coatings show 46% GWP reduction with 33% water savings. Across all bio-coatings studied, GWP reductions range 40–60% depending on renewable energy availability and feedstock sourcing [20, 21].

Table 9 shows nano-cellulose cuts GWP 57% vs PE while using 44% less water [20]. These gains drive regulatory push for bio-coatings.

Table 9A. Quantitative LCA Data – Global Warming Potential, Water Use, and Energy for Bio-based vs Synthetic Paper Coatings. Specific numerical data extracted from published LCA studies show GWP and water reductions of 40–60% for biopolymer coatings compared to PE, with nano-cellulose achieving the lowest environmental footprint across all metrics

Coating Type	GWP (kg CO ₂ e/kg)	Water Use (m ³ /ton)	Energy (GJ/ton)	Recyclability	Biodegradation Time
PE/Polyethylene (Control)	2.8	52	20.5	Poor	>1000 days (none)
Starch-based	1.5	35	13.2	Good	45–90 days (soil)
PLA	1.8	42	16.1	Moderate	180–360 days (industrial compost)
Nano-cellulose	1.2	29	11.8	Good	30–60 days (soil/compost)

Table 10. Comparison of End-of-Life Management Pathways

Coating Type	Recycling	Industrial Composting	Home Composting	Landfill Behavior
PE/PP Synthetic	Poor	Not compostable	Not compostable	Persistent/microplastics
Starch/Chitosan/Cellulose Coat	Good	Fully compostable	Partial–Good	Biodegradable
PLA (bio-based thermoplastic)	Limited–Mod.	Compostable (industrial)	Slow–variable	Biodegradable (slow)
Waxed (natural plant wax)	Good	Compostable	Compostable	Biodegradable

End-of-Life Management

The end-of-life (EOL) management of coated papers is a key determinant of their overall environmental sustainability. How a coated paper product is handled after use recycling, composting, or landfilling depends greatly on its material composition and the local waste infrastructure. Eco-friendly alternatives are specifically designed to minimize environmental burden and maximize resource recovery, differentiating themselves from traditional synthetic-coated papers.

Recycling Compatibility

- **Conventional Synthetic-Coated Paper:** Coatings made with polyethylene (PE), polypropylene (PP), or other plastics act as barriers to fiber recovery in recycling systems. These layers resist water, disrupt pulp processing, reduce recovered fiber yield, and often result in downgraded or contaminated recycled paper batches. Small plastic fragments (“stickies”) can accumulate in process water, requiring extra filtration and disposal steps. In many regions, synthetic-coated papers are excluded from standard recycling streams, leading to more landfilling or incineration.
- **Eco-Friendly Coated Papers:** Bio-based coatings (e.g., starch, chitosan, cellulose derivatives, some proteins) and mineral-based barrier papers are generally hydrophilic or designed to fragment during pulping, allowing for efficient fiber recovery. Many eco-coatings are engineered to disintegrate or dissolve without generating problematic residues, thus maintaining or even improving the quality of recycled pulp. Certifications from organizations like CEPI or INGEDE validate the recyclability of such products under industrial conditions.

Compostability and Biodegradation

- **Biodegradation in Natural and Industrial Settings:** Bio-based coatings such as modified starch, chitosan, and polylactic acid (PLA) readily break down in natural environments and composting facilities. Under aerobic conditions, these substances are metabolized by soil microorganisms, leaving behind water, carbon dioxide, and biomass. Industrial composting speeds up this process, ensuring complete disintegration within weeks to months, provided the coating thickness and formulation meet certification criteria (e.g., EN 13432, ASTM D6400).

- **Home Compostability:** Some thin bio-coatings can degrade in home compost bins, albeit at slower and more variable rates due to lower and less-controlled temperatures and microbe activity compared to industrial composters.
- **Landfill Considerations:** Although biodegradable coatings will break down over time in a landfill, the anaerobic and dry conditions typical in landfills often slow the process considerably. Nonetheless, they avoid the microplastic persistence and accumulation characteristic of synthetic coatings.

Environmental Impact Mitigation

- **Avoiding Microplastics:** Eco-friendly coatings are formulated to degrade fully, thereby avoiding microplastics which are a major concern for marine and terrestrial ecosystems associated with traditional coated papers.
- **No Toxic Residues:** Qualified biodegradable and compostable coatings are required to leave behind no toxic residues or substances of very high concern (SVHC), ensuring soil and water health even in large-scale composting or recycling operations.
- **Circular Economy Enablement:** By facilitating fiber recovery, safe organic degradation, and compatibility with multiple EOL scenarios, eco-coatings contribute to circular economy models. Materials re-enter the product cycle as recycled fiber, compost, or harmless biomass.

Certification and On-Pack Communication

- **Eco-labeling:** Products meeting recyclability and compostability standards may carry recognized labels such as the Recycling Loop, OK Compost, Seedling, or Blue Angel. These labels inform consumers and waste processors about the EOL options.
- **Producer Responsibility:** Manufacturers are increasingly required to provide transparent information regarding disposal, leveraging QR codes, icons, and clear instructions to enable proper sorting and processing by consumers and waste handlers.

Different coated papers behave very differently in recycling, composting, and landfill conditions, and these differences are summarized in Table 10.

Table 10 shows that bio-based coatings such as starch, chitosan, and cellulose derivatives are compatible with both recycling and composting, whereas PE and other synthetic coatings mostly end up in landfill or incineration with higher environmental burdens.

Challenges and Future Directions

- **Infrastructure Gaps:** Effective EOL requires alignment between product design and actual collection, sorting, and processing infrastructure. Regions without composting or advanced recycling facilities may not realize full environmental benefits.
- **Standardization and False “Green” Claims:** Ongoing efforts are needed for robust, harmonized testing and certification to prevent greenwashing and ensure that eco-friendly claims are rigorously substantiated.

In summary, eco-friendly coated papers outperform synthetic-coated counterparts in end-of-life management by enabling circular material flows, minimizing persistent pollution, and complying with emerging legislative and consumer expectations. Ongoing improvements in certification, infrastructure, and public awareness will further bolster their environmental advantages.

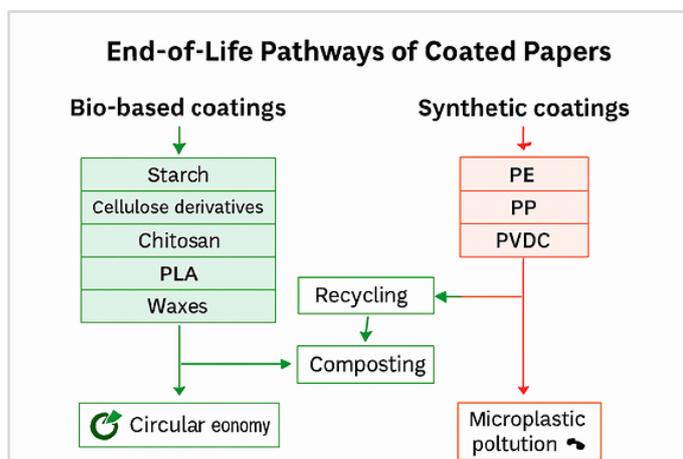


Figure 6. End-of-life pathways of coated papers. Bio-based coatings (starch, cellulose derivatives, chitosan, PLA, waxes) are recyclable and compostable, supporting circular economy systems. Synthetic coatings (PE, PP, PVDC) typically end up in landfill or incineration, generating persistent microplastics and undermining sustainability

As shown in Figure 6, bio-based coatings align with recycling and composting streams, enabling fiber recovery and reducing environmental burdens. In contrast, synthetic coatings divert paper waste toward landfill or incineration, where they persist or fragment into microplastics. This divergence highlights the critical role of end-of-life management in determining the true sustainability of coated papers.

MARKET ADOPTION AND CASE STUDIES

Commercial Eco-Friendly Coated Papers

The increasing demand for sustainable paper products has led to the introduction and commercial advancement of a variety of eco-friendly coated papers across global markets. These products are manufactured by leading paper companies who have leveraged biopolymer, mineral, and hybrid technologies to produce packaging and specialty papers that combine functionality with strong environmental credentials.

Examples of Commercial Eco-Friendly Coated Papers

- **UPM Biofore and UPM Solide Lucent (UPM):**

- UPM Biofore range uses bio-based coatings and FSC-certified fiber to achieve both compostability and recyclability [27]. UPM Solide Lucent, a translucent barrier paper, is designed for flexible packaging and is produced without any fossil-based or fluorinated chemicals, ensuring compatibility with food and other sensitive uses.
- **Sappi Algro Nature (Sappi):**
- Sappi's Algro Nature series is a biopolymer-coated paper board for flexible packaging, using renewable materials such as PLA [27]. This product is industrially compostable and designed to substitute polyethylene-laminated packaging for food, confectionery, and labels.
- **Mondi NAUTILUS and Mondi Functional Barrier Paper (Mondi Group):**
- The NAUTILUS range features recycled fibers and water-based barrier coatings, while the Functional Barrier Paper line offers solutions for dry food, frozen food, toys, and secondary packaging, replacing conventional plastics and promoting recycling.
- **Stora Enso Cupforma Natura Bio and Performa Light (Stora Enso):**
- Cupforma Natura Bio is used for paper cups and foodservice items, incorporating a plant-based barrier layer for compostability. Performa Light, with its mineral and bio-based multilayer structure, is targeted at premium packaging with reduced plastic and energy footprint.
- **Lecta Diva Art Green:**
- Lecta's Diva Art Green is a premium coated paper with a bio-based, recyclable barrier layer designed for books, catalogs, and advertising [27]. It meets stringent European environmental labeling, including Blue Angel and FSC.
- **Indian Paper Manufacturers:**
- Several Indian paper mills (e.g., JK Paper, ITC) have commercialized compostable and biodegradable coated boards using starch or PLA, targeting foodservice and retail packaging segments in response to local plastic bans.

Key Features and Advantages

- **Recyclability and Compostability:** Designed for easy fiber recovery and rapid breakdown in composting environments, most commercial products carry relevant certifications such as FSC, Blue Angel, and industrial compostability standards.
- **Food-Safe and Regulatory Compliance:** Many offerings are manufactured to comply with FDA, EU 10/2011, or BfR food-contact regulations, making them viable for both direct and indirect food packaging uses.
- **Tailored Barrier Properties:** Depending on formulation, these papers provide effective protection against water, oil, oxygen, or aroma migration combining biopolymer, wax, and mineral layer technologies to deliver application-specific performance.
- **Printable and Convertible:** Engineered for compatibility with various printing technologies (offset, digital, gravure) and downstream converting processes.

Market Impact and Adoption

The growth of eco-friendly coated papers in the commercial marketplace is driven by partnerships between packaging converters, retailers, and consumer brands eager to meet sustainability targets and regulatory requirements. Sectors such as food and beverage, e-commerce, cosmetics, and specialty

publishing now routinely specify eco-certified coated paper solutions. Widespread adoption is expected to advance further as cost competitiveness improves, global certification and labeling harmonize, and consumer expectations continue to favor sustainable product solutions.

Success Stories

The adoption of eco-friendly coated papers has witnessed several notable success stories across diverse sectors, demonstrating both the technical feasibility and market potential of sustainable alternatives to conventional plastic-coated papers. These cases highlight how innovation, collaboration, and commitment to sustainability can drive impactful change in product design, manufacturing, and consumer acceptance.

Food Packaging Innovations

- **Stora Enso's Cupforma Natura Bio:** Stora Enso successfully commercialized Cupforma Natura Bio, a fully compostable paperboard coated with a plant-based barrier layer. It is widely used in disposable cups, food trays, and bakery packaging. This product has enabled leading global foodservice brands to reduce plastic reliance while ensuring food safety and maintaining performance under demanding moisture and grease conditions. The product's certification for industrial compostability and recyclability has supported compliance with evolving environmental regulations in Europe and North America, effectively contributing to circular economy goals [27].
- **UPM Solide Lucent for Flexible Packaging:** UPM's Solide Lucent paper offers a fossil-free barrier suitable for flexible food packaging applications. Its successful integration into commercial packaging lines for snack foods, confectionery, and dry goods has proven that bio-based coated papers can match the functionality of traditional plastic laminates while significantly reducing environmental impact. The product's performance in preserving product quality and compatibility with existing converting and printing processes accelerated its adoption among manufacturers and brand owners [27].

Publishing and Printing Sector

- **Sappi Algro Nature for Premium Packaging and Publishing:** Sappi's Algro Nature range features biopolymer-coated paperboard used for packaging luxury goods, healthcare, and cosmetics, as well as high-quality publishing materials. The transition from traditional plastic coatings to bio-based alternatives in Algro Nature has resulted in lifecycle energy savings and improved recyclability. Case studies demonstrated customer satisfaction with print quality, tactile finish, and environmental credentials, helping publishers and packagers meet corporate social responsibility (CSR) targets.
- **Lecta Diva Art Green in Sustainable Publishing:** Lecta's Diva Art Green paper, which incorporates a bio-based, recyclable coating, has been adopted for art books, magazines, and marketing collateral desiring premium appearance with environmental responsibility. Its acceptance by European publishers and commercial printers underscored the viability of eco-friendly coated

papers in high-end print markets without compromising visual appeal or production efficiency.

Regional and Emerging Market Leadership

- **Indian Paper Industry's EcoGreen Board:** Indian companies such as JK Paper and ITC Limited have successfully introduced starch- and PLA-based coated boards under the EcoGreen brand for foodservice and retail packaging. These offerings meet the stringent local regulations on plastic use and waste management, supporting India's plastic ban mandates. The commercial success of EcoGreen boards reflects growing consumer and governmental pressure toward sustainable packaging in emerging economies, setting a benchmark for other regional producers [28].
- **Mondi's NAUTILUS Range in Circular Packaging:** Mondi has integrated recycled fibers with bio-based waterborne coatings in its NAUTILUS packaging papers, targeting food and consumer goods sectors. This product line exemplifies the circular economy by ensuring easy recyclability and minimizing environmental footprint. Several multinational companies have integrated NAUTILUS paper packaging in their sustainable sourcing programs, reinforcing green supply chains.

Collaborative Programs and Research Partnerships

- **Cross-Industry Consortia:** Several success stories emerge from collaborative initiatives between paper manufacturers, coating suppliers, research institutions, and brand owners. Public-private partnerships have accelerated the commercial readiness of eco-friendly coatings, sharing know-how on environmental compliance, life cycle assessment, and consumer education. These programs have resulted in pilot projects and commercial rollouts for bio-based coated papers reaching mainstream markets faster than isolated efforts.

Overall, these success stories illustrate that eco-friendly coated papers are moving beyond niche concepts to become commercially viable solutions adopted by leading industry players. They demonstrate the feasibility of balancing performance requirements with sustainability objectives, fostering shifts in consumer and corporate behavior, and influencing regulatory frameworks worldwide.

CHALLENGES AND FUTURE DIRECTIONS

The transition to eco-friendly alternatives in coated paper technology faces significant challenges that must be strategically addressed to ensure widespread and sustainable adoption. At the same time, ongoing advancements in materials science, manufacturing, and policy provide a robust trajectory for future development.

Key Challenges

- **Performance Gaps:** While considerable progress has been made, many biopolymer and mineral-based coatings still lag behind conventional synthetic coatings in terms of water resistance, mechanical robustness under humid or greasy conditions, and long-term durability—especially for

demanding applications like dairy, frozen food, or extended shelf-life packaging [16,21].

- **Process and Machinery Compatibility:** Many mills use equipment optimized for plastic-based coatings. Switching to bio-based formulations can require substantial adjustments or investment in new machinery due to differences in viscosity, drying characteristics, or film formation [15,17].
- **Cost Competitiveness:** Bio-based coatings (chitosan, PLA, nanocellulose) and some natural waxes are frequently more costly and less readily available than petroleum-based counterparts, inhibiting their competitiveness, particularly in price-sensitive markets [20,21].
- **Variability and Standardization:** The performance of natural materials can vary with feedstock source, seasonality, and batch, complicating process control and product consistency.
- **Recycling and Infrastructure Alignment:** Not all eco-friendly coatings are fully compatible with modern recycling operations, particularly in regions where recycling or composting infrastructure is underdeveloped. Certain blends or multilayer systems may still pose fiber recovery issues [18,26].
- **Verification and Regulation:** Inconsistent or misleading environmental claims (“greenwashing”) erode consumer trust and make it difficult to compare products. Harmonized certification (FSC, EN 13432, OK Compost, Blue Angel) and regulatory clarity are needed [10,14,27].

Future Directions

- **Material Innovations:** Research is intensifying into hybrid coatings, nano-structured materials, and chemically-modified biopolymers. These advances aim to enhance barrier properties, flexibility, and durability while retaining biodegradability and recyclability [16,19,21].
- **Manufacturing Advances:** Process engineering is focusing on lower-energy drying, precision application techniques (digital coating, LbL assembly), and solventless curing to make production more cost- and resource-efficient [22,24].
- **Feedstock Diversification:** Expanding the range of renewable resources (e.g., agricultural residues, algae, waste streams) can reduce feedstock costs and improve supply chain resilience.
- **Circular Economy Models:** Greater emphasis is being placed on design-for-recycling principles, disintegratable coatings, and recovery systems that maximize material loops and minimize landfill.
- **Standardization and Policy:** The development of internationally recognized, application-specific standards for compostability, recyclability, and food safety will build market confidence and streamline certification.
- **Consumer Education and Market Pull:** Outreach to manufacturers, brand owners, and end-users—showcasing performance parity, environmental savings, and clear disposal guidance will be essential in accelerating acceptance and adoption.
- **Collaborative Ecosystems:** Multistakeholder partnerships, including public-private research, government incentives, and industry consortia, are crucial for collectively overcoming technical and market barriers.

To provide a structured view of how eco-friendly coatings can be scaled up in practice, a stepwise roadmap has been prepared and is presented in Table 11.

Table 11. Roadmap for Overcoming Challenges

Challenge	Strategy for Resolution
Performance Gaps	Hybrid materials, nanotechnology, R&D funding
Cost Barriers	Scale-up, supply chain innovation, valorizing waste
Process Incompatibility	Equipment adaptation, process optimization
Recycling/Compostability	Design-for-end-of-life, better infrastructure
Standardization Gaps	International harmonization, robust certification
Greenwashing	Transparent, third-party eco-labeling
Market Awareness	Education, marketing, policy incentives

Table 11 indicates that short-term efforts should focus on pilot-scale coating trials and recyclability validation, while medium- and long-term actions must address cost reduction, regulatory harmonization, and large-scale industrial integration across different paper grades.

As markets and technology mature, the eco-friendly coated paper sector is poised to shift from niche adoption to mainstream deployment. Achieving this will require a holistic approach integrating technical innovation, value-chain collaboration, supportive policy, and ongoing consumer engagement.

CONCLUSION

Eco-friendly alternatives to conventional coated papers represent a vital step towards sustainability in the paper and packaging industries. Driven by growing environmental concerns about plastic waste, recyclability challenges, and the carbon footprint associated with petroleum-based synthetic coatings, research and commercial innovation have increasingly focused on bio-based, biodegradable, and recyclable materials. Natural polymers such as starch, chitosan, cellulose derivatives, and polylactic acid (PLA), along with inorganic mineral additives and natural waxes, offer promising functional properties—providing water, grease, and oxygen barriers while enhancing printability and mechanical performance. Significant progress has been made in adapting manufacturing processes to accommodate these green coatings, including water-based application methods, UV-curing, and novel surface treatments. Encouragingly, many eco-friendly coated papers now achieve barrier properties and durability comparable to conventional products, while enabling improved end-of-life outcomes such as compostability and fiber recovery in recycling streams. Despite these advances, challenges relating to cost, scalability, performance under diverse conditions, and infrastructure compatibility remain. Addressing these barriers requires continued material innovation, standardization efforts, and collaboration across the value chain. Policies that incentivize sustainable materials and transparent eco-labeling will play an important role in accelerating adoption. Earlier reviews focused primarily on laboratory-scale material development and barrier performance comparisons; in contrast, this synthesis bridges materials science, industrial practice, lifecycle thinking, and policy, offering a more complete picture of the pathway toward sustainable coated paper adoption.

Abbreviations

LCA – Life Cycle Assessment
 PE – Polyethylene
 PP – Polypropylene
 PVDC – Polyvinylidene Chloride
 PLA – Polylactic Acid
 FSC – Forest Stewardship Council
 PEFC – Programme for the Endorsement of Forest Certification
 WVTR – Water Vapor Transmission Rate
 OTR – Oxygen Transmission Rate
 CMC – Carboxymethyl Cellulose
 IR – Infrared
 UV – Ultraviolet
 LbL – Layer-by-Layer
 VOC – Volatile Organic Compound
 EN – European Norm (Standard)
 ASTM – American Society for Testing and Materials
 OK Compost – Certification label for compostability

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