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Environmental Sustainability, Food Quality and Convertibility of Bio-Based Barrier Coatings for Fibre-Based Food Packaging: A Semisystematic Review

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Keywords: barrier coating | bio-based coatings | biopolymers | dispersion coating | fibre-based packaging | life-cycle assessment | sustainable packaging

ABSTRACT

The ongoing legislative drive to reduce plastic consumption and promote the circularity of materials in Europe is reshaping food packaging market dynamics and making sustainability a key competitive factor in the sector. Legislation accelerates research and innovation in bio-based, biodegradable and recyclable alternatives and motivates the industry to adopt sustainable designs while enhancing compliance with environmental standards. Renewable and natural resource-based materials, such as polysaccharides, nanocellulose, lignin, lipids, phenolic compounds and proteins, have been extensively investigated in the last decade. Their use in dispersion coatings and biopolymer compounds for paper and paperboard barriers is often referred to as a sustainable packaging solution. This semisystematic review compiled available quantitative and qualitative data on the environmental sustainability, food quality and convertibility of novel bio-based barrier coatings for food packaging. The results highlight a research gap in assessing environmental performance and the overuse of the term 'sustainable' and 'biodegradable'. However, convertibility and film formability issues remain major obstacles that must be overcome before the scaling up of production of such coatings. Although bio-based coatings demonstrate potential to extend the shelf life of certain fruits and mushrooms compared with uncoated paper or paperboard, numerous studies lack direct comparisons with conventional packaging methods. Further exploration of these aspects will facilitate science- and data-driven innovation and decision-making in industry, policy and academia in the development of sustainable bio-based packaging.

1 | Introduction

Paper and paperboard packaging constitute one-third of the global market for packaging materials [1]. They are also the most recycled packaging material in Europe, with approximately 82%–83% of all fibre-based packaging being recycled in 2021 [2, 3]. Metals and glass reached a 75% recycling rate while only 40%–41% of plastic packaging was recycled. The biological origin and high recycling rate of fibre-based packaging contribute to its reputation as a sustainable material, making it appealing to businesses and consumers seeking alternatives to plastic packaging.

The primary roles of packaging include product preservation, brand presentation, information provision and product life expansion. It protects the product from any chemical, biological, environmental or physical damage during transport and storage. However, fibre-based packaging has several drawbacks, including its propensity to absorb water, high oxygen permeability and low grease resistance. These limitations prevent the use of such packaging in applications requiring direct product contact with a high water content or greasy and oily foods. These applications necessitate the use of one or more barrier layers. Conventionally, polymers derived from fossil fuels are utilized for this purpose. However, in contrast to fibre-based substrates to which coatings are applied, most fossil fuel–based plastics do not biologically degrade in the environment. Furthermore, they make the paper-recycling process more challenging and increase recycling costs [1, 4]. In countries lacking a developed recycling infrastructure, this packaging typically undergoes incineration, landfilling or even direct discharge into the environment.

Recently, there has been an increase in the demand for packaging circularity. This demand originates from both consumers [5, 6] and new legislation, such as the Single-Use Plastics Directive (EU 2019/904) [7], the EU Green Deal [8], EU Taxonomy [9] and Packaging and Packaging Waste Regulation [10] (currently pending final approval from the European Council). This legislation includes ambitious recycling targets, stricter regulations on single-use plastics and support for transitioning to a circular economy.

The transition from fossil- to bio-based materials, including biopolymers, natural fibre-reinforced composites and nanocomposites for barrier packaging, has been the primary focus of recent research and development in the fibre-based packaging industry [1, 4, 11–15]. These novel renewable materials must fulfil the criteria for food packaging and ensure sustainability throughout their life cycle. In contrast to plastic films that serve as barrier coatings on fibre-based packaging, these bio-based materials can improve packaging recyclability and compostability while effectively integrating into existing waste management streams.

Several review articles have focused on the trends in bio-based coatings in food packaging for sustainable development [1, 4, 16], biodegradability [12, 17] and improvements to barrier properties [18–20]. Despite the rapidly evolving field of bio-based materials for coatings on food packaging, the research focus has primarily been on the formulation of coatings and barrier properties testing prior to conversion, whereas there is a lack of studies on the changes in barrier properties resulting from the conversion process. To the best of our knowledge no published review article has systematically reviewed the preservation of real foods packaged in such materials through food quality and shelf-life assessments. Additionally, a lack of systematic studies on the environmental assessment of such barrier coatings has been identified, hampering conclusions on their environmental sustainability. These studies indicate that convertibility, preservability and environmental parameters are essential for further technology development and decisions on its enhancement.

This semisystematic review applies the life-cycle thinking approach to review research papers on less-studied topics and identify knowledge gaps regarding sustainable bio-based barrier-coated fibre-based food packaging. First, the purpose of this review was to identify quantitative data on standardized life-cycle assessments (LCAs) and to examine the criteria to justify why developed barrier solutions have been described as sustainable in previous studies. LCA, biodegradability, compostability and recyclability tests are necessary to assert that packaging is truly environmentally sustainable [21]. Second, studies on the film formability of bio-based coatings and their convertibility properties were reviewed. Surface integrity and convertibility tests are critical for food packaging development because they affect the final barrier properties and demonstrate the feasibility of applying coatings in an industrial setting. Third, as the main goal of packaging is to preserve packaged food, studies evaluating the ability of packaging materials to maintain the quality and shelf life of food products during storage were reviewed. Figure 1 illustrates the interrelationship between decisions at each stage of the packaging life cycle and their collective influence on the overall environmental impact of packaging and highlights the focus of this review paper. Notably, intelligent packaging was not included in this study.

The review paper seeks to answer the following questions:

1. What criteria and assessment methods are commonly used in research papers to determine the sustainability of bio-based coatings?
2. What film forming and convertibility issues currently limit bio-based coatings from wider application?
3. How suitable are fibre-based materials with bio-based coatings to meet the protection and preservation requirements set for foods?

The remainder of this paper is structured as follows. Section 2 discusses the context of food packaging sustainability, exploring the diversity of biopolymers and their properties. We also delve into the topics of food quality, shelf life and safety, as well as the functional requirements of food packaging to ensure these attributes. In Section 3, a semisystematic review method and review of the inclusion criteria are described. Sections 4–6 present the results of the analysis and identify the knowledge gaps in the topics covered. Section 7 describes remarks on limitations, and Section 8 outlines the main conclusions.

2 | Conceptual Framework

2.1 | Packaging Sustainability

The terms ‘green’, ‘eco-friendly’, ‘bio-based’, ‘biodegradable’ and ‘sustainable’ are frequently interchangeably used to describe products or packaging despite their distinct meanings. Although ‘green’ is a popular term, its definition remains ambiguous. Similar to the term ‘eco-friendly’, it can be inferred that this term refers to a product that is both environmentally safe and has few environmental impacts. The European Commission defines bio-based products as products derived fully or partially from renewable biomass resources [22].

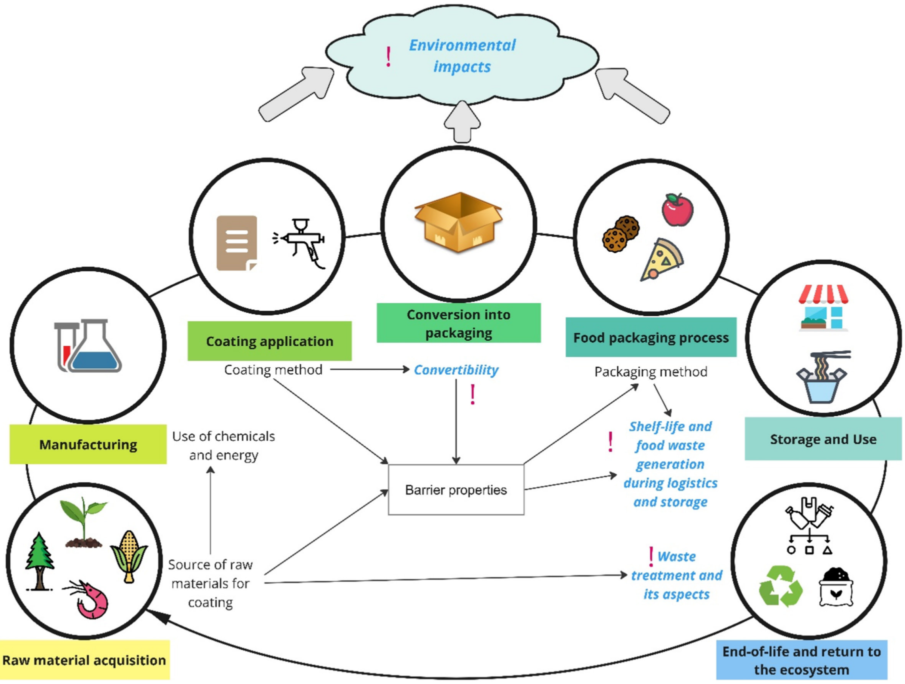

FIGURE 1 | Life cycle of bio-based coatings for fibre-based food packaging. This figure illustrates the stages from raw material acquisition to end-of-life return to the ecosystem, highlighting the interconnections and environmental impacts of decisions at each stage. Research gaps are marked with exclamation marks and blue text, which this review aims to address.

While the term 'bio-based' solely refers to the origin of the material, 'biodegradability' refers to the ability of a material to be broken down naturally by microorganisms. However, the bio-based origin of a material does not imply its biodegradability and does not characterize the overall environmental impact of the product.

Sustainability encompasses more than merely environmental considerations. Sustainable products or packaging improve sustainability across three key pillars: environmental, social and economic [23]. The two most established definitions of sustainable packaging have been developed by the Sustainable Packaging Alliance (SPA) in Australia [24] and the Sustainable Packaging Coalition (SPC) in the United States [25].

The SPA suggests considering the entire life cycle of packaging design, from the raw material used to its disposal. The SPA defines sustainable packaging as packaging that encompasses the following four principles. (1) To be effective: 'reduce product waste, improve functionality, prevent overpackaging, reduce business costs, and achieve a satisfactory return on investment'. (2) To be efficient: 'improve product/packaging ratio, improve energy, material, and water efficiency, increase recycled content, and reduce waste to landfill'. (3) To be cyclic: 'returnable, reusable, recyclable, and biodegradable'. (4) To be clean: 'reduces airborne, waterborne, and greenhouse gas emissions, reduces toxicity and litter impacts' [23]. The SPC definition is similar, except that it highlights the optimal use of renewable energy and materials [26].

Sustainable packaging design encompasses the triple bottom line, which consists of people, planet and profits (3Ps) [27]. Additionally, it incorporates packaging and product as two additional Ps [28, 29]. This stems from the idea that sustainability cannot be achieved solely through packaging, but rather through a combination of the packaging and the product itself. As food packaging exists to protect food, preserve quality and ensure the necessary shelf life, its functional properties are crucial. Figure 2 shows the sustainability criteria specific to a food packaging-product system [30]. When striving for the use of more environmentally friendly, biodegradable and renewable materials, packaging functionality should not be compromised. Reducing the environmental impact at one stage risks shifting the burden to another; for example, by decreasing the preservation properties of packaging, there is a risk of increasing food waste. This consequently has environmental, economic and social repercussions.

Sustainable packaging design is complex and multidisciplinary. Decisions taken during the design phase impact the composition of the packaging, its compatibility with different food products, the lifespan of the packaging material, the required shelf life of the food product, the recommended storage conditions and the fate of the packaging at the end-of-life (EoL) stage. Up to 80% of the environmental impacts of packaging products are determined by decisions made during the design phase [31, 32]. Moreover, sustainable solutions may differ between developed and developing countries. European countries generally favour circular and recyclable product design, whereas sub-Saharan African countries may prioritize biodegradability due to the inadequate disposal of 80%–90% of plastic waste in these countries [33].

LCA has emerged as an effective and predominant quantitative standardized method (ISO 14040 and 14044) for assessing the potential environmental impacts [34, 35] of different products

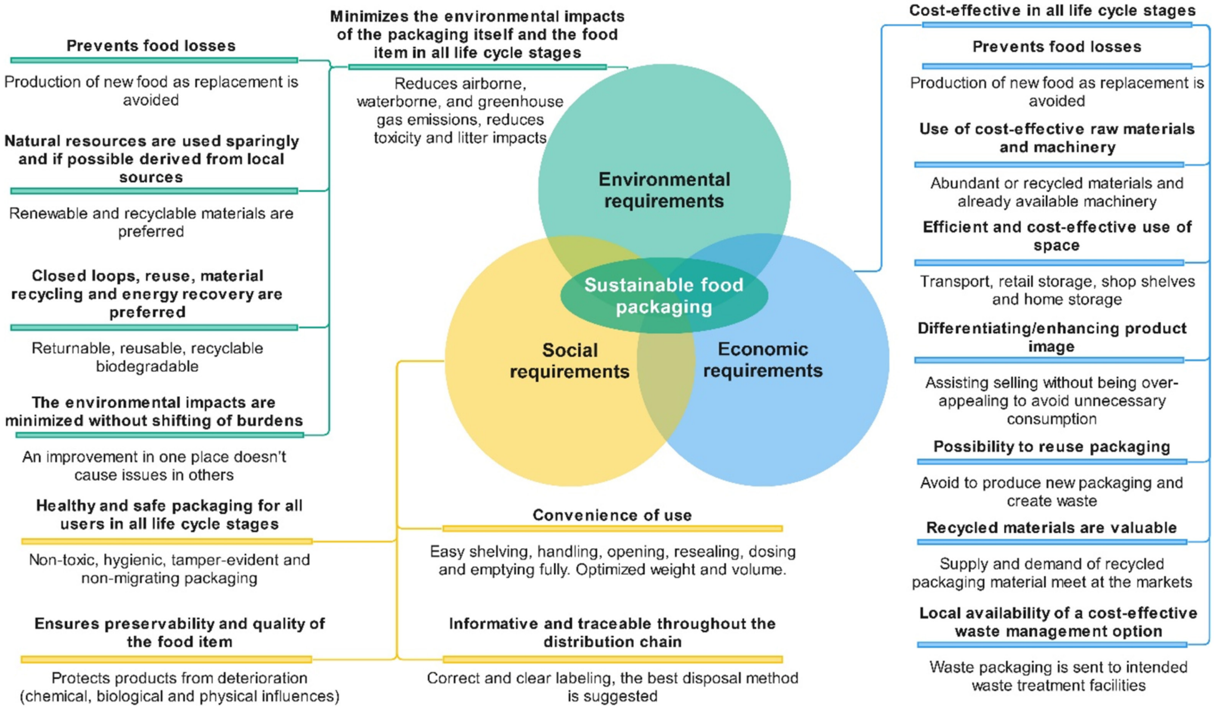

FIGURE 2 | Requirements for sustainable food packaging. Adapted with permission [30].

and services over their entire lifespan. During the early design phase, a streamlined or simplified LCA is often applied [36–39] to define the environmental hotspots of a specific product. In contrast, a more detailed full LCA is usually conducted once the product has been validated. In addition to environmental assessment, life-cycle costing (LCC), which includes all costs incurred during the lifespan of a product [40, 41], can be applied to fully understand the economic consequences of design choices. Both tools assist in making well-informed decisions during the product development process [42]. Environmental and economic indicators are typically easier to quantify than social indicators, such as labour conditions, human rights, democratic participation and fair trade [43]. However, the relatively new social LCA (S-LCA) method [44] aims to address this challenge and can also be applied to the packaging sector [45].

Standardized testing is required to classify the packaging as biodegradable. Multiple biodegradability standards exist from international (e.g., ISO, ASTM and CEN) and national (e.g., DIN in Germany) standardization bodies [46]. The European Committee for Standardization (CEN) has established that biodegradable material undergoes degradation into biomass, carbon dioxide, methane and water via the activity of microorganisms [47, 48]. Biodegradation tests should be selected based on different EoL scenarios, which can occur in different settings, such as compost, soil, freshwater and seawater environments [43].

Standards specifically designed for composting tests have more stringent requirements than those for biodegradation tests, particularly regarding the generated biodegradable products [46], heavy metal contents (European standard EN 13432 2000) and decomposition over time. They typically require conditions similar to those of industrial composting, with a specific temperature (58°C ± 2°C), humidity and aeration [46].

During the testing of new materials for barrier packaging coatings, the developer must ensure that the new barrier material does not pose any issues during paper recycling in paper mills and guarantees material circulation. The Fibre Box Association (FBA) Voluntary Protocol and the Confederation of European Paper Industries (CEPI) laboratory recyclability test methods are the two most commonly used recyclability test methods for paper and paperboard packaging in the United States and Europe, respectively [49]. For instance, the CEPI method replicates the most critical steps (pulping, screening and sheet formation) of a typical paper mill and allows for the evaluation of the quality of fibre separation, appearance of the formed sheets, level of rejection from screening and disruptive materials (adhesives, metals and plastic film), level of dissolved or colloidal solids and strength of the final product [49].

2.2 | Raw Materials and Building Blocks Used for Coating Components

The fabrication of packaging coatings involves the intricate integration of various raw materials and building blocks, each of which plays a crucial role in shaping the characteristics and capabilities of the final coating. This section focuses on biopolymers and biopolymer-based materials, including composites that incorporate biopolymer components.

2.2.1 | Biopolymers

Biopolymers are a class of polymers synthesized by living organisms, such as plants, animals and microorganisms, as depicted in Figure 3. In contrast to synthetic polymers derived from petrochemicals, biopolymers are derived from renewable

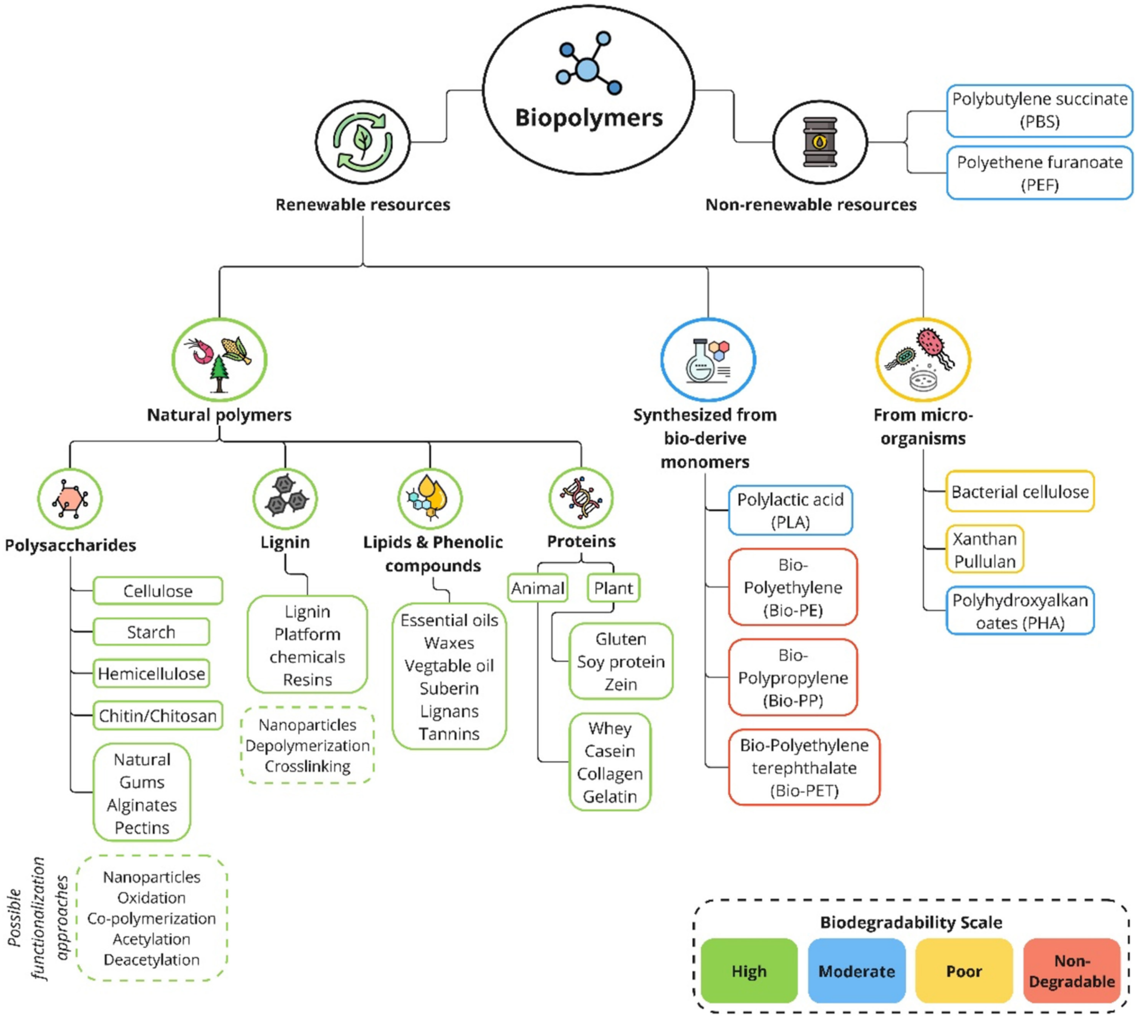

FIGURE 3 | Overview of biopolymers and their potential for functionalization and biodegradability level [4, 13, 50].

biological sources. This makes them viable alternatives for raw material utilization within the framework of a circular bioeconomy [51]. Biopolymers have garnered considerable interest owing to their remarkable properties, such as biocompatibility, biodegradability and the potential to substitute traditional plastics and materials derived from fossil fuels. Therefore, the versatility of biopolymers is evident in their utilization across several industries, including packaging, cosmetics, pharmaceuticals and textiles. However, the modification process is a key factor in incorporating biopolymers into bio-based materials. Various modification processes can substantially influence the characteristics of biopolymers, producing either biodegradable or non-biodegradable materials. Assessing biodegradability in the EoL phase is important for determining the environmental impact [52]. Moreover, it is possible to produce biodegradable synthetic bio-based polymers, such as polylactic acid (PLA) and polyethylene furanoate (PEF).

Lignocellulosic biomass consists of various biopolymers, namely, cellulose (40%–60%), hemicellulose (20%–40%) and lignin (10%–25%), and their relative proportions vary depending on the origin [53]. Cellulose is a linear homopolysaccharide chain that is composed of glucose units connected by β-(1,4)-glycosidic bonds. This creates a robust structure of fibrils, resulting in fibres that are highly versatile due to their strength, swelling capacity, flexibility and surface charge. Due to their widespread availability and low cost, they are considered ideal raw materials for paper and packaging, particularly in the context of food packaging applications. Furthermore, cellulose offers versatility by functioning as both substrates and coatings through targeted modifications [54, 55]. Nanocellulose refers to cellulose with microscale or nanoscale dimensions and can be divided into three nanocellulose categories: cellulose nanofibrils (CNFs), cellulose nanocrystals (CNCs) and bacterial cellulose (BC). CNCs and CNF are typically derived from pulp via a top-down approach, employing enzymatic, chemical or mechanical extraction techniques. In contrast, BC is produced through a bottom-up process, where bacteria synthesize it from low molecular weight sugars [56]. Nanocellulose structures have unique characteristics such as high surface area, improved mechanical properties and increased reactivity due to an increase in the number of hydroxyl groups, making them promising candidates for various types of food packaging technologies [54].

In contrast, hemicelluloses are amorphous polysaccharides containing various sugar units. They have a branched structure, linked by β-(1,4)-glycosidic bonds, consisting of pentoses, hexoses and uronic acids [57]. The specific constituents differ based on the plant source (e.g., glucomannans in softwoods and xylans in hardwoods). Their amorphous structure, in contrast to the crystalline nature of cellulose, renders them susceptible to chemical modifications. Lignin is the most prevalent aromatic polymer in nature and found in the secondary cell wall of plant cells. It acts as a natural composite material alongside cellulose and hemicellulose, improving plant strength and rigidity [58]. Moreover, lignin protects against various threats, including pathogens, insects and enzymatic hydrolysis. The lignin structure is a complex network formed by the biosynthesis of monolignols, which serve as precursors to lignin. The complex lignin network renders it highly resistant to degradation, owing to its aromatic and branched structure. The diverse characteristics of lignin make it promising for applications in numerous fields, including biocomposite materials and bio-based chemicals. Lignocellulosics may also contain other polysaccharides, such as starch, natural gums and chitin.

Starch serves as an energy reserve in plants and is composed of two primary polysaccharides: linear amylose and branched amylopectin. It is widely available in numerous plants, including potato, corn, rice and wheat [58]. Starch has wide-ranging applications in industries such as food, pharmaceuticals and paper production. In comparison, natural gums are predominantly composed of carbohydrates with minor amounts of proteins and fats. They originate from sources such as plant seeds, plant exudates, tree or shrub exudates, seaweed extracts and bacteria [59]. Natural gums have significant potential for modification to attain specific polymer characteristics owing to their desirable properties such as hydrophilicity, the ability to form highly viscous solutions and the capacity to create films through various intermolecular forces. In contrast, chitin is present in the exoskeletons of arthropods and the cell walls of fungi. Similar to cellulose in plants, chitin fulfils a similar role in providing structural support [58]. It consists of N-acetylglucosamine units linked by β-(1,4)-glycosidic bonds, resulting in a rigid and crystalline structure. Chitin exhibits low reactivity, insolubility and extensive hydrogen bonding, contributing to its rigidity and insolubility in common solvents. However, chitosan can be deacetylated to form chitosan, which possesses desirable properties such as enhanced solubility, degradability and biocompatibility.

Additionally, lignocellulosic biomass contains small amounts of pectin, extractives and inorganic components. Plant extracts contain various chemical constituents, such as terpenoids, phenolic compounds, alkaloids, glucosinolates and organic acids [60]. These compounds exhibit unique properties and biological effects. Essential oils are integral components of plant extracts that contribute to their antimicrobial and antioxidant properties, making them desirable in the food industry. Plant extracts serve as environmentally friendly preservatives, enhance food safety and extend shelf life. Their effectiveness stems from their distinct chemical structures, which offer a versatile means for enhancing food preservation.

2.2.2 | Composites

The qualities of packaging and coating applications can be enhanced by incorporating inorganic materials into bio-based components [61]. These inorganic constituents improve the strength, stiffness and toughness of the composites. Common additions consist of glass or carbon fibres to reinforce the composite, as well as fillers (e.g., calcium carbonate or talc) to increase the hardness, stiffness and dimensional stability [62]. Moreover, nanomaterials can be used to enhance the initially inadequate barrier properties of bio-based coatings [63]. Nanomaterials (1–100 nm) have experienced rapid development in various sectors [64]. For packaging applications, nanoscale proteins, lipids or polysaccharides (e.g., starch, chitosan and cellulose) can be introduced as nanofillers to reinforce polymer coatings and improve packaging performance [65]. Due to their natural origins and inherent properties (e.g., small size, high surface-to-volume ratio and superior reactivity), nanoparticles (NPs) can be used to develop biodegradable and biocompatible packaging that possesses enhanced water and gas-barrier properties and good mechanical strength.

2.3 | Coating Applicability and Convertibility

The use of untreated paper and paperboard in food packaging is limited due to the naturally porous structure of the materials, leading to easier permeation of substances, such as oil or water, into the material body [66, 67]. Therefore, improving the surface properties of paper and paperboard is imperative, and the use of barrier coatings represents one approach for achieving this goal [68]. Bio-based dispersion coatings are utilized to fill voids and cavities in paper structures to decrease the number of surface irregularities and reduce paper roughness and air permeability [66, 67, 69]. Appropriate coverage of fibre-based substrates via dispersion coatings eliminates paths for permeation or penetration into the material structure, which refers to the term ‘film formability’ [70]. Additionally, the coating formulations affect the physical properties of fibre-based materials. The characteristics are crucial for providing mechanical support for packaging under demanding conditions [66].

Following production, packaging material has the form of a ‘flat blank’, and it cannot be usually used for packaging until it is transformed into the final package. Further operations, collectively known as ‘converting’, aim to create boxes, sacks, trays or cups from material sheets or rolls and can impose high stresses upon the material surface [71]. During conversion operations, the coating applied to the substrate can be damaged, and the initial barrier properties may be lost [72, 73]. Therefore, a material is expected to possess a set of relevant properties to withstand the stress of the individual conversion processes.

For example, creasing and folding converting operations are often used to form fibre-based materials (e.g., Kirwan [74, p. 280]). Folding alone is required to produce flexible packaging, such as paper sacks or paper bags. Folding cartons, trays and liquid packages are made of thick paperboard, which must be creased to define folding lines and then folded [74]. The direct contact of the creasing rules with paperboard surfaces or the folding of paper-based coated materials over forming tools induces elongation, compression and shear forces in the material structure [74, 75]. Therefore, higher flexibility in the coated surface is preferred during creasing and folding operations, coupled with enhanced fibre structure elongation when the forming processes are considered [76, 77].

2.4 | Food Quality, Shelf Life and Safety

During transportation and storage, foods are exposed to a range of factors that can affect their quality and lead to spoilage, including gases, water, water vapour, light and microorganisms. The composition of foods, such as the water and fat content, as well as the microbial activity, may influence or contribute to different deterioration reactions that affect food quality. Therefore, different types of food have different packaging requirements.

2.4.1 | Microbiological Spoilage

Microbial growth often causes the spoilage of fresh and perishable foods, such as fish, meat and dairy products, due to their physiochemical qualities. The dominant spoilage bacteria can differ among different types of products. The packaging atmosphere influences microbial growth and can favour some bacteria over others [78]. This can result in unpleasant odours, depending on the microorganisms and their activities. The presence of CO_2 inhibits or delays the growth of gram-negative bacteria, such as Pseudomonas [79], whereas others are unaffected by the presence of CO_2, such as lactic acid bacteria [80]. Modified atmosphere packaging (MAP) is commonly used to delay microbial spoilage for a range of products.

2.4.2 | Oxidation

Oxidation is one of the most common chemical processes that causes food spoilage. The oxidation of lipids can result in volatile compounds that yield a rancid odour and flavour, whereas the oxidation of pigments can lead to undesired colour changes. Products with a high fat content are most vulnerable to lipid oxidation. The oxidation rate increases with the degree of unsaturated fatty acids [81] and is accelerated in the presence of catalysts, enzymes, light and high temperatures [82]. The formation of oxidation products and deterioration due to off-odours and flavours are highly affected by the packaging atmosphere. MAP can be used to provide anaerobic conditions and delay or reduce the potential for oxidation [83, 84].

The colour of food products is important for consumer evaluations of their freshness and quality; discoloration may lead to consumer rejection, thereby causing food waste [85]. The content and state of pigments in fresh meat are affected by the packaging atmosphere and are important for colour stability, particularly for red meat and fish [85, 86]. Processed meat, such as cooked ham and cured meat, is prone to discoloration, particularly when exposed to light in the presence of oxygen. Therefore, packaging technology, the gas-barrier properties of the packaging material and the packaging process, including residual oxygen levels and sealing, are of great importance in relation to oxidation.

2.4.3 | Water Content and Drip Loss

Most fresh food products contain large quantities of water. For fruits and vegetables, the packaging should prevent desiccation. The high water content of products such as fresh meat and fish makes them susceptible to drip loss. Drip loss from muscle tissue is natural and should be expected. However, visible liquid in packages is often perceived as unattractive, negatively impacting consumer acceptance, possibly leading to rejection and food waste [87, 88]. Moreover, high drip loss may affect the texture of the product. Increasing the absorption capacity increases drip loss in chicken meat; the packaging method and gas-to-product ratio influence drip loss [89]. Drip loss can also be affected by the mechanical stability provided by the packaging owing to compression [90]. To obtain optimal internal humidity within the packaging, the water vapour-barrier properties of the material are important.

2.4.4 | Food and Packaging Interactions

A range of interactions may occur between food, packaging and the surroundings throughout the storage period, which can affect food quality and safety. They are commonly categorized as permeation, migration and sorption. Permeation involves the transfer of gases, such as oxygen and CO_2, through the packaging, depending on the solubility and diffusivity of the permeate in the specific material. Gas permeation is important for many of the deterioration mechanisms described above and for the use of MAP.

Migration refers to the transfer of undesired compounds from the packaging material to the food matrix, such as plasticizers, adhesives, inks or monomers, some of which cause health concerns, as well as regulatory and safety issues [91, 92]. Ensuring food quality and safety is crucial throughout the packaging process and during storage, transportation and retail. Diverse safety standards have been implemented, ranging from country-level regulations, such as those established by the US Food and Drug Administration, to regional standards set by entities such as the European Food Safety Authority.

Sorption describes the phenomenon of food components absorbed by packaging materials. The sorption of aromatic compounds can lead to undesired organoleptic changes in food. Sorption may also affect the properties of the packaging materials during storage [93]. Exposure to moisture and subsequent water sorption can reduce the mechanical and barrier properties of hygroscopic and hydrophilic materials [94, 95].

3 | Review Methodology

The research method used in this study was a semisystematic review, also referred to as a narrative review. According to Snyder [96], while a systematic review is effective for synthesizing quantitative results and collecting evidence on a specific research question, a semisystematic review is more suitable for quantitative and qualitative research across multiple disciplines, identifying knowledge gaps in the literature. Therefore, the multidisciplinary nature of the sustainable packaging topic and breadth of research questions prevented a full systematic review in this study. The qualitative content analysis method was used to analyse the sustainability aspects, and quantitative data collection was used for the other aspects.

Scopus and Web of Science were selected as search databases. Given the interdisciplinary nature of the review topic, the search words were categorized into one general group and four separate groups. Each group contributed its own set of search words to narrow the focus to a particular issue, as illustrated in Figure 4. The general group included the names of bio-based materials, coating-related terminology, fibre-based substrate names and packaging applications while excluding edible films. The first subgroup covered LCA and carbon footprint terminology, targeting research papers assessing the environmental performance of barrier-coated packaging materials. The second subgroup included articles that contained words related to the sustainability of coatings or packaging in the title to conduct a content analysis and obtain the reasons for using the term. Articles addressing film forming properties of coatings and convertibility of the coated materials were included in the third subgroup. The fourth subgroup focused on the terminology associated with food quality and shelf-life assessments of fibre-based materials coated with bio-based substances. The truncation character '*' and the Boolean operators AND, AND NOT and OR were used to ensure consistent search queries.

Only scientific papers authored in English and published between 2012 and May 2023 were included in our study. Journal articles, conference proceedings and book chapters were considered eligible for inclusion, whereas review papers were excluded from the analysis. The initial screening was performed by assessing the titles and abstracts. If the title and abstract lacked adequate information to determine inclusion, the full text was screened. Bio-based films without fibre substrates were excluded from this review. Two papers were not available in full length, and one was retracted by the authors.

An additional criterion for inclusion in the environmental LCA subgroup was to have conducted LCA or carbon footprint studies and provide quantitative results. In the sustainability subgroup, only articles containing 'sustainable' or cognate words in the title and related to food fibre-based packaging were included. An inclusion criterion for the convertibility subgroup was the discussion of film forming properties of coatings in question and/or at least one conversion operation performed on a coated paper or paperboard with the measurement of barrier properties of the materials. Initially, the review aimed to search for studies where barrier properties were measured both before and after conversion to evaluate the severity of the surface damage; however, very few studies actually met this criterion, and the search was broadened. The fourth subgroup focused on the performance of these materials as actual packaging for real food and their abilities to preserve food quality during storage. This included studies with quality and shelf-life assessments of packaged foods. Studies focusing on active packaging

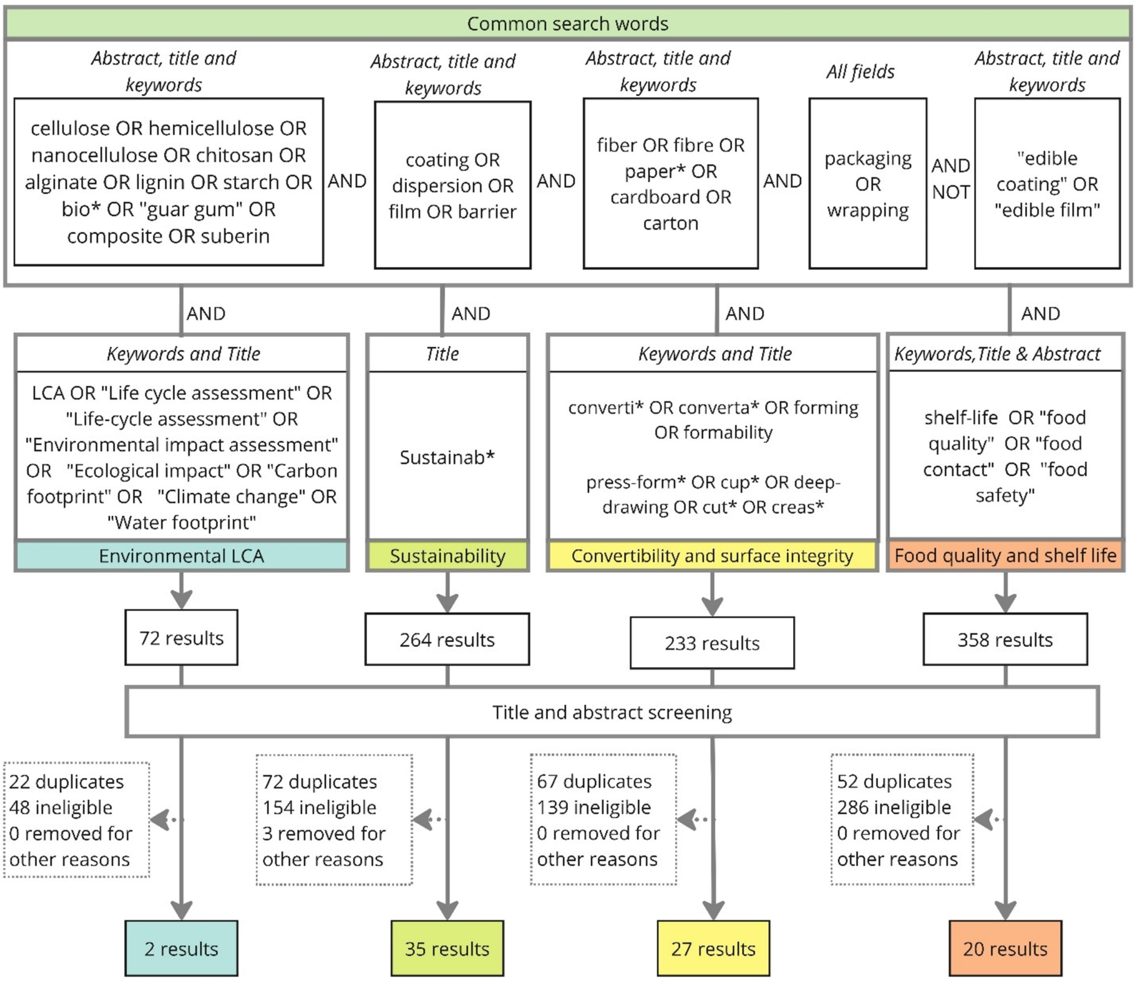

FIGURE 4 | Flowchart illustrating the study selection process for the review articles, including identification, screening and eligibility phases based on specific search criteria and sequential filtering.

were only included if quality analyses of the actual food after storage was reported.

One author independently read the included articles for each of the four search term groups. For each topic, an author with relevant experience in environmental assessments, packaging manufacturing, food quality and shelf life was appointed. Relevant information extracted from the included papers was recorded on the data collection forms.

4 | Environmental Sustainability of Bio-Based Coatings

This section aims to answer the first research question regarding the current status of environmental performance and sustainability of bio-based coated packaging materials. Section 4.1 summarizes the results of the few LCA studies. Section 4.2 and Figure 5 describe the outcomes of the content analysis and emphasize the reasoning behind the use of the term 'sustainable' by the authors of the reviewed papers.

4.1 | LCA Studies

Despite active discussions on bio-based materials for sustainable packaging, a semisystematic review revealed a scarce number of LCAs for bio-based coatings applied to fibre-based substrates. One of the reasons may be the relatively low technological readiness and the lack of accurate LCA data to conduct an academic study. Meanwhile, companies may work on environmental assessment of their patented technologies but prefer not to disclose the results to protect proprietary information and maintain competitive advantages.

The first reviewed LCA study was conducted at the VTT Technical Research Centre of Finland [97] and presents a cradle-to-gate LCA study of unmodified softwood and hardwood kraft lignins esterified with fatty acids and applied to a folding boxboard (FBB) cereal package. The carbon footprint of the tall oil fatty acid (TOFA) lignin barrier coating was 20% lower (37 kg CO_2-eq./1000 boxes) than that of FBB packaging with high-density polyethylene (HDPE) bags, owing to the decreased packaging weight and avoidance of plastic materials. The second LCA [98] was conducted in Sweden for the cradle-to-grave life cycle, including the packaging EoL stage. The materials analysed were starch, latex + kaolin, ethylene vinyl alcohol (EVOH) + kaolin and polyethylene. They compared the global warming potential (GWP) of the packaging using normalization and weighting factors; no absolute values were presented. Starch and EVOH + kaolin coatings showed lower GWP results than other materials in both incineration and recycling EoL scenarios. However, the difference in their barrier properties was not described, which is essential for a fair comparison of packages with the same functions. Both studies were simplified, assessed only one impact category and did not include a proper sensitivity analysis.

Although there is a knowledge gap concerning the full LCAs of fibre-based packaging with bio-based coatings, they are expected to emerge in the near future. LCA studies have already been conducted on many materials used for dispersion coatings. Particularly, LCAs of nanocellulose, which is one of the most common fillers for biocomposites, have been extensively investigated. Several studies [99–101] have examined LCAs for nanocellulose production methods, although many have been conducted at a laboratory scale.

4.2 | Sustainability Criteria

In total, the content of 35 [102–136] articles with the term 'sustainable' and 'sustainability' in their title in relation to bio-based coatings or coated packaging materials was analysed to identify

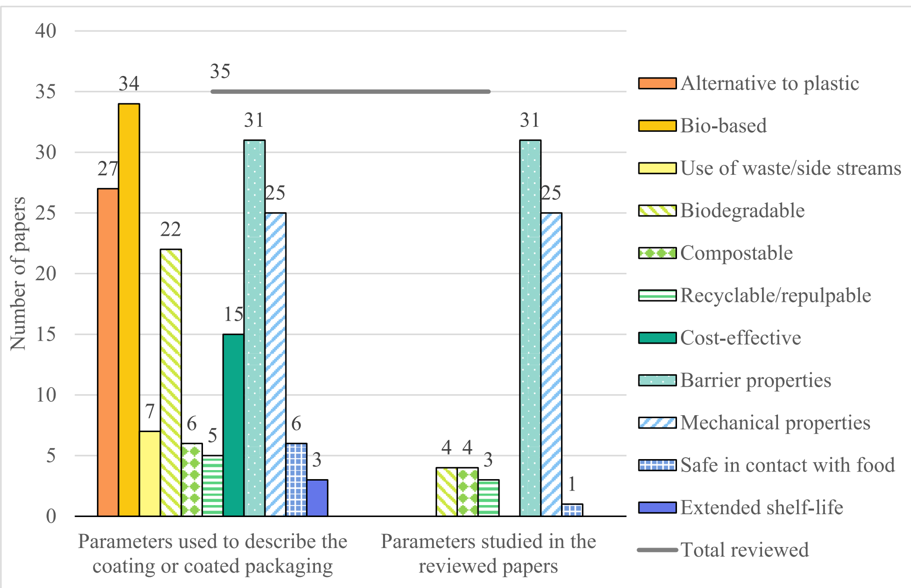

FIGURE 5 | A summary of the rationales behind the categorization of coatings as sustainable, highlighting key factors such as bio-based materials, alternative to plastic components, possible coating biodegradability and relatively good barrier and mechanical properties of coated substrates.

their specific focus. Figure 5 presents the criteria collected to determine the reasons why previous studies call their coatings or packaging 'sustainable'. More detailed review results for each coating individually can be found in Table S1.

Most studies were published between 2019 and 2023, with the earliest dating back to 2014. Coatings can be classified based on their composition, which includes combinations of chitosan, cellulosic, nanocellulose, starch, lignin, tannin, bacterial biopolymers, plant oils and waxes, natural rubbers, bioplastics and clays. As no studies were primarily focused on sustainability assessments, the objective was to identify parameters mentioned in the text that directly (environmental, economic and social impacts) or indirectly (functionality and contact with food effects) influence the packaging sustainability.

The main focus of most of these studies was developing bio-based coatings and composite films that enhance the barrier (31 papers [102–116, 119–130, 132–134, 136]) and mechanical properties (25 papers [102, 103, 105–109, 111, 112, 114, 116–124, 127–129, 133–135]) of coated packaging materials. The main rationale for employing the term 'sustainable' was related to the biological origin of the coating components and their potential as alternatives to conventional plastics, primarily due to their competitive barriers and mechanical properties. However, none of the studies performed an LCA or included economic, social or shelf-life impact assessments. Interestingly, out of 22 studies that called their solutions biodegradable, only four [108, 122, 134, 135] supported this statement with experimental biodegradability and compostability test results. Out of six papers that mentioned safety in the description of their packaging materials, one [108] included a toxicity assessment. Three studies [103, 116, 134] analysed the recyclability of their coated materials. Additionally, 15 papers mentioned cost-effectiveness, and few discussed the ability to preserve food quality and extend the shelf life of products.

Discussions regarding sustainable packaging development often prioritize environmental parameters while neglecting social impacts and economic viability. However, for bio-based barrier coatings, the primary focus remains on the development of the functional aspects. Extensive research opportunities exist in examining the environmental sustainability of newly developed and promising bio-based coated fibre packaging, as well as other aspects affecting the sustainability of packaging. Moreover, considering the entire life cycles of packaging systems, that is, packaging and packaged food, is key to assessing packaging sustainability. The trade-offs between product preservation, packaging environmental footprint, packaging EoL and food loss and waste must be considered to make informed decisions in industry and policy making on packaging for sustainable development [137]. Nevertheless, streamlined LCA studies should not be neglected in the early stages of development of new coatings, as they aid in understanding bottlenecks for further design improvements. Moreover, the Green Claims Directive [21], currently awaiting final approval in the European Parliament, is likely to require that environmental claims made about products be supported by third-party verified assessments. Additionally, the terms 'bio-based', 'biodegradable' and 'recyclable' require more precision when used in public statements.

5 | Issues and Prospectives on Bio-Based Coatings for Applicability at the Industrial Scale

This section presents a summary of the reviewed studies concerning the surface integrity and convertibility properties of bio-based coatings. Additionally, Table 1 summarizes the main conclusions obtained by these studies with regard to convertibility and barrier properties.

5.1 | Formulation of the Barrier Surface

Obtaining a defect-free surface is a fundamental step in the production of coated fibre-based materials [138]; however, thematic literature provides evidence that this task can be challenging when considering bio-based coatings. Although neat coating polymers may possess poor film formability, coating recipe modifications can improve the coating evenness and barrier properties of the obtained surface. For example, applying neat potato and corn starches as dispersion coatings or sizing agents resulted in films with uneven or damaged surfaces. The addition of polyvinyl alcohol (PVOH) [70, 76], glycerol [138], latex and pigments [139, 140] to the coating recipe resulted in enhanced barrier properties owing to improved film formability. Notably, an unoptimized component ratio in a coating recipe can increase the brittleness of the surface [66].

Certain processability issues related to fibre-based materials are associated with the hypersensitivity of paper and paperboard to moisture. A considerable proportion of bio-based coatings comprise water-based dispersion-infiltrating substrates. Water infiltration tends to weaken the fibre bonding in the paper structure [141], resulting in a substantial reduction in the mechanical properties of the material after repeated wetting and drying cycles [67, 70, 139, 142]. Mascarenhas et al. [67] reported that the strength and stiffness of papers coated with micro/nanofibrils (MFC/CNF) decreased by approximately 50% compared with those of uncoated paper. Occasionally, the coatings cannot be applied to very thin substrates that lack the ability to resist infiltration [138]. In contrast, the infiltration of extrusion plastic coatings, such as polyethylene terephthalate (PET), typically strengthens fibre-based substrates [143].

Barrier properties are among the most important considerations when selecting food packaging materials [140]. However, numerous bio-based coatings do not possess adequate barrier functions for long-term food storage, even though they exhibit good film formability [76, 140]. For instance, Leminen et al. [140] obtained adequate coverage (approximately 90%) of a paperboard surface with hydroxypropyl cellulose-based coatings (HPC); however, the best oil resistance achieved was only 25 min in an unconverted state. Moreover, food often requires protection against several deteriorating factors. Compared with conventional commercial fossil-based barrier films, bio-based coatings are generally less universal and typically do not offer barriers against all permeates [138, 142, 144]. Therefore, the material barrier properties should comply with those required for a certain product type.

One of the most important functions of paper coatings is to provide wet strength and water resistance to the substrate [66, 68].

TABLE 1 | Convertibility and barrier properties results for the reviewed studies.

Coating components	Coating grammage	Coating method	Substrate	Barrier properties (before conversion unless stated overwise)	Product types	Processibility remarks	Reference
PLA + talc 1/3/4/5 wt.%	4 wt.% = 27.9 gsm	Extrusion coating	Virgin fibre FBB Grammage: 200 gsm Thickness: 275 µm	WVTR·mm, g·mm/m^2·days: 1.0–1.4 @ 23°C/50% RH 3.5–6.6 @ 38°C/90% RH	Paper cups	Excellent heat sealability starting at 160°C Filler addition benefited the seam formation with hot bar and hot air sealing methods, even though did not significantly lower the temperatures of full fibre tear Cup formability was not affected by fillers addition	[155]
PLA + kaolin 1/3/5 wt.%	3 wt.% = 22.5 gsm			WVTR·mm, g·mm/m^2·days: 1.1–1.5 @ 23°C/50% RH 5.2–7.4 @ 38°C/90% RH			
PLA + calcium carbonate 1/5/10 wt.%	10 wt.% = 17.8 gsm			WVTR·mm, g·mm/m^2·days: 1.0–1.1 @ 23°C/50% RH 4.6–5.2 @ 38°C/90% RH			
PLA	18 gsm			WVTR·mm, g·mm/m^2·days: 1.1 @ 23°C/50% RH 5.4 @ 38°C/90% RH			
Potato starch	20.1 gsm	Rod coating	Triple-coated board, 205 gsm Uncoated board, 271 gsm	OTR: Over limit, uncreased	Not specified	No oxygen resistance after creasing Very brittle coatings with low crack resistance	[76]
Potato starch + glycerol	20.7 gsm						
Potato starch + PVOH + glycerol	14.2 gsm						
Potato starch + PVOH	14.3 gsm			OTR: 186 cm^3/m^2·days, uncreased Over limit, creased			
Starch + latex + talc	14.3 gsm	Triple rod coating	Mineral-coated paperboard, 210 gsm	OGR: 5 h, uncreased	Paperboard trays	Pinholes after creasing Surface cracks even with lower creasing force	[139]
Starch + latex + kaolin	15.7 gsm			OGR: 24 h, uncreased		Pinholes after creasing	
Polyolefin + talc + binder	7.7 gsm			OGR: 5 h, uncreased		Pinholes after creasing	
Uncoated substrate	—	Blade coating	Commercial SBS paperboard 350 gsm	Water contact angle: 99.8° OGR: 0 uncreased/creased	Paperboard trays	—	[140]
Hydroxypropyl cellulose (HPC) 100	10 gsm			Water contact angle: 67.5° OGR: 2 min unconverted, 1 min converted		Stuck to the conversion tools Good formability of trays	
HPC 100 + gelatin 5	12.5 gsm			Water contact angle: 67.4° OGR: 10 min unconverted, 2 min converted		Good formability of trays	
HPC 80 + gelatin 5 + talc 20	10.5 gsm			Water contact angle: 69° OGR: 15 min unconverted, 6 min converted			
(Precoating: CMC 90 + gelatin 10 + MFC 10) HPC 70 + latex 10 + talc 30	11.5 gsm			Water contact angle: 69.2° OGR: 25 min unconverted, 11 min converted			

(Continues)

TABLE 1 | (Continued)

Coating components	Coating grammage	Coating method	Substrate	Barrier properties (before conversion unless stated overwise)	Product types	Processibility remarks	Reference
Printing coating	N.A.	N.A.	Cardboard sheets 300 gsm, coated for printing from one side	OTR: 12 cm^3/m^2·days Cobb: 47 ± 7 g/m^2 KIT number: 0	Folding cartons	—	[142]
MFC (2 wt.%) + printing coating	Layers: ×1: 4 gsm ×5: 9 gsm ×10: 17 gsm	Bar coating		×1 / ×5 / ×10 OTR, cm^3/m^2·days: — / 14 / 13 Cobb, g/m^2: 67 ± 10 / 94 ± 4 / 114 ± 7 KIT: 0 / 1.5 ± 0.5 / 2.5 ± 0.5		Improved compression resistance for folding cartons, comparable with the PE-coating performance; ×10: +20% (MD), −10% (CD) of folding resistance	
Deionized water + printing coating	Number of treatments: ×1: 1 gsm ×5: 4 gsm ×10: 4 gsm			×1 / ×5 / ×10 OTR, cm^3/m^2·days: — / — / — Cobb, g/m^2: 51 ± 4 / 89 ± 8 / 84 ± 11 KIT: 0 / 0 / 0		×10: +10% (MD), −25% (CD) of folding resistance	
PE (reference) + printing coating	×1: 20 gsm	Extrusion coating		Cobb: 5 ± 3 g/m^2 KIT: 12		The compression strength of boxes made of PE-coated baseboard increased by 14% due to the PE layer	
PLA	30 gsm	Extrusion coating	Pigment-coated paperboard, 275 gsm	OP: 381.2 cm^3·mm/(m^2·days·atm) WVTR·mm: 15.4 g·mm/m^2·days OGR (ASTM-F119-82): 12 days	Not specified	Smooth and defect-free surface	[73]
PLA/PBAT	30 gsm			OP: 558.6 cm^3·mm/(m^2·days·atm) WVTR·mm, 19.2 g·mm/m^2·days OGR (ASTM-F119-82): 12 days		PBAT is used to improve PLA toughness	
Potato fruit juice (PFJ) + glycerol 30 + PLA	PFJ: 15 μm (3 layers) PLA: 30 gsm	Rod coating + extrusion coating		OP: 12.5 cm^3·mm/(m^2·days·atm) WVTR·mm, 3.8 g·mm/m^2·days OGR (ASTM-F119-82): 31+ days		PFJ layers crack after creasing. Combined with extrusion coatings, the layers were stretched out after creasing but did not fracture.	
Potato fruit juice (PFJ) + glycerol 30 + PLA/PBAT	PFJ: 5 μm (1 layer) PLA/PBAT: 30 gsm			OP: 71.4 cm^3·mm/(m^2·days·atm) WVTR·mm, 7.6 g·mm/m^2·days OGR (ASTM-F119-82): 14 days			
PFJ + glycerol 30 + PLA/PBAT	PFJ: 15 μm (3 layers) PLA/PBAT: 30 gsm			OP: 13.6 cm^3·mm/(m^2·days·atm) WVTR·mm, 4.0 g·mm/m^2·days OGR (ASTM-F119-82): 31+ days			

The natural hydrophilicity of some solutions, such as cellulose- and starch-based coatings, may conversely reduce the barrier properties [70], thereby increasing the susceptibility of the material to moisture and the number of voids within the structure [67, 142, 145]. For instance, Lavoine et al. [142] observed an increase in moisture absorption of 31% with only a 1-gsm MFC coating on paperboard. This absorption increased to 80% with a 14-gsm coating weight. The increased moisture absorbency of coatings limits their applicability in the packaging industry [145]. However, abrupt water loss or nonoptimized drying techniques can cause bio-based coatings to become more brittle, leading to decreased barrier properties [67, 138].

5.2 | Convertibility

As discussed in Section 2.3, creasing and folding are challenging conversion processes for coated surfaces. Several types of forces affect the material surface during conversion operations, resulting in the potential for barrier coatings to develop cracks [75]. This compromises surface integrity and reduces barrier functions [76, 139]. Bio-based coatings, particularly starch-based coatings, are often brittle because their mechanical properties are significantly poorer than those of the synthetic coatings currently used in packaging [76, 138, 139]. Plastic coatings often withstand substantially higher creasing forces, whereas bio-based films crack under similar loads [76, 139]. Tanninen et al. [139] reduced the creasing force for starch-coated paperboards by 30% (from 170 to 120 N/cm of crease) compared to the PE-coated reference, owing to the emergence of visible cracking on the surface. Nevertheless, scanning electron microscopy (SEM) revealed the presence of microcracks that considerably reduced the material barrier properties [139]. Typically, plastic coatings with a higher coat weight resist cracking better; however, increasing the coat weight of bio-based coatings enhances their barrier properties but simultaneously makes the surface even more susceptible to cracking [70, 76, 144].

The response to the conversion operations varies not only between coatings with different contents but also within the same material owing to paper anisotropy. Heavily influenced by fibre orientation, paper and paperboard normally possess lower stiffness when creased or folded along the machine direction (MD). This results in longer cracks in the MD than in the countermachine direction (CD) [77]. Additionally, folding a paper-based blank typically requires a higher force if folded along the CD [146], indicating that the fibre orientation must be considered in the conversion operations [77].

In addition to material properties, the outcome of packaging production is greatly influenced by the interaction between the converted material and the creasing tooling employed. Unadjusted tooling parameters often lead to undesirable creases, which can cause problems such as excessive material damage [147], insufficient blank foldability [148] and poor sealability [149]. Several factors must be considered to provide sufficient creasing quality. First, the conditions for the creasing rules must be examined. Tanninen et al. [139] reported that the use of worn tools for creasing results in a higher number of cracks on the coated surface. Second, the width of the creasing rules is determined by the thickness and density of the creased material. Rules that are too narrow can cut through the coated surface, even in the case of thick plastic coatings, whereas excessively wide rules can compromise the foldability of a blank [149]. In the tray-forming processes, the creasing pattern also plays a role, requiring an adjustment to the distance between the creases [149]. An excessive amount of creasing in a blank can diminish the strength of the package [148].

Some paperboard conversion techniques, such as press forming and deep drawing, have been derived from sheet metal forming. In contrast to metals, paper-based materials have severe drawbacks, such as high sensitivity to heat and moisture [150]. Although sufficient paper heating improves plasticity and formability and occasionally enables better bonding of substrates and coatings [141, 144], excessive heat input results in detrimental effects. The lower melting points of bio-based coatings often require conversion operations under reduced temperatures compared with those of plastic coatings [149]; otherwise, severe sticking to the conversion machinery can occur [139, 140]. Sticking can cause surface damage and compromise the integrity of the barrier layer. Simultaneously, a lower temperature limits the formability of the paperboard substrate because a typical optimal forming temperature is not achieved [139]. Excessive heating also evaporates moisture from the preconditioned paperboard, thereby reducing material elasticity and eliminating the lubricating action of moisture between the material and tooling [141]. At higher temperatures, bio-based extrusion coatings begin to degrade and lose their mechanical properties and adhesion to the substrate [151].

Although bio-based coated substrates offer renewable products, they are unlikely to exhibit adequate elastic behaviour [139]. Therefore, the convertibility of the coated papers is enhanced by moistening the materials and improving the elasticity, shape stability and visual appearance of the packages [152]. Paper-based materials require long-term storage under appropriate, optimal conditions for humidity control [139, 152], both before and after conversion. Packages require careful consideration of how materials respond to variations in temperature and moisture content because they are constantly subjected to such changes [153]. Rapid humidity changes may result in rapid water intake [138], thereby affecting the quality and durability of a package [153]. Additionally, extended storage times can naturally result in higher moisture intake when conditions are not controlled [69].

Numerous solutions for packaging plastic substitution are currently in the development stage, but they still have severe functional drawbacks that limit their wider utilization. Bio-based coatings can fulfil certain packaging requirements in terms of barrier properties; however, their deficient conversion potential remains a primary problem for wider applicability [154]. One promising approach is to combine a dispersion coating layer with a biodegradable extrusion film. For instance, Koppolu et al. [72] and Poulose et al. [73] reported that applying extrusion-coated PLA to hydrophilic and brittle starch/cellulose-based layers improved barrier performance and convertibility. This improvement was due to the synergetic effect of the coating combination. Notably, novel solutions for paperboard coating are usually tested with conventional tooling designed for fossil-based plastics. Adapting the conversion machinery to the needs of the novel bio-based coatings would enhance material convertibility and facilitate their wider application.

6 | Food Quality and Shelf Life

Shelf-life studies are crucial for evaluating the performance of packaging materials for various food product categories. Different types of foods impose distinct requirements on packaging materials and methods, influenced by factors such as moisture content, oxidation, respiration rates and susceptibility to microbial growth. Consequently, analytical methodologies used to assess food quality during storage may vary depending on the specific food type. These variations reflect the multifaceted nature of food packaging, with materials often tailored to meet the unique demands of various food categories. An overview of the reviewed studies on fibre-based substrates with bio-based coatings investigating the performance of such materials in preserving food quality during storage is presented in Table 2. Fruits, mainly tomatoes [156–158] and berries [159–163], and mushrooms [164–166], are frequently used to evaluate the potential of these materials in food packaging, reflecting their relevance and suitability for assessing the efficacy of such materials.

6.1 | Barrier Properties

In some cases, the relatively low gas and water vapour-barrier properties of cellulose-based materials may prove beneficial compared to plastic packaging due to the condensation and respiration of packaged food. In contrast to certain types of plastics, cellulose-based materials may release water vapour and CO_2, preventing condensation and gas levels from building up inside the package. For example, bags composed of chitosan/CMC-coated paper exhibited superior preservation of mushroom quality compared to the plastic reference [164]. However, the limited water vapour-barrier properties could also lead to higher weight loss in coated cellulose than in plastics for fresh foods with a high water content, which was observed for strawberries in paper coated with CMC, nanocellulose and AgNPs [160], as well as sliced ham in paper coated with pullulan, rockrose essential oil and zein [167]. Weight loss is one of the most important quality characteristics of these products. Unfortunately, most studies did not incorporate plastic as a reference. When comparing cellulose materials with and without coatings, as well as those with no packaging/open air, it is evident that certain bio-based and biodegradable coatings improve the ability of paper and paperboard to delay the weight loss of various products [157–163, 165, 166, 168, 169]. This is presumably due to improved barrier properties. In various studies, the application of coatings resulted in enhanced microbial and sensory qualities in the tested food products compared to those stored using uncoated paper/paperboard or without packaging.

Research on more demanding products, such as meat and fish products, with high gas-barrier requirements for MAP applications was scarce. The few relevant studies, including those on meat products, focused on the storage of cooked beef in CMC/lysine-coated paper [170], as well as raw meat packaged in starch, wax-coated paper [171] or paper boxes [167]. Some of these studies focused on the effects of active agents added to the material [167, 170]. However, the importance of a sealed/airtight package for MAP applications, which is widely recognized for extending the shelf life of susceptible foods such as meat, was not mentioned or commented upon. Despite the positive results in terms of antimicrobial and antioxidant effects, the weight loss was higher for paper than for plastics [167]. Although many studies reported data on air permeability and water vapour-barrier properties, data regarding the oxygen transmission rate (OTR) were scarce. In contrast to OTR, air permeability is often used to reflect the porosity of paper and board, both with and without an additional barrier coating. It is commonly expressed in terms of the volume of air passing through a material at a certain pressure per minute, for example, L/min [160, 164] or mL/min [156]. Low air permeability does not necessarily indicate that a material provides a sufficiently strong oxygen barrier to meet the requirements of oxygen-sensitive food products during storage. The scarcity of OTR data may hint at potential limitations in achieving the gas-barrier properties required for such applications. This prompts questions regarding the suitability of these materials for packaging methods, such as MAP and vacuum sealing. These packaging techniques are known for their ability to extend the shelf life of perishable food products, as described in Section 2.4.1 and 2.4.2.

6.2 | Conversion and Packaging Format

Furthermore, the reviewed articles displayed the predominant use of specific packaging formats. Bags [160, 162, 164, 170, 172, 173] and wrappings [161, 169, 171, 174] emerged as the most frequent options, as did boxes of tomatoes [156–158] and ham [167]. Frequently, the methodology for converting flat materials into 3D-shaped packaging is not well described, despite the importance of this aspect to the resulting packaging properties. As discussed in Section 2.4, it is essential for packaging to have barrier coatings that can tightly seal and prevent pinholes in cellulose-based materials. This is necessary to meet the gas-barrier criteria imposed by food and packaging methods, such as with MAP. Without proper sealing, even materials with excellent gas-barrier properties may prove ineffective. Despite their importance, convertibility and sealing were rarely mentioned. Information on how packages are made, including the sealing methods employed [160, 162, 164, 170, 172, 173], as well as the format in which the material has been tested as packaging [159, 163], was excluded.

6.3 | Combinations of Coating Materials

In the reviewed studies, certain coating materials were used more frequently than others. In the pursuit of optimal packaging solutions, a single material is frequently insufficient to provide the desired protection for food products. Therefore, blends or multilayer coatings consisting of various materials are frequently used [69, 156–170, 172–174]. These composite coatings often provide a synergistic approach for improving material performance. In numerous studies, a range of active agents were integrated into coatings, primarily essential oils [163, 165–167, 169, 172, 173] and NPs, such as AgNPs [157, 158, 160, 161, 174]. In addition to providing antibacterial and antioxidant effects, these agents can influence the mechanical and barrier properties of

TABLE 2 | Fibre-based materials with bio-based barrier coatings from the reviewed studies, along with their effects on food quality and shelf life.

Coating components	Grammage (g/m^2)	Coating method	Fibre-based substrate	Food product	Packaging format	Reference material	Effects on food quality and shelf life	Reference
MFC, NFC, pyrrole	49[a]	Casting	Paperboard 45 g/m^2	Tomatoes	Boxes	Open air, uncoated paperboard boxes	Better maintained texture and appearance compared to uncoated paperboard.	[156]
PBS/PBSA	N.A.	Lamination	Paperboard 220 g/m^2	Fresh pasta	Trays with film lid	No packaging, uncoated paperboard, paperboard with PET/EVOH/LDPE	Delayed mould growth and changes in colour and water activity were similar to those using PET/EVOH/LDPE-coated paperboard but with higher weight loss. Achieved a shelf life of 9 days.	[168]
Starch Wax	N.A.	N.A.	Commercial papers (with coating)	Chicken breast	Wrapping	PE-coated paper	Better preservation of sensory quality by PE- and starch-coated paper compared to wax-coated paper. Microbial quality in terms of total aerobic mesophiles passed the acceptability limit (log 6 CFU/g) in less than 3 days for all materials.	[171]
Chitosan + CMC	N.A.	Immersed in solution	Paper 80 g/m^2	Mushrooms	Bags	PE, no packaging	Prolonged shelf life compared to PE. Similar weight loss, less colour and firmness change and microbial growth than PE.	[164]
Rice bran wax + whey protein isolate	N.A.	Immersed in solution	Paper cups	Popcorn	Cups	Uncoated paper	Popcorn texture and taste improved compared to uncoated paper while there were no significant differences in moisture, pH levels and other sensory characteristics.	[69]
Chitosan + Ag/TiO_2	N.A.	Slot die coating	Paper	Butter	Wrapping	Uncoated paper chitosan-coated, chitosan/TiO_2-coated paper	Prolonged shelf life compared to uncoated paper. Lower peroxide values and less microbial growth for chitosan + Ag/TiO_2-coated papers compared to uncoated and chitosan-coated papers.	[174]

(Continues)

TABLE 2 | (Continued)

Coating components	Grammage (g/m^2)	Coating method	Fibre-based substrate	Food product	Packaging format	Reference material	Effects on food quality and shelf life	Reference
CMC + CNC + AgNPs	N.A.	Immersed in solution	Filter paper 85 g/m^2	Strawberries	Bags (sealed)	PE, no packaging, uncoated paper, CMC-coated paper	Microbial growth was delayed, vitamin C content was maintained better and the visual appearance improved compared to PE, no packaging and uncoated paper. Weight loss was higher than for PE and lower than for no packaging and uncoated paper.	[160]
Starch + cinnamon EO-microcapsules	85–87[a]	Bar coating	Paper 80 g/m^2	Mushrooms	Paper covers box surface (tape sealed)	No packaging, uncoated paper, starch-coated paper	Less weight loss, improved firmness, membrane permeability and microbiological quality compared to no packaging, starch-coated paper and uncoated paper.	[165]
Alginate + TiO_2 + cellulose nanocrystals	N.A.	Blade coating	Bagasse kraft paper 80 g/m^2	Strawberries	N.A.	No packaging, uncoated paper, alginate-coated paper	Less weight loss and better maintained soluble solids content and appearance than without packaging but similar to uncoated and alginate-coated paper. Extending shelf life from 6 days for no packaging to 18 days with coated paper.	[159, 172]
Chitosan + gelatin + beeswax + PVA + curcumin	N.A.	N.A.	Kraft paper 80 g/m^2	Cake	Bags	No packaging, uncoated paper	Less mould growth compared to no packaging, extending the shelf life by 3 days.	[172]
Pullulan + zein + rockrose EO	285–298[a]	Casting + lamination by calendering	Paper 80 g/m^2 from eucalypt pulp	Fresh sliced ham	Boxes	Plastic wrapping	After 7 days of storage, the weight loss was higher, and the texture was harder for ham packaged in the laminates compared to plastic.	[167]

(Continues)

TABLE 2 | (Continued)

Coating components	Grammage (g/m^2)	Coating method	Fibre-based substrate	Food product	Packaging format	Reference material	Effects on food quality and shelf life	Reference
Chitosan + vanillin EO + zeolite	39	Bar coating	Paper	Mango	Wrapping	No packaging, uncoated paper, chitosan–vanillin-coated paper	Zeolite paper exhibited the highest capacity for ethylene adsorption, the disease incidence of wrapped mango fruit was delayed and the severity index of anthracnose disease was lower than for other papers. Changes in physicochemical qualities (weight loss, firmness, titratable acidity, total soluble solid and colour) were less, and sensory acceptance scores were higher compared to chitosan–vanillin and uncoated papers.	[169]
CMC + lysine	N.A.	Immersed in solution	Kraft paper 80 g/m^2	Cooked beef	Bags	PE, no packaging, uncoated paper	The microbiological quality of cooked beef was improved, and shelf life was extended for approximately 3 days at ambient temperature compared to PE.	[170]
1-Methylcyclopropen (MCP) + $KMnO_4$ + cinnamon EO (CEO)	N.A.	N.A.	Paper 80 g/m^2	Mushrooms	N.A.	Uncoated paper, CEO-coated, MCP/CEO-coated, $KMnO_4$/CEO-coated paper	Softening, browning and weight loss of mushrooms were delayed compared to uncoated paper and paper with other coatings due to the ethylene-scavenging properties of the coating materials. The quality of mushrooms was still acceptable after 6 days, extending the shelf life from 4 days for uncoated paper.	[166]
Chitosan + lemongrass EO	257[a]	Bar coating	Paperboard 240 g/m^2	Dry pasta	Pouches	Uncoated paperboard	There was no difference in sensory quality between uncoated and coated paperboard.	[173]

(Continues)

TABLE 2 | (Continued)

Coating components	Grammage (g/m^2)	Coating method	Fibre-based substrate	Food product	Packaging format	Reference material	Effects on food quality and shelf life	Reference
Chitosan + Ag-zeolite	193–206[a]	Bar coating	Kraft paper 200 g/m^2	Tomatoes	Boxes (sealed with glue)	Uncoated paper, uncoated paper with commercial ethylene absorbent sachet, chitosan-coated paper	Firmness, weight and colour were better maintained than for uncoated and chitosan-coated paper. Ethylene levels were lower than in uncoated paper with an ethylene absorbent sachet, delaying the ripening of tomatoes.	[157]
PVA + Chinese fir EO (CFEO) microcapsules (chitosan and gelatin for encapsulation)	16.4	Bar coating	Paper 45 g/m^2	Strawberries	N.A.	Uncoated paper, PVA-coated paper	Firmness, weight, solids content and microbiological quality were better maintained than for uncoated and PVA-coated paper. Extending the shelf life by approximately 2 days compared to uncoated paper.	[163]
CMC + PVA + Ag@Fe_3O_4	N.A.	Blade coating	Filter paper	Tomatoes	Box	Uncoated paper, CMC/PVA-coated paper	Weight loss was lower, and vitamin C content was better maintained than for tomatoes using uncoated and CMC/PVA-coated paper.	[158]
TiO_2 + silane + polylysine	40[a]	Immersed in solution (prior to sheet making)	Bamboo pulp board	Cherries	N.A.	Uncoated paper	Less weight loss, visible mould growth and improved appearance compared to cherries using uncoated paper after 7 days of storage.	[162]
AgNP + zeolite imidazole framework-8 anchored carboxymethyl cellulose (CMC)	N.A.	Immersed in solution	Filter paper	Strawberries	Wrapping	Uncoated paper, CMC-coated paper, AgNPs/CMC-coated paper	Better appearance and lower weight loss than for strawberries using uncoated paper after 7 days of storage	[161]

[a]The total grammage of the fibre substrate with coating.

the packaging materials. For instance, essential oils, which are characterized by their hydrophobic nature, may improve water vapour-barrier properties [163]. Similarly, the addition of a Zn^{2+}-releasing zeolite imidazole framework and AgNPs to carboxymethyl cellulose as a coating on paper improved its water vapour-barrier properties and resulted in lower weight loss in strawberries during storage, as compared to uncoated paper [161].

Other studies cited reasons for applying different coatings, such as improving the barrier properties. However, the absence of relevant properties that would facilitate an evaluation of the success of the coating was noticeable. For instance, some studies focused on enhancing the hydrophobic and water vapour-barrier properties but omitted measurements of the water vapour transmission rate (WVTR) or water vapour permeability (WVP) [156, 162]. Instead, they solely relied on parameters such as the appearance or weight loss of the food product during storage, which failed to comprehensively capture the performance of the coatings. Some studies investigated the antimicrobial activities of packaging materials against various bacteria. Several materials showed antimicrobial effects on specific bacteria; however, in some cases, the microbiological quality of the food during storage was not evaluated [167]. Therefore, the results did not provide a comprehensive understanding of the effects of antimicrobial activity on food quality during storage.

Recognizing the critical role of storage time and conditions is vital in shelf-life studies. The effectiveness of packaging materials may vary considerably depending on the storage duration and environment. Therefore, these materials should be exposed to realistic storage conditions during food shelf-life studies. However, in some studies, food was not stored at refrigerated temperatures. For instance, Li et al. [170] reported that cooked beef was stored at 23°C for 9 days. The use of this temperature was not discussed in this article. The results of this study could have been more universally applicable if the cooked beef had been stored under refrigerated conditions.

To effectively evaluate the functionality of new packaging materials and understand whether they could represent potential alternatives to conventional materials, a comparison of their influence on food quality during storage is essential. In several studies, there was a lack of comparison with conventional packaging materials, which limited the possibility of evaluating the suitability of these materials for specific foods [69, 156–159, 161–163, 165, 166, 168, 169, 172–174].

Replacing plastics as food packaging should not compromise food quality or shelf life, as this could increase food waste. Conducting shelf-life studies is crucial for assessing the effectiveness of food packaging materials in preserving food quality and safety. However, a critical examination of recent literature exposes several notable shortcomings in these studies. Although recent studies have made progress in exploring innovative food packaging materials, there are substantial gaps in the experimental design, methodology and relevance to real-world applications. Addressing these shortcomings is essential to advance the field of food packaging and ensure the practicality and effectiveness of new materials and coatings.

7 | Remarks

Despite the comprehensive nature of this review, several limitations should be acknowledged. The review in the sustainability section was limited to articles that explicitly included the term 'sustainable' in their titles. This selection criterion may have excluded relevant studies that considered sustainable development but did not include it in the title. A separate search of studies focusing only on the EoL aspect, that is, compostability, recyclability, (bio)degradability and repulpability, was intentionally not included in the study due to the large number of articles in both the Web of Science and Scopus databases. Expanding the search area would have increased the number of articles to be screened, which was not possible due to time constraints. A review of only the EoL criteria in the articles could form the basis for a separate review paper.

The food quality and shelf-life section was limited to studies involving storage and quality assessment of real food. 'Food safety' was among the search words, but studies focusing on this aspect alone (without involving storage and quality of food) were excluded from the review. A separate study could be conducted on the safety of these materials as food contact materials, including migration testing of the different coatings or components. Studies focusing on intelligent and active packaging were excluded unless they also involved food quality assessment. The different focus area of the studies—from antioxidant or antimicrobial effects of active agents to packaging material's overall impact on food quality—may have influenced our interpretation of these studies. The complexity of the coatings, most consisting of various materials, combined with relatively few published articles, made it difficult to extract the impact of each component.

The review considered papers published between 2012 and May 2023. While this gives an overview of recent developments, it may miss the most recent papers published while the authors were working on this review.

8 | Conclusion and Future Research

Given the regulatory push to decrease plastic consumption and improve circularity, the food packaging industry requires the successful development of scalable bio-based barrier packaging that is both biodegradable and recyclable. At present, bio-based dispersion coatings are primarily in the development stage, and the fulfilment of the convertibility and surface integrity requirements remains challenging. Some coating formulations exhibit poor film formability, resulting in insufficient surface coverage and reduced barrier properties. Compared to conventional fossil-based plastic coatings, dispersion coatings are more sensitive to changes in heat and moisture, which substantially affect the mechanical properties of materials. Finally, dispersion-coated surfaces are often damaged by the conversion processes. The most promising approach for overcoming the aforementioned issues is the use of a combination of several coating layers. This can be achieved by applying the same substance several times to the substrate or by combining the coatings of different types (e.g., dispersion and extrusion layers). Future research should focus on improvements to barrier coating formulations to enhance their surface performance and the development of converting tools to comply with the requirements for the novel coating conversion.

Paper and paperboard coated with various bio-based materials improved the shelf life of some fruits and mushrooms compared to uncoated paper. However, many of the reviewed studies lack relevant aspects, such as comparisons with conventional packaging materials and commonly used packaging methods (e.g., MAP). The impact of food contact on the structural stability and strength of cellulose-based materials was rarely mentioned, despite the fact that moisture sorption and fat penetration can weaken these materials. Moreover, the suitability of many bio-based coatings on cellulosic materials in the context of food packaging has not yet been tested in real shelf-life studies, and their potential for food preservation should be explored in future research. Considerable obstacles should be addressed before cellulosic materials with bio-based coatings can be widely adopted for commercial use. Limitations in barrier properties, as well as challenges related to the conversion and sealing of gas-tight packages, remain unresolved.

Moreover, the key to making informed decisions on packaging sustainability is to assess the entire life cycles of packaging systems and consider trade-offs between functional properties, packaging environmental footprint, packaging EoL and food loss and waste. With the further development of coating formulations, there is a strong future research need for LCA studies, which is currently limited for fibre-based packaging with bio-based coatings. The inclusion of LCA in the early development stage would help companies in their product development.

The terms 'sustainable coating' and 'sustainable packaging' are often misused to describe the use of renewable materials. The results of most reviewed studies include barrier and mechanical performance of bio-based coated substrates and do not include biodegradability, compostability and recyclability tests while using these adjectives to describe their coating solutions. Industry and academic researchers should be mindful of using all of these terms. Future research should focus on incorporating aspects such as EoL, food contact safety, shelf life and food loss and waste into the development of bio-based coating materials for fibre packaging.

This study encourages researchers and product developers in the bioeconomy and packaging fields to apply a life-cycle thinking approach to the development of new packaging solutions aiming to contribute to sustainable packaging. There are currently knowledge gaps in the environmental assessment, convertibility and food applicability of bio-based barrier packaging. Further exploration of these aspects will facilitate science- and data-driven innovation and decision-making in industry, policy and academia in the development of sustainable bio-based packaging.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.