

Recent Advances in High-Barrier Food Packaging Based on Mono-material and Natural Materials

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Abstract The transition toward sustainable food packaging has intensified over the past decade, driven by regulatory pressure and environmental concerns associated with plastic waste. The increasing demand for sustainable food packaging has driven significant research into eco-friendly high-barrier materials capable of replacing conventional multilayer plastics. This paper provides a comprehensive analysis of recent advances in mono-material and natural-material-based food packaging systems, focusing on their barrier performance, material design strategies, and industrial applicability. Fundamental barrier mechanisms, including diffusion, solubility, and tortuous path effects, are discussed in relation to polymer structure and morphology. The barrier properties of major material groups, such as polyethylene (PE), polypropylene (PP), polylactic acid (PLA), cellulose-based materials, and nanocomposites, were compared and analyzed. Advanced technologies, including inorganic coatings (SiO_x, AlO_x) and bio-based coatings, are critically discussed as strategies to overcome intrinsic limitations of bio-based polymers. Furthermore, the paper examines recyclability and life cycle assessment (LCA) in the context of emerging circular economy policies. Finally, key challenges and future research directions are outlined, emphasizing scalable manufacturing, multifunctional materials, and integration into existing industrial systems.

Keywords High-barrier Food Packaging, Mono-material, Natural material, Nanocomposites, Sustainability

Introduction

Food packaging plays a critical role in preserving food quality, extending shelf life, and ensuring food safety. Conventional high-barrier packaging systems, typically based on multilayer combinations of polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and ethylene vinyl alcohol (EVOH), have been widely used due to their superior oxygen and moisture barrier properties. However, their heterogeneous structure renders them incompatible with current mechanical recycling systems, leading to significant material losses and environmental burden¹⁾.

In recent years, increasing environmental concerns, plastic waste accumulation, and implementation of regulations—such as the European Union's Packaging and Packaging Waste Regulation (PPWR)—have accelerated the transition toward sustainable packaging solutions. In particular, recent policy within the European Union have emphasized the transition toward recyclable and mono-material packaging systems. This

concept of a circular economy has emphasized the need for materials that are recyclable, reusable, or biodegradable while maintaining functional performance.

Currently, two major approaches have emerged as promising alternatives: (i) mono-material packaging systems, which utilize a single polymer family to enable recyclability, and (ii) natural material-based systems, which employ renewable and biodegradable polymers such as cellulose, starch, chitosan, and polylactic acid (PLA). As a result, significant research efforts over the past decade have focused on developing mono-material and bio-based alternatives. However, these systems often suffer from inferior barrier properties compared to conventional multilayer structures.

To overcome these limitations, significant research efforts have focused on enhancing barrier performance through nanocomposite design, surface coatings, and structural engineering. Despite these advances, a fundamental challenge persists: achieving high barrier performance comparable to conventional multilayer systems while maintaining recyclability. Mono-material systems, particularly those based on polyolefins, offer improved recyclability but suffer from inherently poor oxygen barrier properties²⁾. In contrast, natural materials such as cellulose exhibit excellent oxygen barrier performance but are highly sensitive to moisture³⁻⁴⁾. This fundamental

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trade-off has driven the development of hybrid strategies combining structural modification, nanocomposite engineering, and coating technologies⁵.

This review aims to provide a comprehensive and critical overview of recent developments in mono-material and natural-material-based high-barrier food packaging systems, with particular emphasis on barrier mechanisms, quantitative performance evaluation, and industrial applicability.

Barrier Mechanisms and Structure–Property Relationships

Barrier properties in polymeric systems are governed by the solution–diffusion mechanism, where permeability (P) is defined as:

$$P = D \times S$$

where D is the diffusion coefficient and S is the solubility coefficient of the permeating molecule in the polymer matrix.

Gas transport through polymer films typically follows a solution-diffusion mechanism, involving:

- 1) Sorption of gas molecules at the polymer surface
- 2) Diffusion through the polymer matrix
- 3) Desorption at the opposite surface

The permeability is influenced by several factors, including polymer chain mobility, free volume, crystallinity, and intermolecular interactions. The molecular architecture of the material plays a critical role in defining these parameters, particularly in terms of crystallinity, chain mobility, and inter-

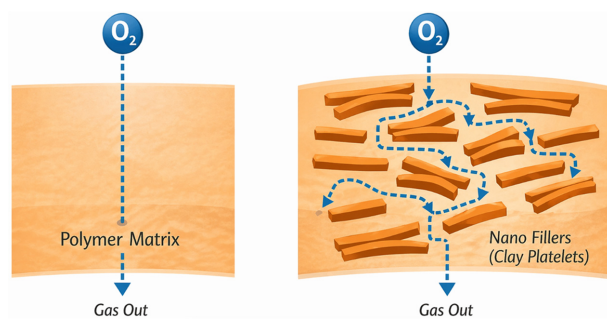


Fig. 1. Tortuous path mechanism in mono polymer matrix and nanocomposite system.

Table 1. Barrier properties of representative major film systems

Material	OTR (cc/m ² ·day)	WVTR	Strengths	Limitations
PE/PP	> 2000	Low	Moisture barrier	Poor O ₂ barrier
EVOH	< 1 (dry)	High	Excellent O ₂ barrier	Moisture sensitivity
Nanocellulose	< 10 (dry)	High	Renewable, high O ₂ barrier	Humidity sensitivity
Nanocomposites	10-100	Moderate	Tunable performance	Dispersion issues
SiOx/AlOx	< 1	Low	Ultra-high barrier	Cracking, adhesion

molecular interactions⁶.

Fig. 1 shows the tortuous path mechanism in mono polymer matrix and nanocomposite system. Hydrophobic polymers such as polyethylene exhibit relatively high oxygen permeability due to their non-polar structure and weak intermolecular forces. Siracusa reported that the high free volume in polyolefins facilitates oxygen diffusion, resulting in poor barrier performance². In contrast, hydrophilic polymers such as cellulose form dense hydrogen-bonded networks, significantly restricting molecular transport.

The nanostructured materials can reduce oxygen permeability by up to two orders of magnitude compared to conventional polymers, approaching the performance of EVOH under controlled conditions^{5,7}. However, persistent challenges including humidity sensitivity⁴, coating brittleness⁸, and scalability limitations remain unresolved.

Aulin et al. demonstrated that cellulose nanofibril (CNF) films exhibit extremely low oxygen permeability under dry conditions, comparable to high-performance synthetic barriers³. This behavior is attributed to the highly ordered fibrillar structure and strong intermolecular hydrogen bonding. Similarly, Lavoine et al. reported that nanocellulose coatings significantly reduce oxygen transmission when applied to porous substrates such as paper⁷.

Nanocomposite systems further enhance barrier properties through the tortuous path mechanism⁹. Bharadwaj showed that high aspect ratio fillers, such as nanoclays and graphene oxide, increase the effective diffusion path length, thereby reducing permeability¹⁰. However, experimental studies indicate that this mechanism is highly sensitive to filler dispersion. Sorrentino et al. reported that agglomeration of nanofillers leads to defect formation, which can negate barrier improvements⁵. These findings highlight that barrier performance is not solely determined by material composition, but also by structural organization and processing conditions.

Quantitative Barrier Performance and Trade-offs

The barrier properties of representative major film systems are shown in Table 1. Quantitative comparison of barrier performance across different material systems reveals a fundamental trade-off that defines the field. Polyolefins such as PE

and PP exhibit oxygen transmission rates (OTR) typically exceeding 2000 cc/m²-day, making them unsuitable for oxygen-sensitive applications²). However, they provide excellent moisture barrier properties due to their hydrophobic nature. In contrast, EVOH exhibits OTR values below 1 cc/m²-day under dry conditions, positioning it as a benchmark material for high-barrier applications¹¹). However, multiple studies have demonstrated that EVOH loses its barrier performance under high humidity conditions. Blanchard et al. reported that oxygen permeability increases significantly at relative humidity above 70%, due to plasticization effects¹²).

Nanocellulose-based materials exhibit similar behavior. Lavoine et al. reported OTR values below 10 cc/m²-day under controlled humidity conditions⁷), while Hubbe et al. demonstrated that permeability increases by more than an order of magnitude at high humidity⁴). This phenomenon is attributed to water-induced swelling and disruption of hydrogen bonding networks. Nanocomposite systems offer a potential solution to this trade-off. Sorrentino et al. reported that polymer–clay nanocomposites can reduce oxygen permeability by up to 90% without significantly compromising moisture resistance⁵). However, achieving consistent performance requires precise control of filler dispersion and orientation.

Overall, these results indicate that no single material system currently provides optimal performance under all conditions. Instead, hybrid systems combining multiple strategies are required to balance oxygen and moisture barrier properties.

Mono-material Systems: Recyclability vs Barrier Performance

The structures of multi-layer and mono-layer based barrier

films are shown in Fig. 2. High-barrier multi-layer films possess barrier properties but present environmental issues due to the difficulty of recycling. Therefore, mono-material packaging has recently emerged as a primary strategy for improving recyclability in flexible food packaging. Polyethylene (PE) and polypropylene (PP)-based systems are particularly attractive due to their compatibility with existing recycling infrastructures. However, their inherently poor oxygen barrier properties remain a critical limitation.

Recent studies have attempted to improve barrier performance through structural modification. Blanchard et al. reported that biaxially oriented polyethylene (BOPE) exhibits reduced oxygen permeability compared to conventional PE due to increased crystallinity and molecular orientation¹²). Similarly, Niaounakis highlighted that density and crystallinity directly influence gas diffusion by reducing free volume¹³). However, these improvements are incremental and insufficient for applications requiring long shelf life.

To overcome this limitation, coating and deposition technologies have been widely integrated into mono-material systems. Currently, the EU, the US, and Korea define and manage films as mono-materials that do not pose recycling issues if the heterogeneous material constitutes 5 wt% or less of the total film. For example, if the typical film thickness of retort food packaging is 120 to 200 μm or more, and the heterogeneous high-barrier coating layer is 5 wt% (equivalent to 6 to 10 μm in thickness) or less, it can be recycled as a mono-material. Li et al. demonstrated that thin SiO_x coatings deposited on PE substrates can reduce oxygen transmission rates (OTR) to below 1 cc/m²-day, approaching EVOH-level performance¹⁴). AlO_x coatings have also shown comparable results, with additional advantages in optical transparency.

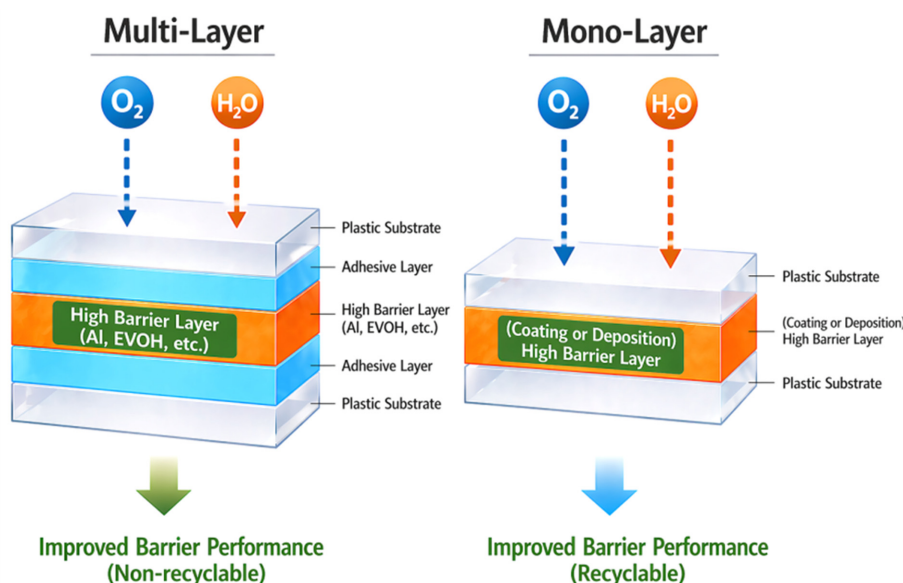


Fig. 2. Structure of barrier films: Multi- vs Mono-layer film.

Despite these promising results, mechanical reliability remains a major concern. Langowski reported that inorganic coatings are highly brittle and prone to micro-crack formation under flexural stress⁸). These cracks act as preferential diffusion pathways, leading to rapid degradation of barrier performance. Furthermore, adhesion between inorganic coatings and polymer substrates is often weak, requiring surface treatments such as plasma activation.

More importantly, the long-term recyclability of coated mono-material systems remains unresolved. While ultra-thin coatings may not significantly affect recycling processes, their accumulation and potential contamination effects have not been fully evaluated. Therefore, mono-material systems with coatings represent a partial solution, but not a definitive replacement for multi-layer structures.

Natural Materials: Nanocellulose as a High-Barrier Benchmark

Nanocellulose has become the most extensively studied bio-based material for high-barrier applications due to its exceptional oxygen barrier properties¹⁵). Its performance is primarily attributed to its nanoscale fibrillar network and strong hydrogen bonding interactions, which create a dense and highly ordered structure. Aulin et al. demonstrated that cellulose nanofibril (CNF) films exhibit oxygen permeability comparable to EVOH under dry conditions³). Lavoine et al. further showed that nanocellulose coatings can significantly improve the barrier properties of paper substrates, making them promising candidates for fiber-based packaging⁷).

However, a critical limitation consistently reported across studies is moisture sensitivity. Hubbe et al. demonstrated that water uptake leads to swelling of the nanocellulose network, increasing free volume and disrupting hydrogen bonding⁴). As a result, oxygen permeability increases dramatically at relative humidity above 70%. Similar observations were reported by Fotie et al., confirming that humidity is the dominant factor limiting the practical application of nanocellulose¹⁶). Several strategies have been proposed to address this issue. Chemical modification, such as acetylation or surface grafting, has been shown to reduce hydrophilicity⁷). However, these modifications often reduce the density of hydrogen bonding, leading to a trade-off between moisture resistance and barrier performance.

Alternatively, multi-layer systems combining nanocellulose with hydrophobic polymers have demonstrated improved stability under humid conditions. However, such approaches introduce complexity and may compromise recyclability, which contradicts the primary goal of sustainable packaging. Compared to other natural materials such as starch and chitosan, nanocellulose consistently exhibits superior oxygen barrier performance¹⁷). However, its sensitivity to environmental

conditions still remains a major obstacle to industrial application. Recent studies on improving barrier properties and sustainability of other biodegradable materials besides nanocellulose are summarized in Table 2.

Nanocomposite Systems: Bridging Performance Gaps

Nanocomposite systems have been extensively studied as a means of enhancing barrier properties while maintaining processability and mechanical performance. The incorporation of nanoscale fillers introduces a tortuous diffusion pathway, significantly increasing the effective path length for gas molecules (Fig. 1). Bharadwaj provided a theoretical model describing this effect, showing that permeability decreases as a function of filler aspect ratio and volume fraction. Experimental validation has been reported in numerous studies¹⁰). For example, Sorrentino et al. demonstrated that polymer-clay nanocomposites can reduce oxygen permeability by up to 90% when fillers are well dispersed⁵). Graphene oxide has also attracted significant attention due to its impermeable structure and high aspect ratio. Cui et al. reported that graphene-based nanocomposites exhibit superior barrier performance compared to conventional nanoclays, even at low loading levels³²).

However, the effectiveness of nanocomposites is highly dependent on filler dispersion. Hubbe et al. emphasized that agglomeration of nanofillers leads to defect formation, which can significantly reduce barrier performance⁴). This issue becomes particularly critical during scale-up, where achieving uniform dispersion is more challenging. Furthermore, the addition of nanofillers can affect mechanical properties and processability. High filler loading may lead to increased brittleness, while processing techniques such as extrusion may not be compatible with certain nanomaterials.

Nanocomposites also raise concerns regarding energy consumption. While bio-based fillers such as cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs) are often considered environmentally favorable due to their renewable origin, their pilot-scale manufacturing processes can be highly energy-intensive. For instance, the mechanical fibrillation process used to produce nanocellulose typically requires energy inputs in the range of 10,000–30,000 kWh per ton, depending on the degree of fibrillation and pretreatment conditions³³). Chemical pretreatments such as TEMPO-mediated oxidation³⁴) or enzymatic hydrolysis can reduce energy demand. However, they introduce additional environmental burdens associated with chemical consumption, wastewater treatment, and process complexity. Furthermore, the overall environmental impact of nanocomposites is highly dependent on filler loading and dispersion efficiency. In cases where high filler loadings are required to achieve significant barrier improve-

Table 2. Recent applications of other biodegradable films for sustainable food packaging⁹⁾

Case	Biodegradable film matrix	Metal oxide nanoparticle	Findings	Impact on gas permeability	Novelty
Fe ₂ O ₃ -PLA Nano-composite for Bakery Packaging	Polylactic Acid (PLA)	Iron Oxide (Fe ₂ O ₃)	Improved preservation of bread by reducing mold growth	Reduced oxygen permeability by 27%	First-time integration of Fe ₂ O ₃ in PLA for bakery applications ¹⁸⁾
CeO ₂ -Alginate Films for Seafood Storage	Alginatebased film	Cerium Oxide (CeO ₂)	Enhanced antioxidant activity, delaying lipid oxidation in fish	Oxygen permeability lowered by 22%	Novel use of CeO ₂ to prevent oxidation in fatty seafood ¹⁹⁾
CuO-Chitosan Film for Fresh Produce	Chitosan	Copper Oxide (CuO)	Improved antimicrobial protection against foodborne pathogens	Gas permeability decreased by 38%	Innovative active packaging solution for fresh-cut fruits and vegetables ²⁰⁾
ZnO-Gelatin-Based Film for Poultry Packaging	Gelatin-based film	Zinc Oxide (ZnO)	Increased shelf life by reducing bacterial contamination	33% decrease in oxygen permeability	Application of ZnO in gelatin for protein-rich food preservation ²¹⁾
TiO ₂ -Soy Protein Film for Snack Packaging	Soy protein-based film	Titanium Dioxide (TiO ₂)	Enhanced UV resistance and mechanical stability	Oxygen barrier improved by 24%	Pioneering use of TiO ₂ in plant-based protein films ²²⁾
MgO-Polysaccharide Film for Dairy Preservation	Polysaccharide-based film	Magnesium Oxide (MgO)	Maintained sensory quality of cheese and yogurt packaging	Water vapor permeability reduced by 35%	New biodegradable application targeting dairy storage ²³⁾
ZnO-Protein-Iso-late Film for Frozen Foods	Protein isolate-based film	Zinc Oxide (ZnO)	Strengthened mechanical properties and frost resistance	30% reduction in gas permeability	Novel protein-isolate integration for frozen food packaging
CeO ₂ -Starch-Based Film for Dry Snack Packaging	Starch-based biodegradable film	Cerium Oxide (CeO ₂)	Improved resistance to oxidation and extended shelf life	Oxygen permeability decreased by 28%	First reported use of CeO ₂ in starch films for dry goods ²⁴⁾
Al ₂ O ₃ -PLA Biodegradable Coating for Beverages	PLA-based coating	Aluminum Oxide (Al ₂ O ₃)	Increased durability and moisture resistance for liquid packaging	Gas permeability lowered by 31%	Unique application of Al ₂ O ₃ for sustainable beverage packaging ²⁵⁾
TiO ₂ -Pectin Nano-composite for Fresh-Cut Vegetables	Pectin-based matrix	Titanium Dioxide (TiO ₂)	Improved transparency, UV protection, and antimicrobial efficacy	Reduced oxygen permeability by 26%	New approach using TiO ₂ for minimally processed vegetable packaging ²⁶⁾
NiO-CuO-PVA/Starch/Chitosan Film for Food Packaging	Polyvinyl Alcohol (PVA)/Starch/Chitosan	Nickel Oxide (NiO) and Copper Oxide (CuO)	Improved antibacterial activity against foodborne pathogens	Significant reduction in gas permeability	Novel incorporation of NiO-CuO for active food packaging applications ²⁷⁾
Eggshell-Derived Hydroxyapatite-Chitosan Bionano-composite	Chitosan	Hydroxyapatite (HAp) from eggshell	Improved mechanical strength and barrier properties	Enhanced barrier against oxygen and moisture	Sustainable use of eggshell-derived nanoparticles for biodegradable packaging ²⁸⁾
Ni-Zn Ferrite-Chitosan Green Films	Chitosan	Nickel-Zinc Ferrite (Ni-ZnFe ₂ O ₄)	Enhanced mechanical properties and gas barrier due to natural juice synthesis	Reduced water vapor permeability	Green synthesis approach using natural juice as a reducing agent ²⁹⁾
Zn Ferrite-Chitosan Film with Natural Acids	Chitosan	Zinc Ferrite (ZnFe ₂ O ₄)	Improved water resistance and mechanical strength	Decreased solubility and gas permeability	Environmentally sustainable approach to chitosan film synthesis ³⁰⁾
NiO-Gelatin/Chitosan Active Packaging	Gelatin/Chitosan	Nickel Oxide (NiO)	Antimicrobial and improved barrier properties for food applications	Enhanced oxygen and water vapor barrier	Combination of NiO with gelatin/chitosan for active packaging ³¹⁾

ment, the cumulative energy demand and processing complexity can offset the environmental benefits associated with bio-based materials. For example, poorly dispersed nanocellulose or graphene oxide can lead to agglomeration, necessitating additional processing steps such as ultrasonication or high-shear mixing, which further increase energy consumption.

Therefore, it is necessary to evaluate the overall environmental benefits of nanocomposites through a full life cycle assessment.

Coating Technologies: Toward Industrial High-Barrier Solutions

Coating technologies represent one of the most advanced approaches for achieving high barrier performance in food packaging. Currently, inorganic coatings such as silicon oxide (SiOx) and aluminum oxide (AlOx) have been widely adopted in commercial applications (Fig. 3). These coatings are typically deposited using vacuum-based processes such as physical vapor deposition (PVD) or plasma-enhanced chemical vapor deposition (PECVD), which are already established at the industrial scale with high throughput and roll-to-roll compatibility. Li et al. reported that SiOx coatings can achieve oxygen transmission rates below 1 cc/m²-day, making them comparable to EVOH¹⁴). Similarly, AlOx coatings provide excellent barrier performance with improved optical clarity and process compatibility.

From an industrial perspective, one of the key advantages of inorganic coatings is their ability to be integrated into existing converting lines without fundamentally altering the base polymer structure. This makes them particularly attractive for mono-material packaging systems, where thin coatings can provide barrier enhancement without significantly compromising recyclability. However, these coatings are not without limitations. Langowski highlighted that inorganic coatings are inherently brittle and susceptible to cracking under mechanical stress⁸). This issue is particularly problematic for flexible

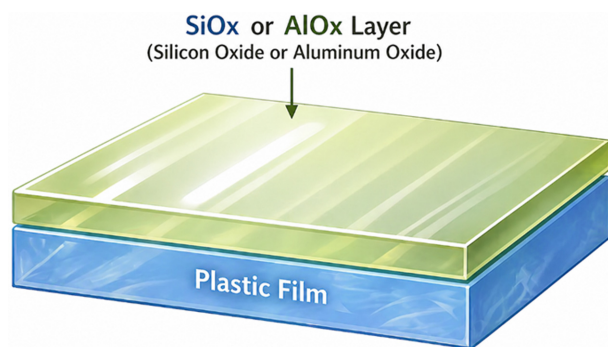


Fig. 3. Schematic illustration of inorganic SiOx/AlOx coating or deposited film for high-barrier packaging.

packaging, where repeated bending and handling are unavoidable. In addition, coating defects such as pinholes and non-uniform thickness can significantly affect barrier performance. Advanced deposition techniques, such as atomic layer deposition (ALD), have been proposed to address these issues by enabling precise control over film thickness. However, their high cost limits industrial applicability.

Bio-based coatings, including polysaccharides and proteins, have also been explored as sustainable alternatives. While these materials provide excellent oxygen barrier properties under dry conditions, their performance deteriorates under humid conditions, similar to nanocellulose¹⁷). As a result, their use is currently limited to dry food applications or requires additional protective layers. To address these limitations, recent research has focused on hybrid coating systems combining inorganic and organic layers. These systems aim to achieve both high barrier performance and mechanical flexibility. Nevertheless, challenges related to scalability, interlayer adhesion, process complexity, and cost remain significant barriers to commercialization. Therefore, future industrial implementation will depend not only on achieving high barrier performance, but also on ensuring cost-effective, scalable manufacturing processes and compatibility with existing recycling infrastructures.

Paper-Based and Fiber-Based Hybrid Systems

The transition toward fiber-based packaging has accelerated in recent years, driven by both regulatory pressure and consumer demand for plastic-free alternatives. Paper and paperboard offer inherent advantages in terms of recyclability and biodegradability, making them attractive substrates for sustainable packaging systems. However, paper-based materials exhibit poor intrinsic barrier properties against oxygen, moisture, and grease. To address these limitations, recent research has focused on hybrid systems combining paper substrates with functional coatings. Herrera et al. demonstrated that nanocellulose coatings significantly improve the oxygen barrier properties of paper, achieving oxygen transmission rates comparable to synthetic high-barrier materials under controlled conditions³⁵). Similarly, Ferrer et al. reported that combining nanocellulose with biopolymer coatings can further enhance barrier performance³⁶).

Despite these advances, moisture barrier performance remains a critical limitation. The hydrophilic nature of cellulose-based materials leads to rapid degradation of barrier properties under humid conditions. To mitigate this issue, multilayer coatings incorporating hydrophobic polymers such as polyethylene or wax-based coatings have been explored. However, such hybrid systems introduce trade-offs in recyclability. While paper-based systems are inherently recyclable,

the addition of polymer coatings may complicate recycling processes. Therefore, optimizing the balance between barrier performance and recyclability still remains a key research challenge.

Industrial Challenges and Scale-Up Limitations

Although significant progress has been achieved at the laboratory scale, the translation of high-barrier sustainable materials into industrial applications remains limited due to a combination of interrelated technical and economic challenges. These limitations can be broadly categorized into three key barriers: cost competitiveness, processing compatibility, and performance reliability under real-world conditions.

First, cost remains one of the most critical barriers to industrial adoption. Nanomaterials such as nanocellulose and graphene oxide are inherently more expensive than conventional petroleum-based polymers due to their energy-intensive production processes. Lavoine et al. emphasized that large-scale production of nanocellulose requires substantial energy input during fibrillation and drying stages, significantly increasing production costs⁷⁾. In addition, upstream processing steps, including chemical pretreatment and purification, further contribute to the overall cost structure. As a result, despite their superior barrier properties, these materials often fail to meet the strict cost-performance requirements of the packaging industry, where margins are typically low and material cost is a dominant factor.

Second, processing compatibility presents a major technological bottleneck. Many high-performance barrier materials rely on laboratory-scale fabrication techniques such as solvent casting, layer-by-layer assembly, or vacuum-based deposition methods, which are not easily scalable or compatible with existing industrial processing technologies. In contrast, conventional packaging materials are produced using highly optimized and continuous processes such as extrusion, co-extrusion, and lamination, which offer high throughput and cost efficiency. The integration of advanced materials into these established production systems often requires significant modification of equipment or processing conditions, creating additional barriers to industrial implementation.

Third, performance stability under real-world conditions represents a critical gap between laboratory results and practical applications. Barrier performance is typically evaluated under controlled temperature and humidity conditions, which do not accurately reflect the complex environments encountered during storage, transportation, and consumer use. Hubbe et al. reported that nanocellulose-based materials exhibit significant degradation in barrier performance under high humidity due to swelling and disruption of hydrogen bonding networks⁴⁾. Similarly, inorganic coatings are prone to mechan-

ical damage such as cracking and delamination under flexural stress, leading to rapid loss of barrier functionality. These findings highlight that long-term durability and environmental stability are as important as initial barrier performance for industrial adoption.

Importantly, these challenges are not independent but strongly interconnected. For example, improving barrier performance often requires increased material complexity or additional processing steps, which can further increase cost and reduce recyclability. Likewise, strategies aimed at improving moisture resistance, such as multilayer structures or hybrid coatings, may compromise processing simplicity and circularity. Therefore, the key challenge in advancing sustainable high-barrier packaging lies in achieving an optimal balance among performance, cost, processability, and sustainability. Bridging this gap requires not only material innovation but also system-level integration, including scalable manufacturing technologies, cost reduction strategies, and compatibility with existing recycling infrastructures.

Sustainability and Life Cycle Assessment (LCA)

Sustainability considerations have become a central aspect of packaging material development. Life cycle assessment (LCA) is widely used to evaluate the environmental impact of different packaging systems. Geueke et al. reported that mono-material packaging systems generally exhibit lower environmental impact compared to multilayer structures due to improved recyclability¹⁾. Similarly, fiber-based systems offer advantages in terms of biodegradability and renewable sourcing. However, trade-offs between performance and sustainability must be carefully considered. For example, while nanocomposites improve barrier performance, their production processes may be energy-intensive. Likewise, coating technologies may introduce materials that complicate recycling processes. Recent studies emphasize the importance of a holistic approach, considering the entire life cycle of packaging materials, including raw material sourcing, processing, use phase, and end-of-life management.

Conclusions

Over the past decade, significant progress has been made in the development of sustainable high-barrier food packaging materials. Mono-material systems and natural materials offer promising alternatives to conventional multilayer plastics. However, no single material system currently satisfies all performance requirements. Polyolefins provide excellent moisture resistance but poor oxygen barrier, while natural materials such as nanocellulose exhibit the opposite behavior. Nanocomposites and coating technologies offer potential solutions,

but challenges related to scalability, cost, and durability remain. Future research should focus on addressing the key limitations identified in current systems. One promising direction is the development of moisture-resistant bio-based materials. One promising direction is the development of moisture-resistant bio-based materials. Advances in chemical modification and hybrid structures may enable improved stability under humid conditions. Additionally, scalable processing techniques for nanocomposites must be developed to facilitate industrial application. Ultimately, hybrid strategies integrating multiple material approaches are required to achieve high barrier performance while maintaining sustainability. Furthermore, bridging the gap between laboratory research and industrial implementation remains the most critical challenge for the field.

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