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Bio-Based, Biodegradable and Hybrid Coatings for Paper-Based Packaging: Functional Performance and End-of-Life Considerations

ABSTRACT

The growing demand for recyclable and high-performance paper-based packaging has intensified research on biopolymer coatings as alternatives to conventional petroleum-derived barrier layers. This review examines peer-reviewed studies published primarily between 2017 and 2026, focusing on chitosan, cellulose and nanocellulose, starch and other polysaccharides, proteins, lignin, bio-based and biodegradable polyester systems. Representative studies were selected to cover major material classes, modification strategies, coating methods, functional properties, processing aspects, and end-of-life performance. Particular attention is given to crosslinking, polymer blending, hydrophobic modification, nanocomposite reinforcement, and multilayer coating design. Relationships between coating composition, morphology, continuity, filler dispersion, coating weight, and processing conditions are discussed in relation to water resistance, water-vapor and oxygen barrier performance, grease resistance, mechanical properties, surface characteristics, and printability. Because experimental and testing conditions differ among studies, the results are compared primarily in terms of general trends and improvements relative to control samples rather than by direct numerical ranking. The reviewed literature shows that no single material class provides optimal performance across all functional requirements. Recent developments increasingly focus on low-coat-weight and scalable coating systems, waste-derived and fully bio-based raw materials, multifunctional coatings, end-of-life criteria such as biodegradability, laboratory-scale repulpability, fiber recovery, and potential compatibility with paper recycling. Future progress will depend on balancing functional performance, processability, resource efficiency, safety, and potential compatibility with existing paper-recycling streams, to be confirmed under industrial conditions.

Milena Ristić
Vesna Gvoić
Živko Pavlović
Miljana Prica

University of Novi Sad, Faculty of Technical Sciences, Department of Graphic Engineering and Design, Novi Sad, Serbia

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1. Introduction

Paper and paperboard are widely used packaging materials due to their favorable printability, availability, relatively low cost, and potential recyclability and biodegradability (Mujtaba et al., 2022; Jahangiri, Mohanty & Misra, 2024). However, their cellulose-based structure is both hygroscopic and porous, which results in limited barrier properties of untreated paper against water and water vapor, gases, aromas, oils, and fats (Li et al., 2019; Mujtaba et al., 2022). These limitations are particularly important in food packaging, where the control of moisture, oxygen, and fatty components, as well as the preservation of mechanical stability under humid con-

ditions, is of critical importance (Mujtaba et al., 2022; Jahangiri, Mohanty & Misra, 2024). One of the most common approaches to improving the functionality of paper is the application of a surface coating that fills the pores, reduces the free volume between cellulose fibers, and forms a continuous protective layer (Li et al., 2019; Jin et al., 2021). Traditionally, synthetic polymers such as polyethylene, poly(ethylene terephthalate), synthetic latexes, poly(vinyl alcohol), and fluoropolymer-based systems have been used for this purpose. Although these materials can provide good barrier and mechanical properties, their use may hinder paper recycling and increase dependence on fossil-based raw materials (Mujtaba et al., 2022; Jahangiri, Mohanty & Misra, 2024). Consequently, increasing attention is being directed toward biopolymer and bio-based coatings based on chitosan, starch, cellulose and nanocellulose, alginate, proteins, polylactic acid (PLA), and polyhydroxyalkanoates (PHA) (Mujtaba et al., 2022; Shorey & Mekonnen, 2022; Jahangiri, Mohanty & Misra, 2024).

The increasing environmental concerns associated with the long-term persistence of petrochemical plastics, the difficulties in managing multilayer packaging systems, and the dependence on non-renewable resources have encouraged the development of renewable and potentially biodegradable materials, subject to application-specific safety assessment, for improving the functional properties of paper-based packaging. In this context, biopolymers represent a particularly important group of materials, as they can originate from plant, animal, microbial, and biomass-derived industrial sources, while certain classes also exhibit good film-forming ability, favorable gas barrier properties, biocompatibility, and the possibility of chemical modification.

This review covers natural biopolymers, bio-based synthetic polymers, biodegradable polymers that may be fossil-derived, and hybrid systems combining biopolymers with synthetic polymers or inorganic nanomaterials. Accordingly, bio-based origin, biodegradability, and biopolymer content are treated as distinct material characteristics (Mujtaba et al., 2022; Jahangiri, Mohanty & Misra, 2024).

Among the materials that have attracted the greatest attention for paper and paperboard coatings are chitosan, cellulose and nanocellulose, starch, alginate, lignin, proteins, and biodegradable polyesters, while more recent research has increasingly focused on their blends, nanocomposites, and multilayer systems (Mujtaba et al., 2022; Eslami & Mekonnen, 2023; Poulose et al., 2024; Adak & Teramoto, 2025). Different classes of biopolymers provide different advantages when used as paper coatings. Polysaccharides, such as chitosan, cellulose, nanocellulose, starch, and alginate, generally exhibit good film-forming ability and can form relatively uniform and compact layers on the paper surface (Mathew & Oksman, 2017; Herrera, Jin et al., 2021; Mujtaba et al., 2022). Natural polyphenols, such as tannins and certain lignin-derived components, can absorb UV radiation and exhibit antioxidant activity (Mujtaba et al., 2022; Zhu et al., 2023). Biodegradable polyesters, such as polylactic acid (PLA), poly(3-hydroxybutyrate) (PHB), and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), are generally more hydrophobic than many polysaccharides. Their lower affinity for water can therefore contribute to improved protection of paper against moisture and direct contact with water (Shorey & Mekonnen, 2022; Calosi et al., 2024; Pieters & Mekonnen, 2024). However, biodegradability does not imply rapid degradation in every environment. The degradation of these polyesters depends on their composition and crystallinity, coating thickness, temperature, moisture, microbial activity, and the conditions of the applied test (Eslami & Mekonnen, 2023; Lors, Leleux & Park, 2025).

At the same time, the natural or bio-based origin of a polymer does not automatically ensure optimal coating performance. Its application may be limited by hydrophilicity, brittleness, insufficient thermal and mechanical stability, aggregation, and poor compatibility between different components (Mujtaba et al., 2022; Jahangiri, Mohanty & Misra, 2024). In polysaccharides such as chitosan and cellulose-based materials, polar functional groups contribute to good film-forming ability, but at the same time increase their affinity for water (Mujtaba et al., 2022; Dodangeh et al., 2026).

This paper presents a review of peer-reviewed studies published primarily between 2017 and 2026. The literature search focused primarily on peer-reviewed publications indexed in major scientific databases (Web of Science and Scopus). Search terms included combinations of “paper coating”, “paper-based packaging”, “bio-based coating”, “biopolymer coating”, “biodegradable coating”, “barrier coating”, “repulpability”, and “recyclability”. Studies were selected to provide representative examples of major material classes, modification strategies, coating methods, functional properties, and end-of-life considerations.

2. Functional requirements of paper-based coatings

Biopolymer coatings can significantly modify the properties of paper and broaden its application in packaging systems. Their performance depends on the type of biopolymer, the composition and structure of the coating, as well as the coating and processing methods. In addition to improving resistance to water, gases, oils, and fats, the coating can also affect the mechanical, surface, and printing properties of paper and provide additional active functions. The homogeneity and continuity of the formed

layer are particularly important, since the presence of pores, cracks, or an uneven distribution of components can reduce the barrier and mechanical performance of the coating (Shorey & Mekonnen, 2022; Mujtaba et al., 2022). Therefore, the performance of biopolymer coatings should be evaluated based on the overall combination of properties rather than on individual test results.

Current developments are increasingly focused on multicomponent and multifunctional systems in which different properties can be simultaneously tailored to meet the requirements of specific packaging applications (Eslami & Mekonnen, 2023; Zhu et al., 2023; Peng et al., 2024).

2.1. Water and moisture barrier properties

The hydrophilic and porous nature of paper limits its application in packaging systems with more demanding product-protection requirements. Interfiber pores facilitate liquid penetration and water vapor transport, while the hydroxyl groups of cellulose exhibit a strong affinity for water. Surface coating can therefore serve two main functions (Mujtaba et al., 2022; Shorey & Mekonnen, 2022): reducing direct contact between cellulose fibers and water, and sealing or narrowing the pores through which moisture transport occurs.

In the reviewed literature, water resistance is most commonly evaluated using the water contact angle (WCA) and Cobb test, whereas water vapor transport is expressed as the water vapor transmission rate (WVTR) or water vapor permeability (WVP). These parameters describe different aspects of material performance: WCA primarily characterizes surface wettability, the Cobb test quantifies the amount of liquid water absorbed by paper, while WVTR and WVP describe water vapor transport through the entire coated system (Shankar & Rhim, 2018; Adak & Teramoto, 2025).

The distinction between surface wettability and actual water absorption is particularly important for hydrophobic polyester coatings. Adak & Teramoto (2025) showed that contact angle values do not necessarily correlate directly with water absorption, while the optimized PBAT/hectorite nanocomposite coating exhibited an exceptionally low Cobb value. In more hydrophilic polysaccharide-based systems, the relationship between coating structure and moisture-barrier performance is more complex. Nanocellulose can form a dense and uniform network that reduces water penetration; however, the addition of a hydrophilic plasticizer may increase moisture uptake. Herrera, Mathew & Oksman (2017) demonstrated that the application of a nanocellulose coating significantly reduced moisture absorption, whereas the addition of sorbitol increased it due to its hydrophilic nature.

Current strategies for improving moisture-barrier properties therefore include hydrophobic modification, chemical crosslinking, combination with more hydrophobic components, and nanocomposite reinforcement (Herrera, Mathew & Oksman, 2017; Shorey & Mekonnen, 2022; Fang et al., 2025; Adak & Teramoto, 2025).

2.2. Oxygen and gas barrier properties

Excessive oxygen transport through packaging materials can promote oxidative processes and reduce product stability. Therefore, coating performance is commonly evaluated by measuring the oxygen transmission rate (OTR), oxygen permeability (OP), or resistance to air permeation (Mujtaba et al., 2022; Shorey & Mekonnen, 2022). Effective gas-barrier performance is generally achieved by forming a dense and continuous layer that restricts gas transport through the material. Nanocellulose is particularly attractive in this respect because of its ability to form compact networks of nanofibrils. Herrera, Mathew & Oksman (2017) showed that nanocellulose-based coatings significantly improve oxygen-barrier properties compared with the uncoated porous substrate, with particularly effective protection achieved using a thin plasticized nanocellulose coating. Another important mechanism involves the formation of a tortuous diffusion path. When platelet-shaped nanofillers are well dispersed within a polymer matrix, gas molecules are forced to diffuse around the impermeable particles, thereby increasing the effective path length through the coating. In PBAT/hectorite nanocomposites, the good dispersion of nanoclay at an optimal concentration resulted in a significant reduction in both oxygen and water-vapor transport (Adak & Teramoto, 2025).

Very high gas-barrier performance can also be achieved with protein-based and biopolyelectrolyte systems. Fisher et al. (2026) developed a fully bio-based coating composed of fish gelatin and DNA, both derived from fish-processing by-products. Under appropriate conditions, gelatin and DNA interact to form a polymer-rich phase known as a complex coacervate. This polymer-rich phase was subsequently applied as a coating to kraft paper, reducing the oxygen transmission rate by approximately 70% compared with uncoated paper. A subsequent thermal treatment at 150 °C induced structural rearrangement and strengthened intermolecular interactions within the coating, resulting in an OTR reduction of approximately 99%. These findings indicate that the formation of a compact polymeric structure followed by thermal stabilization can provide highly effective oxygen-barrier properties without the use of a conventional synthetic polymer matrix.

2.3. Oil and grease resistance

Resistance to oils and fats is particularly important for paper-based packaging intended for products with a high

lipid content. Due to its open fibrous structure, uncoated paper allows relatively rapid penetration of nonpolar liquids. Therefore, a functional coating should reduce the available transport pathways and form a sufficiently homogeneous and continuous surface layer (Shankar & Rhim, 2018; Shorey & Mekonnen, 2022). In the reviewed studies, resistance to oils and fats is most commonly evaluated using the Kit test, while oil-based Cobb tests, oil contact angle measurements, and longer-term penetration tests are also applied. The findings indicate that, in addition to chemical composition, coating morphology plays an important role in determining grease-barrier performance. Shorey & Mekonnen (2022) showed that esterified lignin provides better resistance to oils and fats than the unmodified system, which was associated with improved lignin dispersion and a more homogeneous PBAT/lignin coating structure. The optimized PBAT/hectorite nanocomposite system achieved the maximum Kit rating of 12 (Adak & Teramoto, 2025), while a crosslinked chitosan/tannin system combined high oil and grease resistance with barrier properties against gases and moisture, as well as UV protection (Zhu et al., 2023). High resistance to oils and fats can therefore be achieved through several approaches, including the use of hydrophobic polymers, the incorporation of nanomaterials, and the formation of crosslinked biopolymer networks.

2.4. Mechanical properties

In addition to improving barrier performance, a functional coating should preserve or enhance the mechanical properties of paper. The most commonly evaluated parameters include tensile strength, elongation at break, tear resistance, burst strength, and wet tensile strength. Improvements in these properties may result from stronger bonding between surface fibers, the filling of surface irregularities, and the formation of a more compact polymeric or nanocomposite layer (Herrera, Mathew & Oksman, 2017; Shorey & Mekonnen, 2022). An increase in strength does not necessarily imply better overall mechanical performance. Plasticization can improve flexibility but may also increase sensitivity to water, while a higher degree of crosslinking can enhance structural stability but reduce material elongation. Therefore, an appropriate balance between strength and flexibility is essential in the design of functional coatings (Herrera, Mathew & Oksman, 2017; Dodangeh et al., 2026). The importance of coating structure and crosslinking for mechanical performance was clearly demonstrated by Yu et al. (2022), who developed a multilayer coating based on chitosan and dopamine-modified carboxymethyl cellulose using a layer-by-layer assembly approach followed by oxidative crosslinking. Increasing the number of layers and applying subsequent crosslinking improved the mechanical properties of the paper by promoting stronger fiber bonding and enhanced interlayer interactions. These findings indicate that mechanical reinforcement depends not only on coating composition, but also on coating architecture and the crosslinking strategy. For packaging applications, maintaining mechanical stability in the presence of water is particularly important. Shorey & Mekonnen (2022) showed that esterified lignin incorporated into a PBAT matrix significantly improved the wet tensile properties of paper compared with uncoated paper and systems with poorer lignin dispersion. This improvement was associated with the hydrophobic nature of the coating, more effective fiber coverage, and reduced water penetration into the paper substrate.

2.5. Surface properties and printability

Surface properties of coatings are particularly important in graphic and packaging applications, as coating microstructure, surface roughness, porosity, and binder distribution directly influence ink absorption and the uniformity of the printed surface. Du et al. (2018) demonstrated that the partial replacement of synthetic latex with starch-based bio-latex alters the microstructure of pigment coatings. In contrast to synthetic styrene-butadiene (SB) latex, whose particles deform more readily during drying and form a more continuous film, bio-latex particles tend to retain a more spherical morphology. Increasing the bio-latex content resulted in changes in pore structure, a slight increase in surface roughness, and a reduction in coating gloss. These changes can affect ink absorption and transfer and, consequently, print quality.

Therefore, the replacement of petrochemical binders with renewable alternatives should be evaluated not only from the perspective of sustainability, but also in terms of the relationship between coating microstructure and print-related properties. A more direct relationship between the structure of bio-based coatings and printability was reported by Liu et al. (2023), who developed a starch-based bio-latex modified with cationic cellulose nanocrystals (CCNC). The incorporation of CCNC promoted the formation of a more compact coating structure and simultaneously resulted in higher print optical density, improved surface pick resistance, and lower tone value increase compared with the control systems. These findings highlight the importance of tailoring the microstructure of bio-based coatings in order to achieve both improved sustainability and satisfactory printing performance.

2.6. Additional functionality

Modern biopolymer coatings are increasingly being developed as multifunctional systems that, in addition to basic barrier and mechanical properties, can provide antimicrobial and antioxidant activity, UV protection, reduced migration of selected substances, and improved end-of-life performance (Shankar & Rhim, 2018; Mujtaba et al., 2022; Zhu et al., 2023). A coating based on alginate, carboxymethyl cellulose (CMC), and carrageenan, supplemented with grapefruit seed extract, represents

an example of an active system that combines barrier and antibacterial functions. The coated paper exhibited strong antibacterial activity against Listeria monocytogenes and Escherichia coli under the applied test conditions, demonstrating that the coating can provide an active function in addition to acting as a physical barrier (Shankar & Rhim, 2018). A broader example of multifunctionality is provided by a crosslinked chitosan/tannin system that combines oil and grease resistance, barrier properties against gases and moisture, UV protection, biodegradability, and paper repulpability. Such a combination of properties demonstrates that coating functionality can extend beyond product protection during use to include requirements related to the material's end-of-life behavior (Zhu et al., 2023).

In addition to incorporating active components, multifunctional coatings can be developed by combining materials with complementary properties in multicomponent and multilayer structures. Eslami & Mekonnen (2023) developed a multilayer structure consisting of paper, thermoplastic starch (TPS), and an outer layer of PLA, PBAT, PHBV, or PVOH. TPS primarily contributed to oxygen-barrier performance, whereas the outer polymer layer improved resistance to water, water vapor, and oil. The most favorable overall barrier performance was achieved with the TPS/PHBV system, indicating that distributing complementary functions among individual layers may be more effective than relying on a single material. Although all of the investigated systems contained a bio-based TPS layer, they were not necessarily fully bio-based: PVOH is a synthetic polymer that is not typically bio-based, whereas commercial PBAT is generally produced predominantly from fossil-derived feedstocks despite being biodegradable.

A similar multilayer concept was applied by Yi et al. (2022) using a hybrid nanocellulose–PDMS coating. The first cellulose nanofibril (CNF) layer filled pores within the paper structure and contributed to improved oil and barrier resistance, while the outer layer containing polydimethylsiloxane (PDMS) and CNF microparticles provided pronounced hydrophobicity. Multifunctionality can also include properties associated with the behavior of the material after use. Peng et al. (2024) developed a bio-based coating composed of chitosan, glutinous rice starch, and PLA using an emulsion stabilized by cellulose nanocrystals (CNC). Chitosan and starch formed a continuous polymer matrix, while PLA microspheres contributed to hydrophobicity and the formation of a rougher surface structure. An important advantage of this system is that, in addition to water and oil resistance and self-cleaning properties, it retains biodegradability and the ability to recover paper fibers through repulping, thereby improving its end-of-life sustainability.

For food-packaging applications, functional performance must be considered together with material safety and compliance with food-contact requirements. The natural, bio-based, or biodegradable origin of a coating component does not by itself guarantee its suitability for direct contact with food. Potential migration of residual crosslinking agents, plasticizers, photoinitiators, solvents, nanoparticles, and unreacted coating components should therefore be evaluated under conditions that reflect the intended food type, contact time, and temperature. Active compounds may also affect the sensory properties of packaged products or migrate at concentrations exceeding their intended technological function.

Consequently, the development of biopolymer-based and hybrid coatings for food packaging should include overall and specific migration testing, toxicological assessment where required, and verification of compliance with applicable food-contact legislation, in addition to conventional barrier, mechanical, and end-of-life evaluation (Mujtaba et al., 2022; Jahangiri, Mohanty & Misra, 2024). However, food-contact safety, migration behavior, and toxicological performance are not systematically evaluated in most of the reviewed studies, which represents an important limitation of the available literature. Consequently, these aspects were not included in the detailed comparative analysis presented in this review and should be addressed more systematically in future research.

2.7. End-of-life considerations

The end-of-life performance of coated paper cannot be described using a single criterion. Bio-based origin, biodegradability, compostability, repulpability, fiber recovery, and recyclability represent distinct characteristics and should therefore be evaluated separately. A coating may be derived from renewable resources without being readily biodegradable, while a biodegradable polymer may require specific temperature, moisture, microbial, or industrial-composting conditions for effective degradation. Similarly, laboratory-scale repulpability indicates that the coated paper can be disintegrated and that fibers may be recovered under the applied test conditions, but it does not by itself demonstrate compatibility with industrial paper-recycling processes.

Among the reviewed systems, Zhu et al. (2023) reported both biodegradability and laboratory-scale repulpability for a crosslinked chitosan/tannin coating. Peng et al. (2024) also evaluated biodegradation and paper-fiber recovery for a chitosan, glutinous-rice-starch, and PLA coating. Haider, Wang and Li (2026) investigated the influence of PLA coating weight on barrier performance and laboratory-scale repulpability. Their results showed that coating weight affected both functional performance and the recovery of the paper substrate, demonstrating that end-of-life behavior depends not only on polymer type but also on the amount and structure of the applied coating.

These results indicate potential compatibility with paper recycling, but they should not be interpreted as proof of full recyclability under industrial conditions. Industrial recycling performance also depends on coating detachment, fiber yield and quality, screening losses, adhesive or reject formation, process-water contamination, and the operating conditions of the recycling mill. Therefore, future studies should report the applied repulping procedure, coating weight, fiber-recovery yield, reject content, and the quality of the recovered fibers. Claims of biodegradability or compostability should likewise specify the applied test method, environmental conditions, duration, and degree of degradation or disintegration. Until such assessments are performed under relevant pilot- or industrial-scale conditions, the terms laboratory-scale repulpability, fiber recovery, and recyclability should not be used interchangeably.

The multifunctionality of coatings can therefore be achieved through the incorporation of natural active components, crosslinking, the combination of materials with different properties, and the formation of multilayer structures. Their effectiveness depends not only on composition but also on coating structure, homogeneity, and interactions between individual components. Consequently, current research is increasingly focused on coatings capable of meeting several functional requirements simultaneously, both during use and after disposal (Shankar & Rhim, 2018; Eslami & Mekonnen, 2023; Zhu et al., 2023; Peng et al., 2024). The functional performance of bio-based, biodegradable, and hybrid coated paper should therefore be evaluated using multiple criteria, including resistance to water, gases, oils, and fats, mechanical, surface, and printing properties, additional active functions, and clearly defined end-of-life characteristics. The main functional requirements, evaluation parameters, representative studies, and improvement mechanisms are summarized in Table 1.

As shown in Table 1, no single modification strategy provides optimal performance across all categories simultaneously. Improvement in one property may be accompanied by changes in others; therefore, the development of functional coatings requires a careful balance between barrier, mechanical, surface, and other properties according to the requirements of the intended application.

Table 1 (part 1)

Functional requirements, evaluation parameters, and improvement mechanisms of bio-based, biodegradable, and hybrid coatings for paper-based materials

Functional requirement	Evaluation parameter/test	Evaluated property	Representative studies	Main improvement mechanisms
Water resistance	WCA, Cobb60	Surface wettability and liquid water absorption	Shorey & Mekonnen, 2022; Yi et al., 2022; Peng et al., 2024; Fang et al., 2025; Adak & Teramoto, 2025;	Hydrophobic modification, pore sealing, formation of a continuous coating, and increased roughness of the hydrophobic surface.
Moisture barrier	WVTR, WVP	Water-vapor transport through coated material	Herrera, Mathew & Oksman, 2017; Zhu et al., 2023; Peng et al., 2024; Fisher et al., 2026	Dense polymer network formation, crosslinking, hydrophobic modification, and extension of the diffusion pathway.
Oxygen/ gas barrier	OTR, OP, and resistance to air permeation	Oxygen/gas transport through coated material	Herrera, Mathew & Oksman, 2017; Eslami & Mekonnen, 2023; Ruberto et al., 2024; Adak & Teramoto, 2025; Fisher et al., 2026;	Dense polymeric/nanofibrillar network, pore sealing, reduction of free volume, and multilayer structure
Oil/grease resistance	Kit test, oil Cobb test, and oil contact angle	Resistance to penetration of oils and fats	Shorey & Mekonnen, 2022; Yi et al., 2022; Zhu et al., 2023; Peng et al., 2024; Adak & Teramoto, 2025;	Continuous film formation, pore sealing, hydrophobic modification, and combination of complementary components
Mechanical performance	Tensile strength, elongation at break, tear/ burst resistance, and wet tensile strength	Strength, flexibility and mechanical integrity	Herrera, Mathew & Oksman, 2017; Jin et al., 2021; Shorey & Mekonnen, 2022; Peng et al., 2024;	Intermolecular interactions, crosslinking, fiber bonding, and nanoreinforcement

Table 1 (part 2)
Functional requirements, evaluation parameters, and improvement mechanisms of bio-based, biodegradable, and hybrid coatings for paper-based materials

Functional requirement	Evaluation parameter/test	Evaluated property	Representative studies	Main improvement mechanisms
Surface properties and printability	Surface roughness, gloss, porosity, wettability, optical density, and tone value increase	Surface quality and suitability for printing	Du et al., 2018, Jin et al., 2021; Liu et al., 2023	Control of coating porosity and morphology, binder distribution, and formation of a more compact structure
Active functionality	Antimicrobial and antioxidant activity, UV protection, and self-cleaning properties	Additional protective/active functions	Shankar & Rhim, 2018; Zhu et al., 2023; Peng et al., 2024	Natural extracts, polyphenols, functional additives, and controlled surface morphology
End-of-life performance	Biodegradation under specified conditions; compostability according to applicable standards; laboratory repulpability and fiber-recovery tests; recyclability assessment in relevant paper-recycling systems	Biodegradation behavior, compliance with compostability requirements, recoverability of paper fibers, and compatibility with paper-recycling processes	Zhu et al., 2023; Peng et al., 2024; Haider, Wang & Li, 2026	Selection of materials and coating architectures that facilitate degradation under defined conditions, fiber separation during repulping, or compatibility with established paper-recycling operations

3. Comparative analysis of functional performance

The functional properties of bio-based, biodegradable, and hybrid coating systems depend on the type of polymer, the structure of the formed layer, the modification method, coating weight, and processing conditions (Mujtaba et al., 2022; Ruberto et al., 2024; Gómez et al., 2024). A homogeneous and continuous coating with fewer defects generally contributes to improved functional performance, whereas cracks, pores, or uneven distribution of coating components may reduce barrier efficiency (Ruberto et al., 2024; Gómez et al., 2024). Coating weight is also an important parameter; however, increasing the amount of applied material does not necessarily lead to a proportional improvement in performance. At higher coating weights, changes in formulation viscosity and film formation may impair leveling and promote non-uniform deposition or localized defects (Haider, Wang & Li, 2026).

The dispersion and concentration of functional additives can further influence coating morphology and performance. For example, well-dispersed hectorite nanoclay improved the barrier properties of PBAT-based coatings, whereas excessive nanoclay loading promoted aggregation and reduced coating efficiency (Adak & Teramoto, 2025).

Therefore, when comparing different coating systems, it is more appropriate to consider overall trends and improvements relative to control samples rather than individual numerical values, since differences in polymer composition, coating weight, application method, drying conditions, and testing procedures may affect the reported results (Mujtaba et al., 2022; Gómez et al., 2024).

Table 2 presents a comparative overview of selected representative studies. The studies were chosen to illustrate different coating-material classes, modification strategies, application methods, and functional properties rather than to provide an exhaustive account of all coating systems reported in the literature.

Table 2 (part 1)

Overview of selected studies on bio-based, biodegradable, and hybrid coatings for paper-based packaging

Study	Coating material/ system	Modification	Coating method	Coating weight (g/m²)	Water / moisture barrier	O_2 / gas barrier	Grease/ oil	Mechanical, additional, and end-of-life properties
Vrabič Brodnjak (2017)	Curdlan/ chitosan	Polymer blending	Blade coating	5*	Improved water barrier	—	—	5:5 curdlan/ chitosan ratio showed favorable mechanical performance
Battisti et al. (2017)	Gelatin	Transglutaminase + glycerol + citric acid	Spray coating	NR	Significant reduction in WVP	—	—	Antimicrobial/antioxidant activity; no improvement in mechanical properties
Shankar & Rhim (2018)	Alginate/ CMC/carrageenan + GSE	Ternary blend + active agent	Wire-bar coating	4.5 ± 0.4; 7.6 ± 1.0; 8.8 ± 1.1	Reduced water absorption and WVP; increased hydrophobicity	—	Improved oil resistance	Improved tensile properties; strong antimicrobial activity
Bhardwaj, Bhardwaj & Negi (2021)	Chitosan with different degrees of acetylation (DA)	Degree of acetylation/ deacetylation	Surface coating	1.6 ± 0.2; 2.3 ± 0.3	Improved water-barrier properties	Increased resistance to air permeance	—	burst index, tensile energy absorption, stretch, stiffness, and folding properties
Wang et al. (2020)	Cellulose stearoyl ester	Long-chain esterification	Bar coating	0.5–23.6	Water-vapor barrier ratio up to 90%; WCA ≈ 99–109°	—	—	Smooth and continuous coating; complete surface coverage achieved at 5.2 g/m²
Chi, Wang & Catchmark (2020)	Starch polyelectrolyte complexes	Ionic complexation	Dip coating	≈10	WVP reduced by up to ~40%	—	Kit 12; low oil penetration	Tensile strength ↑ ~18%; Young's modulus ↑ ~21%; dense and defect-free structure
Jeong & Yoo (2020)	WPC/ beeswax/ sucrose	Protein–lipid blending	Brush coating	NR	Strong improvement in water and water-vapor barrier with increasing beeswax content	—	WPC provided oil barrier; high beeswax content increased oil penetration	Clear moisture–oil barrier trade-off
Shorey & Mekonnen (2022)	Esterified lignin/PBAT	Lignin esterification + blending	Doctor blade	12.07–14.81 (20 µm coatings)	Strong water resistance; barrier further improved at higher coating thickness	Improved O_2 barrier; up to 55.2% reduction in oxygen permeability for esterified lignin/PBAT	Improved oil and grease resistance	Esterification improved lignin dispersion and compatibility with PBAT; thicker coatings provided better overall barrier performance

Table 2 (part 2)

Overview of selected studies on bio-based, biodegradable, and hybrid coatings for paper-based packaging

Study	Coating material/ system	Modification	Coating method	Coating weight (g/m²)	Water / moisture barrier	O_2 / gas barrier	Grease/ oil	Mechanical, additional, and end-of-life properties
Zhu et al. (2023)	Chitosan/ tannin-derived epoxy system	Crosslinking	Rod coating	4.05 ± 0.84	WVTR 1252.9 → 298.6 g/m²·d; WCA 102.51°; Cobb60 15.31 g/m²	OP 597.1 → 136.2 cm³/(m²·d·0.1 MPa)	Kit 12	UV shielding; improved mechanical properties; biodegradable and repulpable coating
Ruberto et al. (2024)	CNC/ chitosan bilayer	Multicomponent/ bilayer coating	Slot-die coating + NIR drying	CNC: 22–33; Cht: 3–4	WVP 0.23–0.28 g·mm/(m²·d·Pa) for bilayer systems	Air permeability: 4.2–1.5 nm/(Pa·s); O_2 permeability: 2.7–1.1 cm³·mm/(m²·d·kPa)	—	Scalable deposition; coating homogeneity controlled by suspension viscosity and process parameters
Poulose et al. (2024)	PFJ/PHB multilayer	Multilayer architecture	Rod coating + extrusion coating	PHB: 20 or 30; PFJ: NR*	Specific WVTR reduced by ~95% for two-layer and ~90–91% for three-layer systems	Three-layer structure showed better O_2 barrier than two-layer systems, although OP remained relatively high	Improved grease resistance in three-layer systems	PFJ increased bonding strength; three-layer coatings showed moderate adhesion and improved creasing performance
Adak & Teramoto (2025)	PBAT/ hectorite nanoclay	Nanocomposite reinforcement	Bar coating	22 ± 1; 32 ± 1	WVTR ↓ up to 48.5% relative to neat PBAT coating; lowest Cobb60 = 0.3 g/m²	OTR ↓ up to 58.3% relative to neat PBAT coating	Kit 12; no oil penetration for extended periods	5 wt% nanoclay provided optimum performance; higher loading promoted aggregation
Fang et al. (2025)	Hydrophobically modified chitosan (CHI-g-OA_2)	Hydrophobic grafting + crosslinking	Linear coating machine	4.25 ± 0.81	WCA 121.0 ± 3.0°; Cobb60 8.33 ± 1.2 g/m²; reduced WVTR	Gas-barrier function retained	Kit 10.3 ± 0.6/12; improved oil repellency	Dense crosslinked structure; improved tensile strength and thermal stability
Dodangeh et al. (2026)	Regenerated cellulose/ chitosan/ citric-acid coating systems	Chitosan incorporation + citric-acid crosslinking	Casting-knife coating	NR	WVP as low as (11.0 ± 0.32) × 10^{-5} g/(m·d·Pa) in citric-acid-crosslinked samples	—	—	TS reached 14.20 ± 0.29 MPa for CA20%-RC; combined RC:CH90:10-CA10% system showed TS of 12.30 ± 0.43 MPa

Table 2 (part 3)

Overview of selected studies on bio-based, biodegradable, and hybrid coatings for paper-based packaging

Study	Coating material/ system	Modifi-cation	Coating method	Coating weight (g/m²)	Water / moisture barrier	O_2 / gas barrier	Grease/oil	Mechanical, additional, and end-of-life properties
Cao et al. (2026)	PLA/PHA	Polymer blending + hot pressing	Spray coating + hot pressing	NR	Increased surface hydropho-bicity; higher PHA content generally increased WCA	Lowest OTR, 15.15 ± 1.25 cm³/(m²·24 h), obtained for the 50:50 PLA/PHA blend	—	Hot pressing improved coat-ing uniformity; 50:50 blend provided the most favorable balance of barrier and mechanical properties
Fisher et al. (2026)	Fish gela-tin/DNA	Complex coacerva-tion + ther-mal curing	Wire-wound rod coating	26	WVTR ↓ ~83% after curing at 150 °C	OTR ↓ ~99% after curing at 150 °C	Coating improved grease resistance before curing (Kit 9.2); grease resistance decreased with increasing curing tempera-ture (Kit 4.4 at 150 °C)	Fully bio-based system; thermal curing strong-ly enhanced water-vapor and oxygen-barrier performance
Haider, Wang & Li (2026)	PLA + cit-ric acid	Coat-weight optimiza-tion + plas-ticization	Bar coating	2.00 ± 0.50; 4.50 ± 1.10; 6.68 ± 0.72; 9.98 ± 2.26	Minimum WVTR 83.97 g/(m²·day); Cobb60 reduced from ~20 to ~3 g/m²	—	Maximum Kit 11.2 ± 0.40	Repulpable across the investigated coating weights; 6.68 ± 0.72 g/m² provided the best balance between barrier performance and laboratory-scale repulpability.

Note: '—' indicates that the corresponding property was not evaluated or reported in the cited study, whereas NR indicates that the dry coating weight was not reported. Numerical values from different studies should not be directly ranked because coating formulations, application conditions, coating weights, substrate properties, drying conditions, and testing procedures differ among stud-ies. In addition, the reported OTR, OP, WVTR, and WVP values were obtained under different temperature and relative-humidity conditions and using paper substrates with different compositions, grammages, thicknesses, and surface characteristics. These parameters strongly influence the measured barrier performance; therefore, the numerical values should be interpreted only with-in the experimental conditions of the corresponding study. Where reported, laboratory-scale repulpability, fiber recovery, biodegradability, or other end-of-life characteristics are included in the final column. These terms describe distinct properties and should not be interpreted as evidence of full industrial recyclability.

* For Vrabič Brodnjak (2017), 5 g/m² of coating solution was applied; this value represents the applied solution amount rather than a measured dry coating weight.

* For Poulose et al. (2024), the PHB coating weight was reported as 20 or 30 g/m², whereas the PFJ layers were reported by thickness rather than coating weight.

4. Future directions in bio-based, biodegradable and hybrid coatings for paper and packaging

Future research on biopolymer coatings for paper is increasingly shifting from the improvement of individual barrier properties toward integrated systems that combine high functional performance with renewable raw materials, more sustainable processing, and compatibility with paper recycling. Particular attention is being directed toward coatings capable of meeting several requirements simultaneously, including barrier, mechanical, surface, and end-of-life performance.

One important development pathway is the use of industrial and agro-industrial by-products as sources of functional coating components. Kraft lignin, rice straw, sugar beet pulp, potato processing by-products, waste fatty acids, tannin-rich biomass, and fish-processing residues have all been investigated as sources of polymers, proteins, polyphenols, or nanocellulose. These studies demonstrate that secondary raw materials can contribute to functional barrier and mechanical performance and may reduce the use of virgin or fossil-derived resources, although many reported coating systems still contain synthetic or fossil-derived components (Shorey & Mekonnen, 2022; Saini et al., 2022; Fadel et al., 2022; Poulose et al., 2024; Zhang et al., 2024; Fisher et al., 2026). An important future challenge will be to increase the proportion of renewable and secondary raw materials while maintaining simple processing, functional performance, repulpability, and recyclability of coated paper.

Another major direction is the development of multifunctional coatings that provide additional functions beyond conventional moisture, gas, and grease barriers. Depending on their composition, biopolymer-based systems may exhibit antimicrobial activity, antioxidant properties, UV protection, or self-cleaning behavior. For example, polysaccharide coatings containing grapefruit seed extract have shown antibacterial activity, while chitosan/tannin systems provide both barrier performance and UV protection. Pickering-emulsion-based coatings containing chitosan, starch, and PLA have further demonstrated the possibility of combining hydrophobic, oil-resistant, self-cleaning, biodegradable, and repulpable characteristics within a single system (Shankar & Rhim, 2018; Zhu et al., 2023; Peng et al., 2024). The design of nanocomposite and multilayer structures offers an additional route for tailoring coating performance. Well-dispersed nanomaterials can improve barrier properties at relatively low filler contents, whereas excessive concentrations may promote aggregation and reduce coating efficiency. Multilayer systems provide greater flexibility because individual layers can be designed to perform complementary functions. Combinations of thermoplastic starch with biodegradable polyesters, as well as protein-based layers combined with PHB, illustrate how gas, moisture, oil, and mechanical performance can be distributed across different layers rather than being provided by a single material (Eslami & Mekonnen, 2023; Poulose et al., 2024; Adak & Teramoto, 2025).

Future progress will also depend on the environmental impact of the coating process itself. For this reason, increasing attention is being paid to waterborne formulations, solvent-free systems, lower-energy processing, and alternative curing methods. Photocrosslinking is particularly promising because it can form stable polymer networks without prolonged thermal treatment. Kuo, Chuang & Liao (2026) for example, developed a bio-based photocurable coating based on acrylated epoxidized soybean oil and curcumin as a natural photoinitiator, demonstrating the potential of combining renewable components with rapid curing and good water resistance. However, future applications, particularly in food packaging, should also consider the safety of photoinitiators and possible residual unreacted components.

Overall, future progress is likely to depend less on identifying a single optimal polymer and more on designing complete coating systems in which raw-material selection, modification strategy, coating architecture, processing conditions, functional performance, and end-of-life considerations are evaluated together. Promising systems should achieve the required performance at low coating weights, be compatible with efficient processing, and demonstrate potential compatibility with paper-recycling processes. However, their performance, processability, and recyclability must be confirmed under relevant pilot- and industrial-scale conditions.

5. Conclusions

The reviewed studies demonstrate that a broad range of coating materials and systems can improve the functional performance of paper-based packaging. These include natural biopolymers, bio-based synthetic polymers, biodegradable polymers that may be fossil-derived, and hybrid systems combining biopolymers with synthetic polymers or inorganic nanomaterials. Improvements have been reported in resistance to water, water vapor, oxygen, oils and grease, as well as in mechanical and surface properties. However, bio-based origin, biodegradability, compostability, repulpability, and recyclability are distinct characteristics and should not be treated as equivalent. Moreover, no single material or modification strategy provides optimal performance for all packaging requirements.

Coating performance depends not only on material composition but also on coating continuity and morphology, pore sealing, polymer-network density, filler dispersion, coating weight, layer architecture, and application and drying conditions. The most appropriate strategy—such as crosslinking, hydrophobic modification, polymer blending, nanocomposite reinforcement, or multilayer design—therefore depends on the required function, intended conditions of use, coating weight, and processing method. Particular attention should be given to systems that achieve the required barrier performance at low coating weights and are compatible with continuous coating processes. For applications in the graphic and packaging industries, preservation of suitable surface properties and printability should also be considered alongside barrier and mechanical performance. Nevertheless, industrial scalability must be confirmed under relevant processing conditions, including coating speed, formulation rheology and stability, foaming, drying requirements, and energy consumption.

Future development should focus on multifunctional coating systems that balance functional performance, material safety, responsible raw-material selection, resource-efficient processing, and appropriate end-of-life performance. The renewable or waste-derived origin of coating components, the environmental impact of coating production, biodegradation or compostability under specified conditions, and compatibility with paper-recycling processes should be evaluated separately but as complementary sustainability criteria. Since most of the reviewed systems have been investigated at laboratory or pilot scale, further validation under industrial processing and recycling conditions is required before their practical environmental advantages and suitability for large-scale paper-based packaging applications can be confirmed.

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