

Repulpability and Biodegradability of Paper-based Packaging Products with Water-borne Barrier Coatings: A Review

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Published findings are reviewed related to the recovery and recycling, as well as the biodegradability, of single-use food packaging materials that include waterborne barrier coating layers. Such layers can replace petroleum-based plastics, such as polyethylene, which tend to build up in the environment and contribute to microplastics issues. Barrier layers, of either type, can block the transport of oxygen, water vapor, liquid water, grease, contaminants, and flavors in and out of such packaging systems. Key concerns include whether such layers can be readily dispersed in water, thereby allowing the packaging material to be used again in subsequent generations of recycled paper products. The process efficiency, including the yield of recovered materials, is also of concern. Because single-use food packaging products, in most regions, are not yet routinely routed to paper recycling, this review also considers findings related to biodegradability and compostability of waterborne barrier layers. Based on the reported findings, there are numerous waterborne formulations that can meet practical needs in terms of biodegradability and repulpability, leading to relatively high yields in paper recycling operations. Chemical components of future waterborne coating formulations need to be considered on a case-by-case basis regarding their contributions to toxicity, compostability, general biodegradability, and circular systems of recovery and reuse.

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INTRODUCTION

Single-use containers for shipping or serving food items offer many advantages in modern society (Xayachak *et al.* 2024; Murugesan and Li 2026). Such containers help to reduce the amounts of spoiled food. The relatively low cost and low weight of typical single-use food-contact packaging products make them attractive for on-the-go people. The challenge to be considered in this review article is whether non-renewable plastic components of single-use food containers can be replaced by materials that are genuinely biodegradable and also capable of being recycled in ordinary paper recycling mills. In particular, the question is whether the twin goals of biodegradability and recyclability can be achieved by coating the paper with environmentally friendly film compositions. A further challenge, which has been addressed by others (Kathuria and Zhang 2022; Dey *et al.* 2026), is to meet similar barrier performance levels as various non-renewable packaging materials that are being replaced while maintaining the desired biodegradability and recyclability of the paper-based packaging.

Definitions

Barrier coatings

To set the context for the questions just posed, some definitions may be helpful. The term “water-borne barrier coating,” when used in this article, will be assumed to include at least one water-soluble or water-dispersible polymer component. Examples include the natural products starch (Miranda *et al.* 2015; Matheus *et al.* 2023) and chitosan (dos Santos *et al.* 2022; Ruberto *et al.* 2024; Fang *et al.* 2025). In addition, examples such as poly(vinyl alcohol) (PVOH) also will be included in the discussion (Muiliya *et al.* 2026). PVOH, though derived from petroleum products, is known to be biodegradable and water-soluble (Röhrle *et al.* 2023).

The most promising current formulations of barrier coatings are comprised of multiple components, and often they are comprised of multiple layers. As will be described in more detail later, it has been found that a variety of different film components, working in combination, can be helpful in an attempt to match or beat the performance of petroleum-based layers, which presently dominate the field of single-use food containers (Yin and Woo 2024). As will be shown in examples to be provided in this article, water-borne barrier coatings, in addition to water-soluble or dispersible polymers, often contain other components, such as plasticizers, mineral particles, and nanocellulose products, among others. The fact that future water-borne barrier coatings are likely to be complicated mixtures, rather than pure components, means that it may be insufficient just to consider effects of individual components one by one when considering repulpability or biodegradability. For instance, a hydrophobic (Guo *et al.* 2026) or a crosslinked (Dey *et al.* 2026) starch film might have different biodegradability and recyclability performances in comparison to a film composed of starch by itself.

Another way to define a barrier coating is by what it does. Blocking the passage of oxygen gas can be one of the most effective ways to extend the period of food freshness (Huang *et al.* 2014). If this were the only requirement, it could be achieved by forming a dense layer of nanofibrillated cellulose (NFC; which is also called cellulose nanofibril) (Kumar *et al.* 2017; Shanmugam *et al.* 2019). But such NFC films lose their ability to resist the diffusion of both oxygen and oils in the presence of liquid water or high relative humidity (Aulin *et al.* 2010). A popular way to overcome such problems is to employ a hydrophobic additive, either throughout the carrier structure or at least in its outer layer

(Upadhyay *et al.* 2025). To gain even higher resistance to the permeation of oxygen, oils, water vapor, *etc.*, many recently published formulations contain a platy mineral; the idea is that such particles make it necessary for any diffusing molecules to take a longer and more tortuous path in order to pass through a film. Thus, the question that was considered earlier can be reframed as, “Do the performance requirements of barrier coatings, which can imply dense film structures, hydrophobic nature, and impermeability, tend to block biodegradability of the film structures? In addition, do these properties mean that it will be substantially more difficult to repulp such a single-use container in an ordinary paper recycling facility, even if all of its components have been selected based on environmentally friendly criteria?”

A third way to define a water-borne biodegradable and recyclable barrier layer single-use food package is to contrast it with the kinds of products that are currently dominant for such applications. Though it is widely known that petroleum-based plastics dominate that market, the degree of refinement of such products is often overlooked. For example, poly(ethylene vinyl alcohol) is well known for its superior ability to block oxygen transport (Schmid *et al.* 2012). However, it is not biodegradable. Plastics of various types, including bioplastics, may be co-extruded as a multiple-layer films (Giardi *et al.* 2003; Ai *et al.* 2026). In this way, one may achieve a combination of favorable contributions to barrier properties and strength properties.

Waterborne

The term waterborne, which serves to further define the scope of this review article, implies that the coating formulation is prepared in water. As has already been noted, water-soluble polymers such as starch, chitosan, and PVOH are popular choices in recent related research publications. Other options might include latex particles (Chen *et al.* 2024; Benz *et al.* 2025; Upadhyay *et al.* 2025), rosin emulsion particles (Lu *et al.* 2025; Zhu *et al.* 2025), and even certain bioplastics that have been modified in various ways to render them dispersible in water (Aayanifard *et al.* 2024; Calosi *et al.* 2024; Elkholy *et al.* 2025; Hämäläinen *et al.* 2025).

A reason for focusing on the water-borne category of barrier coating options in the present review is that such products are expected to have more favorable behavior with respect to repulpability and biodegradability in comparison to a competitive type of formulation, which will be briefly described next.

Non-aqueous barrier layer films prepared by melt-forming, etc.

Certain bioplastic compounds, such as poly(lactic acid) (PLA), can be formed into barrier films by melt-extrusion or casting from a non-aqueous solution (Tao *et al.* 2024). Because these forming methods do not start with the use of water to disperse or dissolve the components in an initial formulation, it is reasonable to expect different behaviors with respect to reprocessing the material after it has completed its function as a single-use container. For instance, an extruded or melt-blown film applied to paper would likely have a greater tendency to maintain its film-like form when placed in the repulper of a paper recycling mill. It might be possible, in some instances, to remove such film remnants, for instance by screening or other separation processes (Srivatsa and Markham 1993). Such non-aqueous barrier systems are outside the scope of the present review and are mentioned only to provide context for the distinction between water-borne and non-aqueous approaches.

Three Paths for Used Single-use Food Containers

The three pathways considered in this review represent distinct end-of-life or environmental-fate scenarios: repulping or recycling; composting; and unmanaged biodegradation. The importance of each pathway in practice varies with regional collection systems, recycling infrastructure, composting capacity, consumer behavior, and waste-management policies.

Available quantitative data highlight substantial regional variation in the end-of-life management of paper-based packaging. In Europe, paper and cardboard packaging achieved a recycling percentage of approximately 87% (Confederation of European Paper Industries [CEPI], 2026). In the United States, approximately 67.4 million tons of paper and paperboard were generated in 2018, representing 23.1% of total municipal solid waste (MSW) generation. Of this amount, approximately 46 million tons were recycled, corresponding to a recycling percentage of 68.2% for paper and paperboard. A further 4.2 million tons were combusted with energy recovery, accounting for 12.2% of all MSW combusted, while 17.2 million tons of paper and paperboard were landfilled, representing 11.8% of all MSW landfilled (U.S Environmental Protection Agency [EPA], 2025). These figures indicate that recycling remains a major route for paper-based packaging, although the distribution among recycling, combustion, and landfiling differs across regions. Data specifically quantifying the proportion of paper-based packaging that is composted remain more limited. It is also important to distinguish managed waste routes from environmental release. Recycling, industrial composting, and landfiling are controlled waste-management pathways, whereas littering, open dumping, and uncontrolled release represent mismanaged waste. Therefore, biodegradation in soil or other natural environments could be considered an environmental-fate process rather than a conventional waste-management pathway. This distinction is important when assessing the fate of paper-based packaging, particularly given substantial regional differences in waste collection, treatment, disposal, and uncontrolled release (Wilson 2023).

To address various problems related to present and future generations of single-use food packaging, based on waterborne barrier coatings, three main paths of events will be considered. As illustrated in Fig. 1, these can be briefly called recycling, composting, and biodegradation under natural environmental conditions.

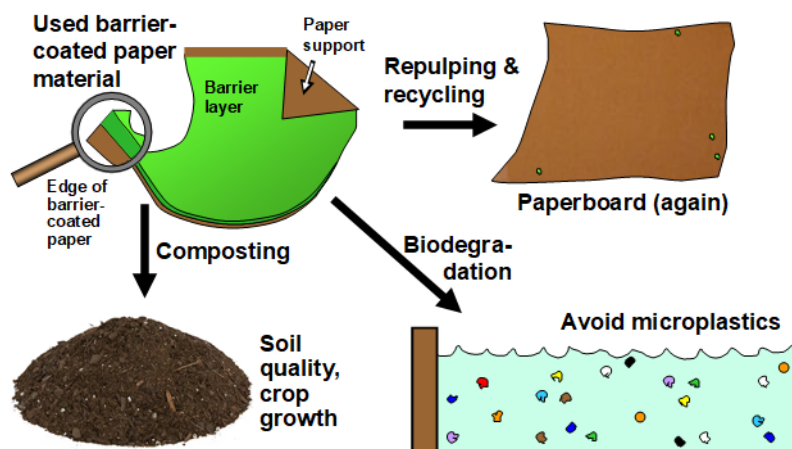


Fig. 1. Schematic of three main paths that can be envisioned for the fates of suitably designed paper-based food packing prepared with waterborne barrier layers

Recycling as an envisioned preferred path for single-use food containers

It will be assumed, in this article, that the combined environmental impacts can be minimized by setting up a system in which any single-use packaging containers are efficiently recycled. It will be assumed that the main goal of such recycling will be to recover valuable cellulosic fibers, which can be used in a wide variety of paper products, including the inner plies of various paperboard products. No assumptions are being made regarding whether such recovered material will or will not be returned to its previous cycle of usage that may include food contact. Rather, the assumed goal will be to use the recovered fibers in any paper or paperboard product.

There are several factors that support the desirability of recovering and reusing cellulosic fibers from used repulpable single-use food containers. First, such containers are likely to contain high-quality bleached kraft fibers, which have a relatively high inherent value for papermaking (Brogdon and Lucia 2023). As explained in the cited article, the cellulose macromolecules in such recovered pulp are likely to have a relatively high molecular mass. A sufficiently high chain length of the cellulose molecules has been correlated with favorable paper strength properties (Brogdon and Lucia 2023). Second, there is a relatively mature technology and infrastructure to support recycling of paper (Bajpai 2024). Third, success has been reported in recovering fibers even from some difficult-to-recycle food packages, such as milk cartons (Srivatsa and Markham 1993). Such recycling of beverage cartons has been considered for large-scale implementation in Belgium, the Netherlands, and Luxembourg (Luoto 2022).

There are various challenges in the way of recycling food containers, at least in the near term. First, most local or regional waste and recovery systems presently deal with most single-use food packages, even those mainly composed of paper, as part of the general trash stream. Landfilling is the most common fate of the materials, especially when composting is not mandated. Second, the presence of residual food can raise concerns about health and odors. It follows that even if paper recycling is being viewed as a preferred outcome, there would need to be a back-up plan that can be in place, at least during an interim period. Two such interim approaches will be considered in this article: industrial composting and biodegradability in natural environments.

Composting as an alternative path for single-use food containers

Though composting fails to recover the full value of cellulosic fibers, which are expected to be a major component of paper-based single-used food-packaging, composting has a lot of advantages. Like paper recycling, industrial composting can be regarded as a mature technology (Sharma *et al.* 1997). Infrastructure for large-scale composting is becoming widely available in the US, especially with respect to processing of yard wastes (Amlinger *et al.* 2003). In Europe, composting of food-related waste has become essentially required, since biodegradable materials are not permitted in landfill facilities (Cesaro *et al.* 2015). By using optimized systems of turning, aeration, and the size of compost piles, in addition to adjustment of carbon-nitrogen-phosphorus ratios, it has been possible to achieve high reliability and efficiency, leading to production of mature compost that generally has a favorable effect on soil properties (Aylaj and Adani 2024). Another favorable aspect of industrial composting is that relatively high temperatures (*e.g.* 60 °C) are reached (Hubbe *et al.* 2010). Such temperatures are high enough to promote rapid biodegradation and breakdown of various objectionable microorganisms (Yuan *et al.* 2025).

In the relatively near term, specialists advocate composting as the best disposal option for food wastes (Zaini *et al.* 2023). In summary, composting can be regarded as an appropriate technology to deal with both food waste and with ordinary paper products. However, it is not well suited for discarded items that contain non-compostable plastics.

General biodegradability as a third path for single-use food containers

In an ideal world, single-use food containers would all be properly routed to some form of processing or disposal, depending on local ordinances and routine practices. But the reality is that some fraction of such waste is currently being disposed of as litter, illegal dumping, or becoming released into waterways, such that the materials eventually can reach the sea.

There is urgent concern regarding petroleum-based plastic waste. The very poor biodegradability of typical petroleum-based plastics means that they tend to build up in the environment. Such non-biodegradability can be regarded as an advantage when placing plastic items in a landfill (Demetrious and Crossin 2019). This is because non-biodegradable plastics are not expected to emit methane when placed in the anaerobic conditions of a landfill. Unfortunately, when plastic items in the environment break down partially, the result can be microplastics, which are of serious concern. Microplastics have been found to be building up in the fat tissues, brains, and other organs of animals and people in all corners of the world (Xayachak *et al.* 2024). In addition, landfill biodegradation of polyfluoroalkyl substances (PFAS) associated with food packaging can give rise to toxic gaseous emissions (Ye *et al.* 2024).

For these reasons, there is an urgent need to replace the existing plastic-based single-use food containers with something else, something that does not accumulate in the environment and cause unintended harm (Xayachak *et al.* 2024; Murugesan and Li 2026). Based on these considerations, if single-use food packages are going to continue into the future, then they need to achieve three main goals simultaneously – repulpability, industrial compostability, and general biodegradability, avoiding materials that will harm the environment (Kathuria and Zhang 2022)

Of these three potential routes for materials management, repulpability can be regarded as particularly attractive, since it offers a way to recover a high proportion of the value of the most prominent materials in multiple cycles of usage. But most single-use food packaging is not repulped, and many technological and policy hurdles will need to be overcome before such practices become widespread (Kathuria and Zhang 2022; Belle *et al.* 2024). Composting, at an industrial scale, is a mature technology, but the presence of non-compostable petroleum-based plastics in most present-day single-use food packaging presently discourages the use of composting (Kathuria and Zhang 2022). Planning and coordination of policies, logistics, and infrastructure will be needed to overcome that hurdle.

In the immediate future, most packaging waste, of all kinds, is likely to be routed for landfills, but much of it can be expected to end up in the environment due to illegal dumping, careless littering, and other consequences of lack of a complete management plan (Demetrious and Crossin 2019). All of this means that, while repulping and composting can be regarded as prime goals for the future, it is important to include biodegradability among the required attributes of the next generation of single-use food packaging systems.

TECHNOLOGICAL BACKGROUND

Barrier Attributes

Overview

To provide context for the considering of repulpability and biodegradability issues, this section will provide some background related to the barrier properties needed in various food packaging systems, as well as some of the most widely studied formulations that are being considered in current research. The discussion is intended to provide sufficient context for understanding the relationship between barrier performance and end-of-life behavior, rather than to provide an exhaustive review of barrier mechanisms and formulation design. Figure 2 provides a schematic of some of the main substances that can be of concern when they are able to migrate either into or out of a food container. Note that the green line in the figure indicates the position (in cross-sectional view) of a hypothetical waterborne barrier layer.

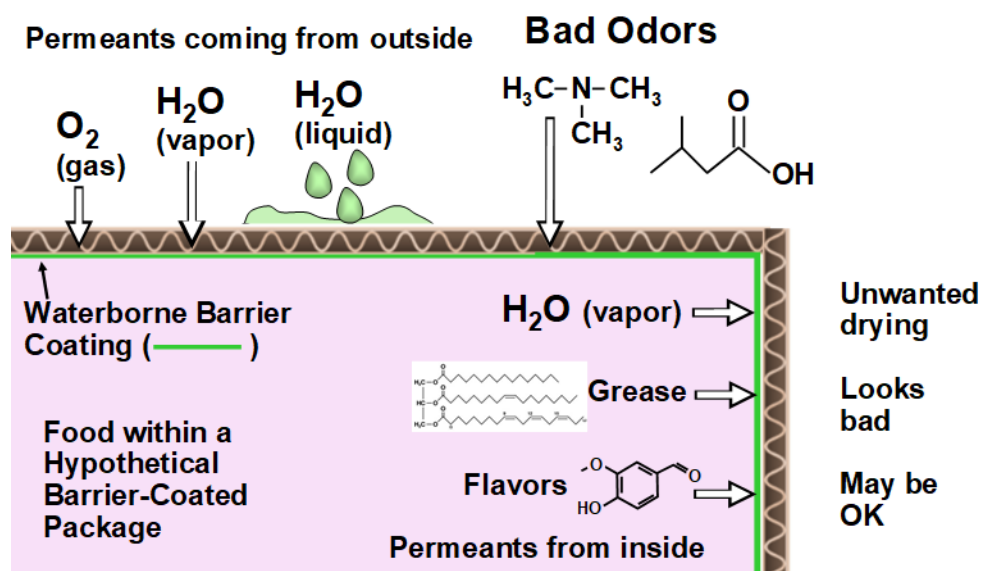


Fig. 2. Schematic illustrating some of the main substances of interest when designing barrier layers or coatings for food packaging. The “bad odors” depicted in the figure are trimethylamine (rotten fish) and isovaleric acid (sweat). The “flavor” depicted in the figure is vanillin.

Oxygen resistance

A high-priority objective of barrier coatings as part of food packaging systems is to minimize the transport of oxygen (Huang *et al.* 2014; Tyagi *et al.* 2019). Oxygen is required for many of the natural processes leading to the decay of various food items (Muiliya *et al.* 2026). Thus, oxygen permeability is one of the most widely used tests when evaluating the performance of alternative barrier film products.

Grease resistance

Grease resistance is a very important property to consider, especially in the case of greasy or oily foods (Appiah *et al.* 2025; Feroce *et al.* 2025). It is inherently quite difficult to block the transport of grease and oils due to their relatively low interfacial energy (Hubbe and Pruszyński 2020). A liquid having a low surface tension tends to wet solid surface easily, even when some of those surfaces are within pores or cracks within a barrier layer

(Marmur 2009; Hubbe *et al.* 2015). Historically, two broad approaches have been particularly important for achieving grease and oil resistance in paper-based packaging.

The older approach to resist grease penetration, developed in the early 1900s, has involved forming highly dense, relatively defect-free layers, as in the case of highly refined cellulosic fibers (Wright 1922; Kjellgren and Engstrom 2004). More recent studies have examined the use of such greaseproof papers as substrates for alternative barrier treatments, including starch coatings (Kjellgren and Engstrom 2008).

For many applications, another approach has been to treat the paper surfaces with perfluorinated alkyl substances (PFAS), thereby reducing the surface free energy of the solid surfaces sufficiently to prevent wetting even by greases and oils (Hubbe and Pruszyński 2020; Glenn *et al.* 2021). Recently, various harmful effects have become known related to the usage of PFAS, which are listed as “forever chemicals” due to their persistence in the environment (Brunn *et al.* 2023). So, there is a need to replace PFAS with alternative barrier systems.

Resistance to liquid water

Resistance to water, in its various forms, represents a special challenge when the barrier film is prepared from a water-borne formulation. This is because the formulation must ultimately provide resistance to water, which was used during its own preparation. Fortunately, a variety of well-known technological systems can be used to impart a hydrophobic nature to cellulosic materials under such conditions (Szlek *et al.* 2022). The purpose of the hydrophobic treatment, which might be focused on the surface or throughout the film material, is not only to protect the food item from wetting, but also it can be used to prevent the wetting of underlying layers in a multilayer barrier film structure.

Resistance to water vapor

If water vapor is able to diffuse from a food item and through the packaging material, then the contents might become undesirably dried out. This has been especially a challenge when attempting to maintain the fresh appearance of fruit items, such as strawberries (Cheng *et al.* 2024b; Liu *et al.* 2024; Ning *et al.* 2026). A challenge in attempting to block water vapor is that paper structures tend to swell under humid conditions, and even more-so under wet conditions (Hubbe *et al.* 2024). Thus, there will be a need to prepare barrier structures in which any cellulose-based components are somehow protected from the effects of swelling.

Overview of Water-borne Barrier Layer Compositions

In view of the various aspects of needed barrier performance, as outlined above, there are several general approaches that have become widely reported in studies involving waterborne barrier coatings. In such studies, the usual goal is to match or exceed the performance of petroleum-based food packaging structures or films. Components considered in such studies include nanocellulose films, hydrophilic polymers, platy mineral particles, and various hydrophobic substances. These options are illustrated schematically in Fig. 3.

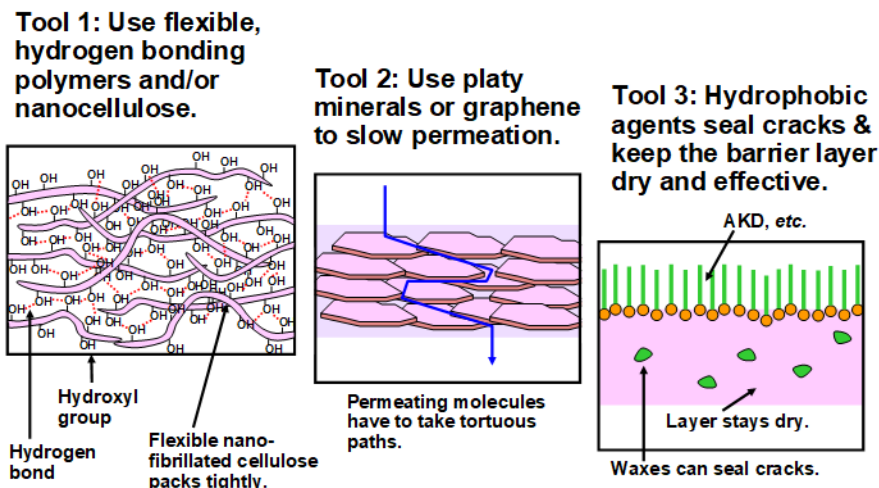


Fig. 3. Schematic illustration of different contributing options for enhancement of barrier properties of waterborne coatings by means of adding different film components. Tool 1 primarily contributes to oxygen and grease resistance through formation of dense, hydrogen-bonded networks; Tool 2 primarily improves resistance to gas and vapor transport by increasing the tortuosity of permeation pathways; and Tool 3 primarily improves liquid-water and water-vapor resistance by reducing wetting, swelling, and defect-mediated transport. The effects may overlap depending on formulation and test conditions.

Cellulose-based polymers and their derivatives represent an important category of waterborne coating materials beyond nanocellulose for paper-based packaging. Earlier reviews have highlighted the potential of cellulose derivatives and other bio-based polymers as alternatives to petroleum-derived coatings, owing to their film-forming ability, affinity for paper substrates, and potential to provide functional barrier attributes (Rastogi and Samyn 2015; Nechita and Roman 2020; Kunam *et al.* 2022). However, the hydrophilic nature of many polysaccharides can limit their moisture resistance. Researchers have considered chemical modification and combinations with other biopolymers, nanofibers, and nanofillers to improve coating performance. More recent work has demonstrated the potential of aqueous cellulose-derivative coatings based on hydroxypropyl cellulose (HPC) and hydroxyethyl cellulose (HEC). Palmieri *et al.* (2024), for example, reported that aqueous HPC and HEC coatings improved the water-vapor barrier of paper, with reductions in WVTR of approximately 40% for HEC and HPC coatings and up to 60% for a higher-concentration HPC coating; incorporation of detonation nanodiamonds further increased the reduction in WVTR to as much as 70%. These findings demonstrate that cellulose derivatives can serve as effective film-forming matrices for water-borne barrier coatings, while nanofillers can further enhance their performance. At the same time, chemical modification and incorporation of additional components may alter properties such as hydrophilicity, swelling, and interactions within the coating, which can influence its subsequent biodegradation and repulpability.

Nanocellulose films

Although ordinary paper is much too porous to serve an effective barrier against gaseous or liquid permeants, it has become well known that excellent resistance to oxygen, in particular, can be achieved by forming films from very highly fibrillated cellulose. Nanofibrillated cellulose (NFC), which is also called cellulose nanofibril, has a tendency to form films with sufficiently high density, in combination with a high density of hydrogen

bonding, such that its resistance to oxygen gas transport can be superior to that of petroleum-based plastic films (Spence *et al.* 2011). The cited authors showed that even higher performance can be achieved by coating such layers with beeswax, which appears to help seal imperfections in the nanocellulose-based films. The major drawback of nanocellulose-based barrier films is that they lose much of their performance at very high humidity or when wetted by water. Thus, they need to be protected by hydrophobic layers or hydrophobic surface treatments (Tyagi *et al.* 2019; Szlek *et al.* 2022; Upadhyay *et al.* 2025).

Hydrophilic polymers (matrix options)

Consistent with the principle mentioned above about creating a high density of hydrogen bonding, as a means to be able to block oxygen and greases, barrier coatings can be prepared with hydrophilic polymers such as starch, chitosan, or poly(vinyl alcohol) (PVOH) as the principal ingredient (Cazón and Vázquez 2020). In addition to serving as a standalone barrier material, nanofibrillated cellulose (NFC) can be incorporated into these hydrophilic polymer matrices as a reinforcing and barrier-enhancing phase. Its high aspect ratio and ability to form hydrogen-bonded networks can improve the mechanical integrity of the coating and, under appropriate conditions, contribute to reduced permeant transport. Such films can therefore be reinforced with NFC, although the NFC content is often kept relatively low, with levels of 2% or less reported in some nanocomposite system, to minimize agglomeration of the reinforcing particles (Ferrer *et al.* 2016; Ilyas *et al.* 2019; Chen *et al.* 2023). However, the hydrophilic nature of both the polymer matrices and NFC can increase water uptake and swelling under humid or wet conditions. Consequently, strategies to reduce moisture sensitivity may be necessary, including crosslinking, optimized incorporation of hydrophobic compounds, or protection of the hydrophilic barrier layer with a more hydrophobic layer.

Platy minerals

Especially when the formulation is based on the use of hydrophilic polymers, as just mentioned, the barrier performance can be increased markedly by using highly platy particles such as sodium montmorillonite (bentonite) (Muiliya *et al.* 2026), hectorite (Venkateshaiah *et al.* 2022), or various graphene-type particles (Huang *et al.* 2014; Vishnuvarthanan and Ramji 2023; Dong *et al.* 2024). In theory, highly platy particles will increase the average path that a permeating molecule needs to take in order to pass through the film, especially if the plates have a tendency to orient themselves in a planar manner in the course of film processing. A study by Wolf *et al.* (2018) showed that only in the case of platy particles was it possible to achieve consistent increases in barrier performance. Fibrillar or blocky particles often had an opposite effect, which suggests a mechanism whereby particles sometimes may promote defects within films. Clay minerals generally have sufficient hydrogen bonding ability to be highly compatible with such matrix polymers as starch, chitosan, and PVOH. This compatibility favors good mixing and development of dense, defect-free films.

Hydrophobic components

Due to the inherent vulnerability of both nanocellulose and hydrophilic polymers to swelling in the presence of water, hydrophobic components are commonly utilized in water-borne barrier formulations (Lu *et al.* 2025). These materials can include natural products such as rosin and fatty acids. To be most effective, such monomers need to be

anchored. In principle, this can be achieved by using a mordant such as aluminum sulfate (Strazdins 1981; Ekhtera *et al.* 2008). Another option is to use silane-type chemical treatments (Li *et al.* 2021). For instance, alkyltrimethoxysilane reagents can covalently bond to -OH groups on polymers or fibers (Szlek *et al.* 2022). Meanwhile, the alkyl groups associated with those reagents will contribute to hydrophobicity. Alternatively, an additive such as alkenylsuccinic anhydride (ASA) or alkylketene dimer (AKD) can be used to form a hydrophobic monolayer that is bonded with ester linkages at -OH sites on the surfaces of polymers such as cellulose, starch, or PVOH (Nadeem *et al.* 2023a,b; Appiah *et al.* 2025). Both ASA and AKD can be cured during the routine drying of paper, during its production, thereby creating a water-resistant product (Szlek *et al.* 2022).

BIODEGRADABILITY OF REPULPABLE BARRIER COATINGS

Overview

When considering the biodegradation of a current or future paper-based barrier system, it is useful to distinguish between the material being evaluated and the environment in which degradation is assessed. At the material level, biodegradation can be considered for the paper or paperboard substrate alone, for the water-borne coating as an isolated material, or for the complete coated-paper packaging system. These distinctions are important because the biodegradation behavior of an isolated coating may differ from that of the complete packaging system, in which the paper substrate is often the major component. At the environmental level, biodegradation may be evaluated under aqueous, soil, or other biologically active conditions, while industrial composting represents a specialized, managed biodegradation environment. Accordingly, the studies discussed below are considered with attention to both the material being evaluated and the degradation environment.

Because the studies reviewed here differ substantially in specimen geometry, coating grammage, substrate, degradation environment, temperature, moisture, microbial population, test standard, endpoint, and duration, the reported biodegradation values should generally be interpreted as study-specific observations rather than as directly comparable absolute measures of material biodegradability.

Background: Biodegradability of Paper Products

As was noted in the Introduction, future recycling of paper-based packaging products with water-borne barrier coatings offers a preferred way to recover the value of at least the cellulosic fibers, which are expected to be the main component of future single-used food packaging systems. Composting can be regarded as a highly promising secondary way to minimize environmental harm and to gain some value from such materials after their use in containment or the serving of food. But neither of those outcomes can be regarded as a full success unless one has achieved an answer to issues such as the accumulation of litter and bioplastics in the environment. Conditions present in soils, waterways, and oceans are often less aggressive in their biodegradation, compared to industrial composting, as a way to fully break down packaging components. For instance, a recent review considered the biodegradation of cellulosic fibers (Hubbe *et al.* 2025). Though cellulosic materials are susceptible to natural, enzymatic breakdown, the process takes many days or weeks, depending on the conditions. Because barrier coatings are designed to resist wetting and permeability of a package, it is reasonable to expect them to

delay biodegradation. The important question is whether such delays, in various cases, are sufficient to raise concerns.

Approaches to speed up biodegradation

The rates of biodegradation of paper-based items can be promoted in various ways, and some of these ways can be incorporated into composting practices. One such approach is inoculation, *i.e.* the addition of living microbes to the mixture. Inoculation is widely practiced, on a very large scale, during the aerobic biological treatment of wastewater. In such operations it is routine practice to treat the incoming wastewater with a fraction of the sludge that is being collected from the base of the clarifier (Ouyang *et al.* 2020). Microbes that are present in that sludge will already have become acclimated to the composition of the incoming wastewater.

When the material to be degraded consists of mainly cellulose-rich packaging material, there may be insufficient nitrogen present to support biological growth (Hubbe *et al.* 2010). In such cases, biodegradation can be promoted by adding optimum levels of nitrogen-rich substances such as manure (Greff *et al.* 2022). Especially under industrial composting conditions, microbial metabolism can be expected to raise the prevailing temperature within the compost pile, thereby promoting the activity of many of the enzymes that are present. However, excessively high temperatures will bring about more rapid denaturation (loss of activity due to protein conformational changes), depending on the mesophilic or thermophilic nature of those enzymes.

Factors affecting paper's biodegradation

Much is known about the rates of biodegradation of paper products, which can be regarded as being mainly structures composed of cellulosic fibers. Large amounts of papermaking fibers are disposed each day into sewer systems, especially in the case of toilet tissue products. Though such fibers can be degraded by cellulase enzymes, the amount of time that such fibers spend in a typical aerobic type of wastewater treatment facility has been found to be insufficient to achieve full breakdown of such fibers into monomers such as sugars (Li *et al.* 2019; Liu *et al.* 2022). Rather, it is common for most of the weight of such fibers from tissue paper to end up as part of the sludge that is hauled to landfill sites. The moist, anaerobic conditions of typical landfill operations is expected to allow a gradual transformation of the cellulose within the discarded fibers to methane, which is a potent greenhouse gas (Li *et al.* 2018; Monster *et al.* 2019). Though modern landfill sites have equipment to collect methane, some fraction of the generated methane can be expected to escape to the atmosphere.

When discarded to moist soil, ordinary paper products will generally become degraded to the point that they are no longer readily identifiable after a month or two of biodegradation, depending on the details (Hubbe *et al.* 2025). Such a rate of degradation is of a similar speed, and sometimes faster than other nature-based cellulosic materials, such as leaves. The presence of lignin within wood and other biomass materials tends to slow down biodegradation rates due to lignin's dense, somewhat hydrophobic nature and its complex molecular structure (Venelampi *et al.* 2003). Much or essentially all of the lignin will have been removed from the fibers used for the manufacture of different paper-based packaging products, which can give them an advantage in terms of rates of biodegradation. On the other hand, many paper products will have been treated with hydrophobic agents, such as rosin-alum systems, ASA, or AKD. Though such treatments can reasonably be

expected to slow down rates of biodegradation of paper in soils, there is a need for further study to determine whether such effects are large enough to be important.

Further uncertainties regarding the rates and extents of biodegradation are associated with various minor components of typical paper products. For example, water-soluble acrylamide products are widely used to help retain fine particles in the sheet during its formation. Though such compounds are expected to degrade, there is limited available data, and it would be difficult to assess their biodegradation when paper is placed into soil. At the other extreme, biocidal compounds have been added to some barrier films (Vishnuvarthanan and Ramji 2023). These can be expected to at least slow down biodegradation.

In addition to soil degradation tests, the consumption of oxygen associated with biodegradation can also be quantified. Such tests are commonly applied when evaluating the biodegradation of various materials, including cellulose, under aqueous conditions (ISO 2019; Kwon *et al.* 2021). A recent editorial (Hubbe *et al.* 2026) discussed possible reasons why such tests often show incomplete biodegradation of cellulose even after several weeks.

Barrier Coatings & Biodegradability

Reported biodegradability

Table A (see Appendix) lists highlights from studies that included biodegradation tests. The Web of Science database was used to search the literature. The following is an example of the kinds of search strings that were employed: “Title: barrier; Topic: repulpable or recycl* or dispersible; Topic: Packaging.” Multiple searches were carried out using a variety of alternative terms in an effort to cover key aspects of the overall scope of the articles, with particular attention to this section of the review. In each search attempt, only articles providing relevant and useful information were considered further.

In most cases represented in Table A, a paper substrate had been coated with a water-borne barrier formulation. Most of the researchers whose studies are represented in Table A monitored the breakdown of paper-based products added to soil. Most used locally obtained soil, ambient temperature (20 to 25 °C), and intermediate moisture contents (Hubbe *et al.* 2025). In broad terms, most of the studies relied on periodic visual observations and weight loss tests following placement of paper-like specimens at specific depths within the soil. A few of the articles, as noted, reported biodegradation in aqueous media, for which the results were based on the consumption of oxygen or the corresponding release of CO₂ during biodegradation. These options are highlighted in Fig. 4. Because composting represents a controlled form of biodegradation, studies conducted under composting conditions are included within the broader biodegradation analysis in Table A. Studies specifically addressing composting are subsequently considered separately in Table B, with emphasis on studies using controlled or simulated composting conditions relevant to compostability. Vermicomposting studies were not included in Table B because vermicomposting represents a distinct biological treatment process rather than the conventional composting conditions considered in this section.

According to Table A (see Appendix), the observed periods required for relatively complete biodegradation were mainly between one and about 25 weeks (7 to 180 days). The periods of burial leading to the loss of most of the original paper weight depended on the composition of the specimen and other details. Although this range appears wide, the studies collectively reveal several consistent principles governing the biodegradation of waterborne barrier coatings. The results indicate that biodegradation is controlled less by

whether a coating is derived from renewable resources than by how the coating chemistry modifies the accessibility of the polymer network to water, enzymes, and microorganisms. Consequently, the same structural modifications that improve water, grease, and oxygen barrier performance often influence the degradation rate after disposal. The challenge for coating developers is therefore not simply to maximize barrier performance or biodegradability independently, but to optimize both properties simultaneously.

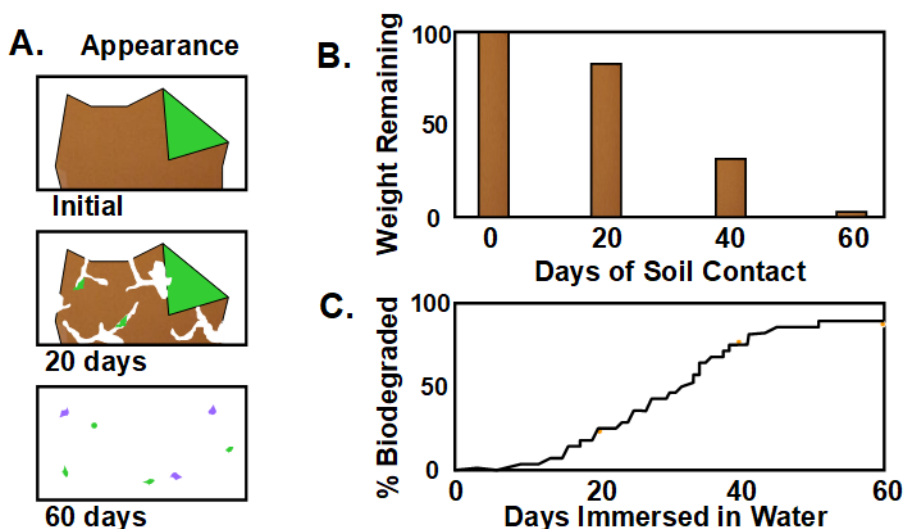


Fig. 4. Schematic illustrating the most commonly used approaches to assessing the extent of biodegradation of waterborne barrier coating films, whether or not in combination with a paper substrate. A: appearance; B: weight loss; C: oxygen consumption or CO₂ release

Trends revealed by biodegradation results

One of the clearest trends emerging from the literature is that strategies used to improve barrier performance frequently delay biodegradation rate because they create a denser and more stable polymer network. For example, Kisku *et al.* (2014) directly compared starch/poly(vinyl alcohol) films with and without nanosized CaCO₃ during a 180-day soil burial test. The unfilled starch/PVA films were fully degraded within 180 days, whereas the CaCO₃-containing nanocomposites degraded at a lower rate, with biodegradability decreasing as the CaCO₃ loading increased. The authors attributed this reduction to the strong interfacial interactions between the CaCO₃ nanoparticles and the polymer matrix. Thus, the 180-day period represents the duration of the test rather than a specific time required for the CaCO₃-containing films to reach complete biodegradation. This result indicates that the presence of an inorganic filler did not prevent biodegradation, but it reduced the rate relative to the unfilled polymer matrix. Mohan *et al.* (2017) similarly reported delayed biodegradation when nanoclay was incorporated into starch films, although the magnitude of the effect cannot be directly compared with Kisku *et al.* (2014) because the two studies used different clay types, polymer formulations, and experimental conditions. Channa *et al.* (2022) likewise observed a moderate reduction in the degradation rate of PVOH films containing glass flakes during soil burial. Taken together, these studies suggest that mineral fillers can retard biodegradation, but the extent of retardation depends on filler loading, filler–polymer interactions, and the resulting structure of the composite. The available evidence therefore supports a rate-reducing rather than a biodegradation-preventing effect. In Kisku *et al.* (2014), the authors associated the reduction with strong

interfacial adhesion between nano-CaCO₃ and the polymer matrix, while the other studies suggest that incorporation of mineral phases can alter the structure and accessibility of the biodegradable polymer. These effects can improve barrier and mechanical properties but may also make the polymer phase less readily accessible to water and microorganisms.

While Kisku *et al.* (2014) and Mohan *et al.* (2017) reported slower biodegradation after incorporation of CaCO₃ and nanoclay, respectively, Venkateshaiah *et al.* (2022) observed the opposite behavior for a different mineral–polymer configuration. In that study, a spray-applied waterborne sodium-hectorite coating was deposited onto gum kondagogu films, and biodegradation was quantified from CO₂ evolution under aerobic aqueous conditions. The coated films exhibited a moderately higher biodegradation rate than the uncoated gum films. The authors attributed this behavior to swelling of the hectorite upon water uptake, which caused fragmentation of the film and increased the surface area available for hydrolytic and microbial degradation. This mechanism differs from the behavior reported for the starch-based CaCO₃ and nanoclay systems, where mineral incorporation was associated with reduced biodegradation. The contrast may reflect differences in the mineral itself, the polymer matrix, and, importantly, the manner in which the mineral was incorporated into the material. Whereas dispersed fillers can strengthen filler–polymer interactions and create a more resistant structure, a water-responsive hectorite surface layer may swell and promote fragmentation when sufficiently hydrated. Thus, these studies do not support a simple rule that mineral fillers either accelerate or retard biodegradation. Rather, they demonstrate that the effect depends on the resulting filler–polymer structure and its response to the degradation environment. These studies demonstrate that the physical architecture of the coating can be as important as its chemical composition in determining degradation behavior. This finding has important implications for coating design because the tortuous diffusion pathways responsible for improved barrier performance may also prolong environmental persistence after disposal. The practical takeaway is that filler loading and dispersion should be optimized not only to achieve barrier performance but also to preserve acceptable biodegradation rates.

Crosslinking and chemical modification

Crosslinking or chemical modification provides another illustration of the balance between functional performance and end-of-life behavior. Gürler *et al.* (2021) compared unmodified potato starch (PPS), 3-aminopropyltrimethoxysilane (3-APTMS)-modified starch, and a 3-APTMS-modified starch/PLA bilayer under controlled composting conditions according to ISO 14855. After 46 days, biodegradation was 9.30% for PPS, compared with 5.45% for PPS-3APTMS and 5.08% for the PPS-3APTMS-PLA bilayer. The lower biodegradation following 3-APTMS treatment coincided with reduced film solubility and swelling and improved water-vapor barrier and thermal properties, which may have contributed to the slower degradation. Thus, the study demonstrates that the silane treatment was associated with slower biodegradation, but it does not isolate the effect of crosslinking from the accompanying changes in physicochemical properties. The further reduction observed for the PLA-containing bilayer was attributed by the authors to the slower degradation tendency of PLA. Choe *et al.* (2024) likewise reported lower marine biodegradation for boric-acid-crosslinked PVOH-coated paper, providing additional evidence that modifications that increase network stability can retard degradation. However, taken together, these studies support an association between increased material stability and slower biodegradation rather than establishing crosslinking alone as the controlling mechanism. These observations are consistent with the effects of crosslinking

and other structural changes that can strengthen intermolecular interactions and reduce polymer mobility, thereby making the network less susceptible to hydrolysis and microbial attack. At the same time, these structural changes can improve mechanical stability and moisture resistance during product use. Together, these studies highlight one of the central design challenges for sustainable packaging: modifications that improve package durability may often reduce degradation rates after disposal. Future coating formulations should therefore seek an optimum level of crosslinking that provides sufficient barrier performance without unnecessarily sacrificing biodegradability.

Barrier performance vs. biodegradability

Importantly, improvements in barrier performance do not necessarily prevent subsequent degradation, although they may alter its rate. Dong *et al.* (2024) demonstrated this tradeoff using starch films containing up to 10 wt% MXene nanoplatelets. At 10 wt% MXene, the Young's modulus increased from 456 to 1923 MPa, while water-vapor and oxygen permeability decreased by 92.9% and 74.0%, respectively. However, the increased reinforcement was accompanied by greater stability during soil exposure. Pure starch films began fragmenting after approximately two weeks, whereas the MXene-containing films, particularly at higher MXene contents, remained more stable before undergoing apparent decomposition within six weeks. The authors attributed this increased stability to strong hydrogen bonding between starch and MXene, while disruption of these interactions by soil moisture and biological activity ultimately allowed the films to break down. Thus, the study demonstrates that substantial improvements in barrier and mechanical properties can be accompanied by some retardation of physical degradation, rather than being achieved entirely without an end-of-life tradeoff. Importantly, the reported six-week disappearance was based on visual observation during soil burial and was not a quantitative measurement of mineralization. The authors themselves noted that CO₂ evolution, such as that measured according to ASTM D5988, would be needed to quantitatively assess biodegradation. Consequently, the study provides evidence of eventual physical breakdown but does not establish the extent or rate of complete biodegradation. Its main lesson for coating design is therefore more nuanced: strong filler–polymer interactions can provide substantial barrier improvements while still permitting eventual breakdown, but the resulting change in degradation rate and the distinction between physical disintegration and microbial mineralization must be considered when evaluating end-of-life performance. This study provides two valuable points. First, substantial improvements in barrier performance can be achieved while retaining the potential for biodegradation, although higher MXene contents may delay degradation. Second, claims regarding biodegradability should be supported by standardized testing rather than visual observations alone, since fragmentation or visual disappearance does not necessarily indicate complete microbial mineralization. These conclusions are particularly relevant as increasing numbers of high-performance bio-based coatings are proposed for commercial packaging applications.

Not all additives reduced biodegradation. Fernández-Santos *et al.* (2021) demonstrated that biodegradable plasticizers including xylitol, sorbitol, glycerol, and maltitol improved both the flexibility and barrier properties of cellulose nanocrystal films while simultaneously increasing their biodegradation under controlled composting conditions. Interestingly, the enhanced biodegradation occurred despite improvements in resistance to water penetration, suggesting that enzyme accessibility to the cellulose network is not governed solely by water absorption. Among the plasticizers investigated, xylitol produced the highest biodegradation, consistent with its own rapid microbial

degradation. These findings contrast with the effects of mineral fillers and extensive crosslinking, illustrating that the influence of additives depends not simply on whether they improve barrier properties but on how they alter polymer structure and microbial accessibility. From a formulation standpoint, this study demonstrates that additive selection can be used strategically to compensate for reductions in biodegradability associated with other barrier-enhancing modifications.

Hydrophobic modification

Several recent studies further demonstrate that hydrophobic surface modification can substantially improve packaging performance while maintaining eventual biodegradability, although the degradation period is often extended. Huang *et al.* (2026) developed regenerated bamboo films coated with epoxidized soybean oil that exhibited excellent water and gas barrier properties while allowing the biodegradation rate to be tuned by controlling the thickness of the hydrophobic surface layer. Increasing the coating thickness progressively delayed degradation because the hydrophobic layer reduced water penetration, microbial colonization, and hydrolysis of the underlying biomass, yet the coatings ultimately biodegraded through hydrolysis of ester bonds followed by microbial metabolism. Similarly, Guo *et al.* (2026) developed hydroxypropylated and acetylated starch coatings that provided excellent water and oil resistance, remained fully repulpable, and completely degraded during soil burial within approximately 110 days. These studies are particularly encouraging because they demonstrate that appropriately designed hydrophobic modifications can satisfy the demanding barrier requirements of food packaging while still supporting circularity through biodegradation and, in some cases, recyclability. Rather than viewing hydrophobicity and biodegradability as mutually exclusive objectives, these studies show that both can be achieved when the coating chemistry is carefully engineered.

Biodegradation evaluation methods

Another important observation emerging from the literature concerns the methods used to evaluate biodegradation. Reported degradation times cannot be directly compared because the published studies employed markedly different testing protocols, including soil burial, aqueous biodegradation, vermicomposting, marine degradation, industrial composting, and standardized respirometric measurements based on carbon dioxide evolution. Emmert *et al.* (2021), for example, evaluated biodegradability according to ISO 14855 under controlled industrial composting conditions, demonstrating more than 90% conversion of organic carbon to carbon dioxide within six months. Fernández-Santos *et al.* (2021) similarly quantified biodegradation using carbon dioxide evolution during controlled composting, whereas many other investigations relied primarily on weight loss or visual changes during soil burial. As Dong *et al.* (2024) emphasized, visual disappearance should not be equated with complete biodegradation because fragmentation does not necessarily indicate mineralization by microorganisms. Consequently, differences among studies often reflect variations in testing methodology in addition to differences in material composition and process. Greater use of internationally standardized biodegradation methods would therefore improve comparisons among emerging coating technologies and strengthen environmental claims associated with sustainable packaging materials.

An area of needed research

A notable gap in the current literature is that most studies continue to evaluate free-standing films rather than coated paper products. While film studies provide valuable insight into degradation mechanisms, they do not fully represent commercial packaging structures in which the coating interacts with a porous cellulose substrate. The relatively limited number of studies evaluating coated paper indicates that biodegradable barrier coatings generally slow degradation without preventing the eventual biodegradation of the paper product. Future research should therefore place greater emphasis on complete coated packaging systems evaluated under standardized composting conditions while simultaneously considering barrier performance, repulpability, and biodegradability. Such an integrated approach will provide a more realistic assessment of whether emerging waterborne barrier coatings can satisfy both performance requirements during use and sustainability objectives at the end of their service life.

Times and Extents of Biodegradation

A general finding from the reviewed studies was that the incorporation of different additives into a primary matrix polymer in a barrier film often decreased the extent of biodegradation measured over the reported test period, although the magnitude of the effect was generally modest. Thus, the primary component of a film, such as starch, PVOH, or chitosan, *etc.*, appeared to have a greater influence on biodegradation than lesser ingredients such as nanocellulose, nanoclay, or hydrophobic components. Such comparisons are shown graphically in Fig. 5 for studies listed in Table A.

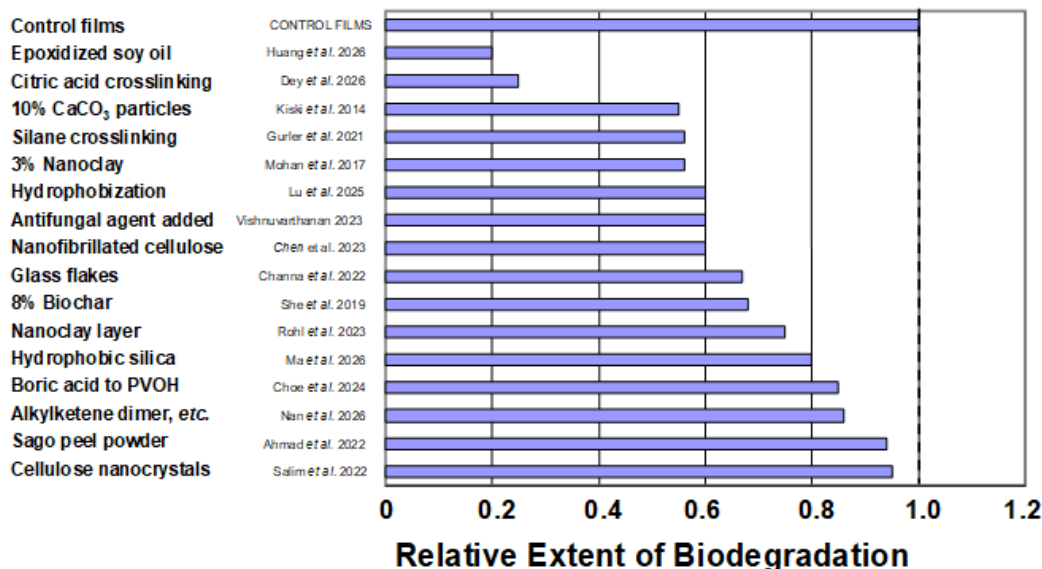


Fig. 5. Approximate relative extent of biodegradation of barrier-film systems containing various additives, relative to the corresponding control materials, for studies listed in Table A. Values represent the extent reported at the respective test endpoint and are not directly comparable across studies because of differences in test method, environment, and exposure time.

Because the studies employed different biodegradation environments, test methods, and exposure periods, the values shown in the figure should be regarded only as approximate relative values rather than as directly comparable measures of biodegradation kinetics or ultimate biodegradability. Note that the top bar of the figure, labeled as “Control

film,” represents the default conditions of each of the listed studies, and that value is set to 1.0. The other bars represent the reported extent of biodegradation relative to that control under the conditions and time used in the respective study.

As shown, all of the studies included in the plot gave results in the range of 0.2 to 0.94, relative to the corresponding extents of decompositions of the default films. These results indicate that several additives reduced the extent of biodegradation observed within a reported test period. However, the available data do not establish whether these reductions reflect slower degradation kinetics or a lower ultimate extent of biodegradation.

To help put the results listed in Table A further into perspective, Fig. 6 plots the reported periods of observation corresponding to about 80 to 90% biodegradation. In some cases where the reported biodegradation was somewhat different from 80 or 90%, the time was interpolated, based on a logarithmic scale. The relatively wide range of reported times, within most of the categories, can be understood based on the fact that the different reported findings were based on entirely different conditions. Details such as specimen thickness, soil conditions, temperatures, and moisture were often strongly different from each other. In addition, some authors based their results on appearance, others by weight loss, and yet others by the consumption of oxygen during biodegradation.

By focusing on the calculated average biodegradation times (shown as the red, open square symbols), the specimen categories can be arranged approximately according to increasing time required to reach 80 to 90% biodegradation, while recognizing the substantial overlap within the logarithmic ranges among the individual studies. For purposes of interpreting this distribution, categories with calculated mean times of approximately 50 days or less were grouped descriptively as “relatively easy to biodegrade”. On this basis, gums/alginate, starch, PVOH, and nanocellulose fall within this group. The category labeled “Gums, alginate” also includes polysaccharide mucilage, carrageenan, gelatin, and protein. This ~50-day value is used only as a practical boundary for interpreting the distribution of the compiled studies and is not intended as a standardized criterion for biodegradability. Although cellulose itself is generally regarded as much more resistant to biodegradation in comparison to starch (Hubbe *et al.* 2025), the relatively short times observed for nanocellulose in Fig. 6 may reflect its high accessible surface area as well as the removal of lignin, rendering it more degradable in comparison to ordinary cellulosic materials. The fact that PVOH finds membership in the “relatively easy to biodegrade” category underscores the principle that biodegradability is not the same thing as “bio-based”.

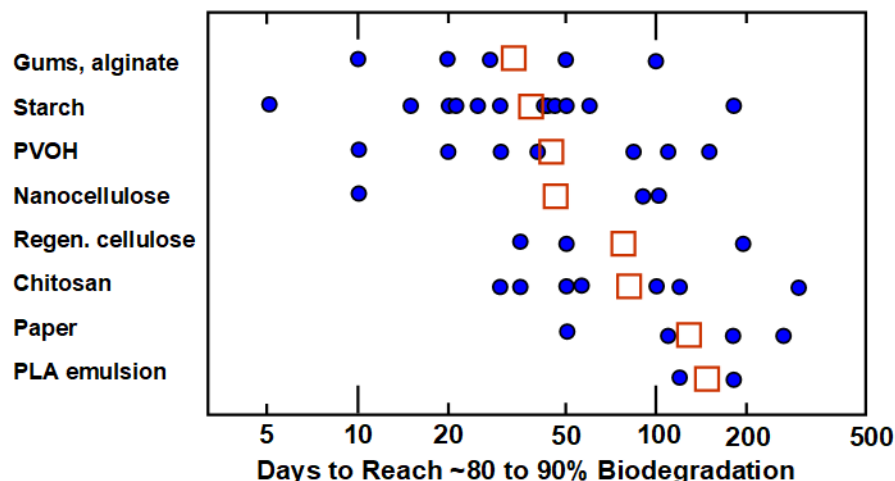


Fig. 6. Reported or estimated time to achieve ca. 80 to 90% biodegradation of barrier-type films (or the associated paper material). The red unfilled squares indicate the calculated average values (based on the $\log_{10}$ values) for each category.

An intermediate class of barrier film materials, based on the positions of the open square symbols in Fig. 6, includes regenerated cellulose and chitosan. The reported regenerated cellulose materials were not in the nanocellulose category. Thus, their generally longer times required for biodegradation in comparison to nanocellulose is consistent with their lower accessible surface area per unit mass. Regeneration involves conversion from cellulose I to cellulose II, which usually has a lower degree of crystallinity (Armira *et al.* 2021); however, the specific contribution of this structural change to the biodegradation behavior of the regenerated cellulose materials cannot be separated from other material characteristics. The fact that chitosan-based films tended to be less biodegradable than starch-based films is consistent with their more hydrophobic nature (Cunha *et al.* 2008). As described elsewhere (Hubbe 2019), during the drying of such films, the outermost chitosan molecular segments at the air-exposed surface may orient such that their hydrophilic groups general face inward, leaving the outer surface deficient in polar or ionically charged, hydrophilic groups. Such an orientation can be expected to delay wetting and swelling of the films, thereby potentially delaying biodegradation.

The most biodegradation-resistant specimens, according to the positions of the open square symbols in Fig. 6, were “paper” and “PLA emulsions”. It should be noted, first of all, that there was no attempt in this work to separately collect information about the biodegradation rates of cellulose-based paper; rather, such information came from some of the articles focused on barrier coatings. Some of these articles included tests in which the coated paper was evaluated for biodegradability, rather than testing the coatings. The much greater mass per unit area, in addition to the larger size of papermaking fibers in comparison to true film components can be used to explain somewhat longer required periods to achieve biodegradation. Rates of biodegradation of paper, as well as other cellulosic materials, have been recently reviewed (Hubbe *et al.* 2025). It is important to keep in mind that cellulosic materials, including those associated with paper, routinely biodegrade in natural environments (Hubbe *et al.* 2025). In other words, the rates of biodegradation far exceed what is needed to avoid accumulation of those materials in soils or water bodies. Thus, with the possible exception of PLA emulsions, all of the categories represented in Fig. 6 can be included in the “biodegradable” category.

Though poly(lactic acid) (PLA) is compostable under industrial conditions (see next section), tests have shown that it fails to break down readily under typical soil or aqueous conditions (Karamanlioglu *et al.* 2017). However, it is reasonable to expect that an emulsified form of PLA might behave differently, and such systems were included in the present literature search. A possible greater biodegradability of smaller PLA particles had been speculated in an earlier review article focused on the formulation of PLA-based barrier films (Hubbe *et al.* 2021). The fact that the emulsified PLA systems were in the “least biodegradable” category represented in Fig. 6 is consistent with the known non-biodegradable nature of macroscopic PLA material. Future work will be needed to determine whether or not emulsified PLA materials can pose hazards associated with microplastics in the environment (Xayachak *et al.* 2024; Panda *et al.* 2026).

An unresolved issue in essentially all of the studies in Table A is whether or not there was still a residue of non-degraded material left over in the soil after visible remnants no longer could be detected by eye. For example, some other studies have reported the presence of microplastic particles within soils (Guo *et al.* 2020), and such particles were assumed to have had their origins in the partial breakdown of macroscopic plastic pieces. Hazards and fates of such microplastics have been less studied in soils, in comparison to studies of their presence and behavior in ocean environments (Xayachak *et al.* 2024).

COMPOSTING AND WATER-BORNE BARRIER COATINGS

Effects of Composition on Compostability

Table B (placed after Table A in the Appendix) provides highlights of studies considering compostability. As noted by Dey *et al.* (2026), industrial composting systems often involve the temperature range of 50 to 60 °C in the presence of a dynamic community of microbes. Such conditions are expected to accelerate the biodegradation, especially in cases where the breakage of ester bonds in a coating material is needed. Industrial composting most often involves control of air flow at the base of relatively large rows of biodegradable material. In such operations, attention is paid to such variables as temperature, moisture, and the ratios between carbon, nitrogen, and phosphorus in the mixture (Hubbe *et al.* 2010).

Conditions are optimized to achieve mature compost, meaning that any further biodegradation of such compost will be limited. This approach avoids excessive shock to crops being grown using that compost as a soil amendment. Ideally, mature compost will add value to soil due to its water-holding ability, its nutrient contents, and its sufficiently low potential for further oxidative biodegradation. Because composting can be regarded as a subset of biodegradation, the studies selected for Table B are also included in the broader biodegradation analysis in Table A. Table B focuses specifically on studies that evaluated the materials under controlled, simulated, or other explicitly identified composting conditions; studies based on other biological treatment processes, such as vermicomposting, were not included.

Abiotic conditions required to degrade PLA

Three out of the five composting studies represented in Table B were associated with the use of PLA in barrier coatings. In other research, PLA has been found to require high temperatures for its degradation, and the mechanism of its biodegradation appears to involve abiotic processes that are associated with its softening or melting (Karamanlioglu

et al. 2017; Banerjee *et al.* 2024). These requirements are often met under the conditions of industrial composting.

Suitability of compost for soil amendment or landfilling

There are some additional issues related to composting of barrier-coated food packaging materials that seem to merit further research. For instance, none of the relatively few articles considered in Table B included extensive evaluation of the toxicity and maturity of the compost that had been prepared with food packaging materials. Future studies of that type may be needed. There is a further approach that is worth considering in the case of waste mixtures that have been judged to be unsuitable for addition to soil for agricultural purposes. For instance, the material might have excessive levels of heavy metals (Zheng *et al.* 2022; Aylaj and Adani 2024). In such cases, it is proposed that a composting process has potential to be used as a preparatory step before landfilling. The idea is that by intentionally metabolizing and oxidizing the organic content, there is potential to greatly decrease the generation of methane if and when the material encounters moist, anaerobic conditions within a landfill (Pearse *et al.* 2018). Though modern landfills are generally set up to capture much of the evolved methane, there is expected to be great diversity in the efficiency of such collection at different landfill sites in different regions.

REPULPABILITY OF PAPER AND BARRIER LAYERS

Overview

As stated in the Introduction, the recycling of water-borne barrier coated paper can be regarded as a preferred option after such items have been used. Such processing achieves another cycle of usage of the cellulosic fibers. The ideal would be to enable multiple cycles of reuse of the fibers. In some cases, it may also be possible to recover and reuse other solid components of the material, such as components of the barrier layers. To set the context for discussing the repulpability of such systems, the next topic to discuss will be repulpability of used paper products in general. Subsequent topics within this section will include factors affecting the redispersal of fibers during repulping of paper coated with barrier layers, factors affecting the yield of the repulping process, and various reported or expected adverse effects of retained barrier coating materials in the recycled paper.

Background: Repulpability of Paper-based Products in General

As described elsewhere (Doshi 2002), the repulpability of a wide variety of paper products can be judged by carrying out standardized mechanical disintegration of pieces of the paper in water. Two criteria must both be met in order for a paper product to be regarded as repulpable. First, the standardized dispersing treatment needs to succeed in individually dispersing the fibers. As illustrated in Fig. 7, if the mixture still contains more than a specified amount of non-dispersed material, such as flakes, the material will be classed as non-repulpable. For example, paper that contains a very high level of wet-strength treatment may fail to redisperse into its component fibers and fine particles under standardized conditions (Hubbe 2026). A second criterion is that a high yield has been achieved. That means that the ratio of recovered material (usually based on its dry mass) is sufficiently high relative to the starting material's dry mass. The yield is decreased not only by the possible loss of undispersed "flakes" of paper, but also by any losses of fine

material, colloidal material, or soluble components that do not become included in the next generation of paper.

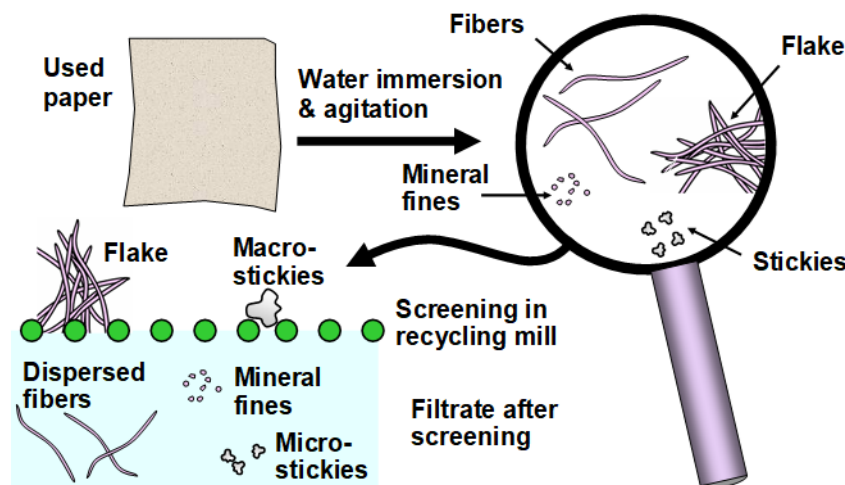


Fig. 7. Schematic illustrating two key steps of a repulping operation in a paper recycling mill, including different possible outcomes for the fibers and the stickies components

Necessary steps in recycling a paper product

Before considering outcomes of the repulping of barrier-coated paper products, it can be useful to consider the steps involved in the recycling of paper products in general. In brief, these steps can include sorting, rewetting, fiber separation, deinking (if needed), and management of stickies (if needed). Sometimes the fibers are subjected to a minor amount of mechanical refining. Such refining can be justified based on the fact that cycles of drying of paper will reduce the ability of those fibers to swell and develop inter-fiber bonding. Such effects, which are called hornification (Stone and Scallan 1966; Weise and Paulapuro 1999), can be partly overcome by application of a minor degree of mechanical shearing and internal delamination of the fibers (Giacomozzi and Joutsimo 2017). At the same time, the refining also can help to fully redisperse the fibers (Cai *et al.* 2020; Penkin and Kazakov 2022).

Sorting

The sorting of recovered paper can be a prudent step in cases where the intended product of the next cycle of papermaking has to meet challenging specifications, such as low dirt count or high brightness. In modern facilities it is preferred to employ optical and other sensing equipment, in combination with automatic sorting equipment. For instance, Ramasubramanian *et al.* (2012) showed that a well-chosen combination of sensors and algorithms can enable efficient sorting of waste papers at high speed.

Rewetting

Rewetting of recovered paper usually happens readily when the recovered paper is added to the agitated water within a repulper (Bajpai 2024). Often at a fiber solids content within the range of 4% to 10%, a sturdy rotor at the base of the pulper will cause the suspended bales or sheets of paper to rub against each other in a wet condition. This is often sufficient to break up sheets and flakes of paper, allowing the fibers to become fully wetted. Resistance to rewetting is sometimes observed in the case of paper products having

exceptionally high hydrophobic character. For instance, a wax-impregnated corrugated container may have been unintentionally added to the batch of recyclable materials. Resistance to rewetting can be overcome by increasing the pH within the pulper to about 10 (Hong *et al.* 2008), which is expected to promote fiber swelling (Hubbe *et al.* 2024). Also, raising the temperature by adding steam at the pulper can be expected to help overcome the residual effects of hydrophobic agents remaining in the pulp material.

Stickies

The topic of stickies and their control has high relevance when the recovered paper material contains water-borne barrier layer components. Earlier review articles and book chapters have considered problems that can arise when recycling paper products that contain pressure-sensitive adhesives, hot-melt adhesives, and water-based coatings, among others (Doshi 2002; Hubbe 2026). When present in papermaking pulp, such stickies can result in breaks of the paper web, which hurt the production efficiency of papermaking. Wet-press felts can become gradually filled with stickies, which can reduce the effectiveness of wet-pressing in water removal. If the stickies are large enough, there can be visual blemishes on the paper products. Various water-borne barrier coating formations contain copolymer components that can be included in the category of stickies (Elkholy *et al.* 2025; Upadhyay *et al.* 2025; Muiliya *et al.* 2026).

Reported Repulpability of Barrier Layers

Table C (last in the Appendix) presents highlights of studies that have considered the repulpability of waterborne barrier layers applied to paper or paperboard substrates. A general finding that emerges from these published studies is that packaging with waterborne barrier coatings is readily recyclable. In cases where yields were determined, their values were in the range from about 80% to nearly 100%, based on the weight of the recovered material. There were no reports of a lack of dispersibility when placing the packaging material back into water and applying agitation.

Trends revealed by repulpability findings

At first glance, improving water resistance while maintaining repulpability appears to present conflicting objectives. Waterborne barrier coatings are intentionally designed to resist water penetration during product use, whereas repulping relies on the dispersion of paper fibers in water. However, the studies summarized in Table C demonstrate that these objectives can often be achieved simultaneously. The explanation emerging from the recent literature indicates that resistance to liquid water during service does not necessarily prevent controlled disintegration under repulping conditions. Instead, repulpability is governed primarily by the nature of the interactions between the coating and the cellulose fiber network, as well as the ability of these interactions to be disrupted during conventional repulping. Thus, the critical issue is not whether a coating provides high water or grease resistance, but whether it can be separated from the fiber network without generating excessive rejects, stickies, or fiber damage. Although barrier technologies have historically been criticized for compromising recyclability, recent literature demonstrates that careful coating design can overcome this limitation, while remaining compatible with existing paper recycling systems.

One of the most consistent observations throughout the published literature is that coatings based on cellulose and other hydrophilic polysaccharides generally retain excellent compatibility with conventional paper recycling processes. Early work by Bideau

et al. (2018) demonstrated that a conductive coating composed of TEMPO-oxidized nanofibrillated cellulose and polypyrrole could be removed from paperboard simply by immersion in water, allowing recovery of the underlying paper fibers with a yield of approximately 80%. Although the study focused primarily on developing functional conductive packaging, it provided an important proof of concept that even multifunctional nanocellulose-based coatings need not interfere with fiber recovery. Similar conclusions were reached by Shanmugam *et al.* (2019), who applied nanofibrillated cellulose by spray coating to improve barrier performance without compromising repulpability, and by Nadeem *et al.* (2023a,b), who reported fiber recovery yields ranging from 86 to 97% after repulping nanofibrillated cellulose-coated papers. Particularly noteworthy is the work of Abenghal *et al.* (2025), who subjected highly refined hardwood kraft fibers coated with microfibrillated cellulose to six consecutive papermaking and recycling cycles. Fiber recovery remained consistently between 90 and 98%, demonstrating that repeated recycling did not progressively degrade the ability of the fibers to be recovered or reused. Considered together, these studies establish an important design principle: cellulose-derived barrier layers are inherently compatible with cellulose-based substrates because they participate in the same hydrogen-bonding network as the paper fibers themselves. Rather than behaving as foreign contaminants during repulping, they redisperse together with the fibers, thereby preserving both fiber yield and pulp quality. This finding is particularly significant for the paper industry because it suggests that nanocellulose-based barrier coatings can improve packaging performance while remaining compatible with the existing recycling infrastructure, eliminating one of the major disadvantages traditionally associated with polyethylene-laminated papers.

Multilayer systems and crosslinking

While cellulose-based coatings represent the simplest route to achieving repulpability, recent studies demonstrate that excellent recycling performance can also be achieved in considerably more sophisticated coating systems, including multilayer and crosslinked formulations that were once expected to interfere with fiber recovery. One of the most informative examples is the work of Ning *et al.* (2026), who developed a multilayer waterborne coating consisting of calcium-crosslinked sodium alginate, acrylic emulsion, poly(vinyl butyral), and silica nanoparticles. From a coating design perspective, this formulation incorporated several features normally associated with reduced recyclability, including ionic crosslinking, inorganic nanoparticles, and multiple functional layers intended to maximize barrier performance. Nevertheless, standardized repulpability testing showed a fiber recovery of approximately 99%, with only minimal reject material remaining after screening. The authors attributed this performance to controlled disintegration of the coating during repulping, allowing separation of the fibers while preventing the formation of large coating fragments that could interfere with recycling equipment. A remarkably similar conclusion was reached by Kwon *et al.* (2024), despite employing a completely different coating chemistry. In that study, poly(vinyl alcohol) was first modified with oxalic acid and subsequently crosslinked through calcium ions to improve water resistance. Although crosslinking substantially enhanced the durability of the coating during service, the ionic interactions could still dissociate under mildly alkaline repulping conditions, resulting in almost complete fiber recovery. Perhaps the most convincing evidence of the effectiveness of this strategy came from comparison with polyethylene-coated paper, which remained largely intact during repulping and produced plastic agglomerates that would require physical removal before recycling could proceed.

These two studies fundamentally challenge the common assumption that crosslinking inevitably compromises recyclability. Instead, they demonstrate that the reversibility of the crosslinking mechanism is more important than the mere presence of crosslinks. Reversible ionic interactions can provide sufficient wet strength during product use while still allowing efficient fiber liberation during recycling. For researchers developing next-generation barrier coatings, this represents an important shift in design philosophy. Rather than avoiding crosslinking altogether, greater attention should be directed toward designing crosslinking chemistries that are stable during service but intentionally reversible or can be disrupted under controlled repulping conditions.

Hydrophobic coatings

Several studies further demonstrate that chemical assistance during repulping can preserve recyclability even for highly hydrophobic coatings. Weng *et al.* (2023), Tan *et al.* (2023), Peng *et al.* (2024), Guo *et al.* (2026), and Ma *et al.* (2026) reported successful recovery of pulp or fibers after treatment with relatively mild chemical solutions, including dilute acetic acid, sodium hydroxide, or solvent washing. However, the extent to which these studies evaluated changes in the recovered fibers or recycled handsheet properties varied considerably. Weng *et al.* (2023) and Tan *et al.* (2023) primarily used ATR-FTIR analysis to confirm removal of coating components from the repulped material, while Peng *et al.* (2024) examined the recovered fiber structure using optical microscopy. Lu *et al.* (2025) provided additional evidence from optical microscopy, FTIR analysis, and recycled handsheets, showing effective coating removal and recovery of the cellulose fibers, although the recycled handsheets exhibited a somewhat looser fiber network than the original paper. In contrast, Ma *et al.* (2026) quantitatively evaluated the tensile performance of recycled handsheets. The tensile index was approximately 45 N·m/g for the recycled uncoated paper and approximately 42 N·m/g for the recycled OS/KSiD-coated paper. Given the overlapping variability shown by the error bars, these values indicate broadly comparable tensile performance under the conditions investigated. These studies collectively illustrate that increased hydrophobicity does not necessarily eliminate repulpability; however, successful coating removal alone does not establish that the recovered fibers or recycled paper retain their original quality. Quantitative evaluation of fiber yield, fiber morphology, rejects/stickies, and recycled-handsheet properties is therefore important for assessing the practical effects of chemical-assisted repulping. The practical implication is that coating developers should consider the entire recycling process during formulation rather than optimizing only in-service barrier properties. A coating that requires mild chemical assistance may still be compatible with recycling, whereas one requiring harsh treatment or generating excessive rejects may be less attractive for practical implementation.

Yield and rejects

An equally important contribution of the recent literature is the recognition that repulpability should be evaluated by more than simple fiber recovery. Upadhyay *et al.* (2025) demonstrated that multilayer coatings containing a microfibrillated cellulose base layer substantially reduced the formation of stickies compared with styrene-butadiene latex coatings alone. The MFC layer formed strong hydrogen bonds with the paper surface, limiting migration of latex into the fiber network, while nanoclay further immobilized latex within the coating by increasing its surface area. As a result, reject levels decreased to values approaching those of uncoated paper, and stickies counts were also markedly

reduced. This finding is particularly important because stickies are among the most serious operational challenges faced by paper recycling mills (Hubbe 2026), leading to equipment fouling, reduced paper quality, and process interruptions. The work of Upadhyay *et al.* (2025) therefore extends the concept of repulpability beyond simple fiber recovery by demonstrating that coating architecture also influences the cleanliness and quality of recycled pulp. Future coating development should therefore evaluate reject rates, stickies generation, and pulp quality simultaneously rather than relying exclusively on repulpability yield.

Free-standing films

Another trend emerging from Table C is that not all of the relevant recycling studies have directly addressed the repulpability of coated paper products. Several investigations, including those of Lyu *et al.* (2024), Ren *et al.* (2024), Cheng *et al.* (2024a), Dong *et al.* (2025), Chen *et al.* (2026), and Abookleesh *et al.* (2026), demonstrated that free-standing films could be dissolved, recast, or reformed with little change in chemical structure or, in some cases, even improved barrier performance after repeated processing. For example, Lyu *et al.* (2024) showed that PVOH/pCAPE (polymerized caffeic acid phenethyl ester) films could be redissolved and recast several times while maintaining their chemical structure and even exhibiting lower water vapor transmission after recycling, indicating enhanced hydrogen bonding during remodeling. These studies clearly demonstrate the recyclability of the film materials themselves. However, they do not fully address the practical challenges associated with recycling coated paper packaging, where coatings must first be separated from cellulose fibers during industrial repulping. Consequently, results obtained from recast films should not be interpreted as equivalent to successful repulpability of coated paper. This distinction is important because packaging recyclability ultimately depends on efficient recovery of the fiber substrate rather than only the ability to reform the coating material.

Standardization

The literature indicates that standardized evaluation methods are becoming increasingly important for demonstrating industrial relevance. Earlier studies often described repulpability qualitatively by observing dispersion or redispersion of coatings, whereas more recent investigations increasingly employ standardized protocols such as the Fiber Box Association procedure, PTS-RH 021/97, UL-ECVP2485, or the CEPI recyclability method to quantify reject rates and fiber recovery. These standardized approaches allow more meaningful comparisons among coating technologies and provide stronger evidence that emerging barrier-coated papers can satisfy industrial recycling requirements. Nevertheless, relatively few studies simultaneously evaluate barrier performance, repulpability, stickies formation, recycled paper quality, biodegradability, and packaging performance within the same investigation. Future research should therefore adopt a more integrated approach in which the coating is assessed throughout its entire life cycle—from application and service performance to repulping, fiber recovery, and final biodegradation. Such studies will provide a more complete understanding of how waterborne barrier coatings can support a truly circular paper-based packaging economy.

Factors Affecting Yield of the Paper Recycling Process

Thickness of the barrier layer

As noted earlier, the yield of recovered material in comparison to the dry mass of the starting mixture is an important criterion by which to judge whether or not a paper products can be called repulpable. One way to achieve a relatively high yield when repulping water-borne barrier coated paper is to minimize the mass per unit area of the coating layer on the paper. It follows that high effectiveness of the barrier coating may be critical, thereby making it possible to achieve the barrier objectives with a thin film.

Recovery of barrier layer contents

A related question is whether and to what extent various non-cellulosic materials present in such coatings can be retained in the next generation of paper products. Such retention, though technologically possible, is not assured. As described in more detail elsewhere (Bajpai 2024), paper recycling operations are usually set up in such a way as to emphasize recovery of just the fibers. Other items, including water-dispersible adhesive particles, mineral particles, and coating ingredients are routinely removed by such processes as screening, hydrocyclone action (cleaning), flotation, and sending filtrates to wastewater treatment operations (Bajpai 2024).

A potential strategy to increase the yield percentage when reprocessing used barrier-coated paper-based packages would be to recover some of the components of the coating layer and somehow include them as components in future products. For example, in some cases such materials might be collected by screening (Doshi 2002; Hubbe 2026). The efficiency of collection might be increased, in some cases, by adjusting the aqueous conditions to favor agglomeration, thereby increasing the size of the particles of recovered material. Dissolved air flotation (DAF) has been found to be an effective way to separate small hydrophobic particles, including micro-stickies, from process water in paper recycling operations (Doshi 2002; Hubbe 2026). By using a combination of screening, flotation, and hydrocyclone units (to separate particles according to their density), it should be feasible to isolate a stream that is rich in stickies from other components of the recovered paper.

There will likely be a challenge in finding valued uses for such material due to its expected sticky nature and the fact that it will be a mixture of different materials. In some cases, the sticky or unsightly components of papermaking materials can be placed into a middle ply of a paperboard product (Hubbe 2026). In some other cases the recovered material could be used for a layer of relatively hydrophobic material as part of a multi-ply paperboard product. Components of barrier layers in a previous generation of packaging products might be used in such recycled products. Such options might initially be regarded as too risky, relative to the performance of the newly formed components of barrier layers. However, future mandates on the percentage of recovery and reuse of single-use packaging products may make such options seem attractive.

Fractional retention of barrier contents in recycled paper

In cases where recovered material from barrier layers is added back to the fibrous mixture for manufacturing of a successive generation of paper, there are some steps that can be taken to minimize the likelihood of such problems as web breaks, the filling of wet-press felts, deposits on forming fabrics, and visible spots in paper products (Doshi 2002; Hubbe 2026). For instance, the material can be passed through a disperger, which applies high shear to break up any macrostickies (particles large enough to be retained on a

standard screen) into smaller particles. Such dispersal is often accompanied by a treatment with detackifying agents, which can include highly platy minerals such as talc, delaminated clay, montmorillonite, or hectorite (Sutman and Nelson 2022). Alternatively, there are a variety of amphiphilic copolymers that are designed to adsorb onto hydrophobic particles and render their surfaces more water-loving and less sticky. The goal often is to retain the material as suitably small particles, having reduced stickiness with high efficiency during production of the recycled paper (Hubbe 2026).

CONCLUDING COMMENTS

This article started with a question of whether or not two basic goals can be achieved by suitable developmental work in the field of barrier coatings for food packaging. The first of these goals is to achieve full biodegradability. The second goal is to achieve repulpability, which involves two aspects. One is full dispersibility of the fibers into aqueous suspension under typical conditions of paper recycling. The other is to recover and reuse as much as possible of the used food packaging material in the production of the next generation of recycled paper. The following are the concluding remarks from the reviewed literature:

- **Biodegradability:** Water-borne barrier coatings based on readily biodegradable polymers such as starch and chitosan can achieve substantial biodegradation. However, chemical modification, crosslinking, hydrophobic components, and some bioplastic additives can slow degradation. Reported biodegradation assessments also remain limited in their ability to evaluate residual chemicals and potential environmental effects.
- **Repulpability:** Most studies reviewed demonstrate that water-borne barrier coatings can be repulped and that cellulose fibers can be recovered for subsequent papermaking. However, successful repulping does not necessarily indicate that recovered fibers and recycled handsheets retain their original quality. Fiber yield, rejects/stickies, fiber morphology, and recycled-handsheet properties therefore warrant greater attention.
- **Barrier performance versus end-of-life behavior:** Improving water, water-vapor, oxygen, or grease resistance through hydrophobic modification, crosslinking, mineral fillers, or multilayer structures can alter biodegradability and repulpability. Thus, barrier performance should be evaluated together with end-of-life behavior rather than optimized independently.
- **Chemical assistance during repulping:** Highly water-resistant coatings may require additional chemical or solvent-assisted separation. Mild treatment such as increased pH or heating can facilitate coating removal, but the practical suitability of such approaches depends on chemical demand, fiber quality, rejects, and compatibility with existing recycling operations.
- **Compostability and environmental safety:** Biodegradability alone does not establish suitability for industrial composting or environmental release. Future studies should consider standardized compostability assessments and the fate of residual coating components and transformation products as well as their

sustainability for agricultural purposes. There is concern that some components of waterborne barrier coating formulations, such as latexes or emulsified bioplastics, may fall into the category of microplastics.

- **Design Implications:** Future water-borne barrier coatings should be developed using a lifecycle-oriented approach that balances barrier performance, coating grammage, biodegradability, repulpability, and recovery of coating components. There is also a need for research that includes analysis of residual components, including potential toxins. Readily biodegradable matrices such as starch, chitosan, and cellulose derivatives provide promising options, while persistent or poorly degradable components require careful consideration.
- **Research needs:** More standardized and quantitative studies are needed to compare fiber recovery, rejects/stickies, recycled-paper quality, biodegradation rates, and barrier performance across coating systems. Such data would enable more meaningful assessment of the practical circularity of water-borne barrier-coated paper packaging. Attention needs to be paid to increasing the yields of recovery during repulping. One way to achieve higher yields will be to enhance the intrinsic performance of barrier coatings, thereby making it possible to reduce their weight. In addition, value-added uses need to be found for all components of recovered single-use food packaging and serving items.

A limitation of the present review article is that it did not consider barrier performance. Accordingly, the authors are planning a companion article that will address the usage of waterborne coatings, factors affecting resistance to permeation by different permeants, and ways in which different chemical or mineral components can be used in combination, based on literature reports.

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APPENDIX

Table A. Reported Results of Biodegradability Studies Associated with Waterborne Barrier Coatings and their Coated Paper Packaging Materials

Coating Composition (Table A)	Specimen Form	Test Method/Endpoint/Environment	% Biodegraded (days)	Important Findings	Citation
Methylcellulose & poly(caprolactam)	Free-standing film	Aqueous medium, 25 °C; mass loss	87 to 88 (42)	The composite films lost mass gradually.	Khan <i>et al.</i> 2012
Starch, poly(vinyl alcohol), CaCO ₃	Free-standing film	Soil burial; weight loss	~100 (180)	The virgin starch/PVOH matrix was fully degradable, whereas increasing nano-CaCO ₃ content progressively reduced biodegradation rate. The authors related this to strong interfacial interactions between CaCO ₃ and the polymer matrix.	Kisku <i>et al.</i> 2014
Starch with nano-clay	Free-standing film	Bacteria-inoculated aqueous medium; microbial growth observed over 30 days	~100 (20 to 25)	Nanoclay addition reduced water absorption and swelling and delayed the biodegradation in comparison with unfilled starch film; the effect depended on clay content and composite morphology.	Mohan <i>et al.</i> 2017
Gutta percha natural sealant with biochar	Free-standing composite film	Soil burial at ~28 °C; weight loss	12 to 17 (60)	Biochar improved barrier and mechanical properties, while its effect on biodegradation varied with loading. The composites degraded more than PE under the test conditions.	She <i>et al.</i> 2019
Chia polysaccharide mucilage & protein	Free-standing film	Soil burial; weight loss under light/irrigation conditions	30 to 59 (35)	Weight loss was greatest with light exposure and irrigation. The chia mucilage was more resistant to biodegradation than the protein.	Vega <i>et al.</i> 2020
Aminated hemicellulose with Glass-like ORMOCER units	Free-standing coated film	Industrial composting; ISO 14855-1; CO ₂ evolution; 58 ± 2 °C	~90 (180)	Addition of aminated hemicellulose produced a barrier coating capable of reaching >90% biodegradation under industrial composting condition	Emmert <i>et al.</i> 2021

Coating Composition (Table A)	Specimen Form	Test Method/Endpoint/Environment	% Biodegraded (days)	Important Findings	Citation
Cellulose nano-crystals & sorbitol, glycerol, maltitol, or xylitol, etc.	Free-standing film	Controlled aerobic composting; adapted ISO 17556; CO ₂ evolution tracked by respirometry	~30 to 90 (90)	The plasticizing agents promoted faster biodegradation of the CNC films. Xylitol-containing films showed the highest biodegradation.	Fernández-Santos <i>et al.</i> 2021
Silane crosslinked starch with or without PLA (cast films)	Free-standing cast film/bilayer film	Controlled industrial composting; ISO 14855; CO ₂ evolution; 58 ± 2 °C	~50 to 95 (48)	Crosslinking of the starch with amino-propyl tri-methoxy silane slowed down biodegradation. Addition of PLA reduced it further. The dense network and slower degradation of PLA contributed to the decrease.	Gürler <i>et al.</i> 2021
Starch, poly(vinyl alcohol, solvent casting	Free-standing film	Soil burial at ~27 °C, 70% RH; weight loss and visual observation	~90 (21)	The films rapidly degraded in soil, becoming invisible after 21 days.	Patil <i>et al.</i> 2021
Poly(vinyl alcohol) with chitosan	Free-standing film	Vermicomposting/soil environment	~50 (100)	The films gradually degraded under vermicomposting conditions	Talukdar <i>et al.</i> 2021
Sago starch, peel powder, glycerol, gum Arabic	Free-standing film	Soil burial at ~20 °C; weight loss	47 to 73 (15)	Increasing peel content generally increased biodegradation relative to starch-rich formulations.	Ahmad <i>et al.</i> 2022
Poly(vinyl alcohol) with glass flakes	Free-standing film	Soil burial; weight loss and visual observation	40 to 60 (5)	Results were judged by the appearance of the films after soil burial. The glass flakes slowed degradation moderately, while the PVOH matrix remained biodegradable.	Channa <i>et al.</i> 2022
Chitosan films reinforced with CNC	Free-standing film	Soil burial; weight loss; modified ISO 846	19 or less (150)	Adding the cellulose nanocrystals progressively reduced weight loss. Strong interactions between CNC and Chitosan produced a more resistant structure.	Salim <i>et al.</i> 2022
TEMPO-ox. NFC, MXene, Ag NPs	Free-standing nanocomposite film	Soil burial; periodic weight/appearance observations	~100 (150)	Despite the dense nacre-like structure and excellent barrier properties, the films completely biodegraded during the soil test.	Tang <i>et al.</i> 2022

Coating Composition (Table A)	Specimen Form	Test Method/Endpoint/Environment	% Biodegraded (days)	Important Findings	Citation
Gum kondagogu with sodium hectorite clay	Free-standing film with waterborne clay coating	Aerobic aqueous medium; ISO 14851-based respirometry	~20 to 60 (28)	In contrast to several other clay-containing systems, the hectorite-coated films degraded somewhat faster than uncoated gum. Clay swelling and film fragmentation were proposed as contributing factors.	Venkateshaiah <i>et al.</i> 2022
Poly(vinyl alcohol) & starch with glycerol or sorbitol	Free-standing film	Soil burial; weight loss	90 to 100 (40)	Glycerol and sorbitol moderately promoted biodegradation, likely through increased moisture uptake and solubility.	Zehra <i>et al.</i> 2022
Poly(vinyl alcohol) with NFC	Free-standing composite film	Humid environment; Degradation based on physical deterioration	Deformed, weakened (42)	The addition of the nanocellulose increased the durability of the PVOH film to moisture-induced deterioration	Chen <i>et al.</i> 2023
Poly(vinyl alcohol) with alginate or HPM cellulose and nanoclay	Free-standing multilayer film	Aerobic wastewater sludge; DIN ISO 14851; CO ₂ evolution	~10-14 (35)	PVOH showed very limited biodegradation in wastewater. Alginate degraded substantially, while the central nanoclay layer slowed biodegradation through barrier effect. Greater biodegradation was found for separate coatings without all the components.	Röhl <i>et al.</i> 2023
Chitosan with cardanol glycidyl ether	Coating on paper and free coating film	Soil burial; weight loss	56 to 82 (35)	A pure chitosan film had greater resistance to biodegradation than one with the cardanol glycidyl ether. The coating remained biodegradable.	Tan <i>et al.</i> 2023
Carrageenan, natamycin, graphene	Free-standing film	Soil burial; weight loss	43 to 72 (9)	Natamycin is an antifungal. Both natamycin and graphene reduced the extent of weight relative to carrageenan alone; greater filler incorporation generally reduced biodegradation.	Vishnuvarthana n & Ramji 2023
Chitosan & tannin extract epoxy	Coating on paper; free-standing coating	Soil burial of coating films: weight loss	~60 (49)	Crosslinking increased coating density and delayed degradation. The coated paper itself was not the specimen used for the biodegradation measurement.	Zhu <i>et al.</i> 2023a

Coating Composition (Table A)	Specimen Form	Test Method/Endpoint/Environment	% Biodegraded (days)	Important Findings	Citation
	tested separately				
Na alginate, NFC, ethylcellulose, poly(vinyl butyral)	Coated paper	Soil burial; weight loss at 15-day intervals	~40 (60)	Large pieces of both coated and uncoated paper remained after the test. The coating did not eliminate biodegradation but slowed it.	Zhu <i>et al.</i> 2023b
Quaternized chitosan complex with sodium alginate	Free-standing film	Soil burial; visual observation	~ 80 (20)	Both the quaternary chitosan films and polyelectrolyte complex films prepared by mixing with sodium alginate were mostly degraded after 20 days in soil.	Bi <i>et al.</i> 2024
Starch, gelatin, bee's wax film	Free-standing film	Soil burial/ natural outdoor exposure; visual observation	~80 (5)	The hydrophobic film retained good barrier properties but was reported to biodegrade rapidly; Photographs show that the films were mostly not present any more at the surface after five days of contact.	Cheng <i>et al.</i> 2024a
Poly(vinyl alcohol) crosslinked with boric acid on kraft paper	Coated paper	Marine biodegradation; respirometric monitoring	~60 to 90 (110)	Marine biodegradation (not soil) was monitored by respirometer. Boric acid crosslinking yielded the lowest degradation results.	Choe <i>et al.</i> 2024
Starch films with MXene nano-platelets	Free-standing film	Soil burial; visual observation	~80 (42)	Pure starch films and those containing 2.5% to 10% MXene were completely gone after 6 weeks, despite strong improvements in barrier properties. The authors noted that visual disappearance does not establish complete mineralization.	Dong <i>et al.</i> 2024
Chitosan with berry wax	Free-standing film	Soil burial at ~30 °C and 80% RH; visual observation	~10 to 70 (20)	Adding 25% berry wax to the chitosan greatly increased the rate of biodegradation.	Khan <i>et al.</i> 2024
Poly(vinyl alcohol) modified with oxalic acid & Ca ²⁺	Barrier coating on paper	Simulated industrial compositing; ISO 20200; 58 ± 2 °C; mass loss	>90 (84)	The crosslinked coating retained high biodegradability while providing improved water and gas barrier performance.	Kwon <i>et al.</i> 2024

Coating Composition (Table A)	Specimen Form	Test Method/Endpoint/Environment	% Biodegraded (days)	Important Findings	Citation
Starch, chitosan, CNC and PLA Pickering coating	Coated paper	Soil burial; weight loss	~85 (60)	The coated paper showed greatly increased resistance to biodegradation than uncoated paper, attributed mainly to the relatively slow degradation and hydrophobicity of PLA.	Peng <i>et al.</i> 2024
Chitosan & stearic acid, cured 80 °C	Coated pulp-molded paper product	Soil burial; visual observation	~80 (120)	Both coated and uncoated materials gradually degraded; complete fragmentation occurred by 120 days.	Shen <i>et al.</i> 2024
Poly(vinyl alcohol) arabinogalactan with vanillin	Free-standing film	Soil burial at 25 °C, 50-70% RH; weight loss	50 to 100 (30)	The films were placed on the top of moist soil. The vanillin absorbed UV light, and it was antioxidant and antibacterial.	Zhang <i>et al.</i> 2024a
Acetylated NFC with fatty acid esterification (plant-oil-based polyester)	Free standing composite film	Soil burial; morphological changes and degradation observations	~90 (105)	The composite film was completely degradable in soil within about 15 weeks. Incorporation of acetylated cellulose nanofibers provided mechanical, thermal, and barrier improvement while retaining the degradability of the composite.	Zhang <i>et al.</i> 2024b
Chitosan with cellulose fiber molded pulp	Molded cellulose-fiber packaging product	Soil burial; weight loss and visual observation	~90 (266)	The molded cellulose-chitosan material retained water and oil resistance while remaining biodegradable. Photos and weight loss data show ~90% degradation of the molded fiber in 38 weeks.	Fang <i>et al.</i> 2025
Cellulose modified by dopamine & dodecyltrimethyl siloxane	Free-standing cellulose-based film	Soil burial at approximately 10 cm depth; weight loss measured at 7-day intervals	~70 (42)	Hydrophobic modification substantially improved water resistance and strength but did not eliminate biodegradation. The modified film showed lower degradation than unmodified cellulose under the soil-burial conditions.	Fu <i>et al.</i> 2025
Carboxylated PLA/PBAT	Functionalized polyester-coated kraft paper and coating material	Simulated industrial compositing; 58 ± 2 °C, 50 ± 5% RH; CO ₂ evolution measured by direct respirometry	~70-95 (120)	Thermophilic composting (48 °C) showed delay relative to cellulose, but no plateau effect (linear CO ₂ production with time).	Hamdani <i>et al.</i> 2025

Coating Composition (Table A)	Specimen Form	Test Method/Endpoint/Environment	% Biodegraded (days)	Important Findings	Citation
Chitosan, acrylic rosin, silane superhydrophobic coatings for paper	Coated paper	Soil burial; weight loss and visual observation	~80 to 100 (56)	The hydrophobic components (acrylic rosin and silane treatment) slowed degradation relative to uncoated paper: uncoated paper lost 91.26% of its mass in 28 days and was completely degraded by 35 days, whereas the coated paper lost 28.22% after 28 days and 98.08% after 56 days. The authors attributed the slower degradation to pore filling, reduced microbial penetration, and the hydrophobic surface.	Lu <i>et al.</i> 2025
Polyvinyl alcohol, glucomannan, & essential oil	Free-standing film	Soil burial at 25 °C, 50-70% RH; weight loss	75 (15)	Addition of glucomannan substantially increased weight loss relative to PVOH alone, with cracks and holes developing during burial. (~40%) in 15 days.	Shen <i>et al.</i> 2025
Cassava starch, onion peel powder, glycerol	Free-standing film	Soil burial; weight loss	29-32 (28)	Onion-peel addition slightly reduced biodegradation relative to pure starch, possibly because phenolic compounds inhibited soil microorganisms	Torche <i>et al.</i> 2025
Starch, carboxy- methyl cellulose, crosslinking	Free-standing film	Soil burial; weight loss	~90 (43)	Crosslinked films remained highly biodegradable; Filter paper degraded to a lesser extent under the same condition.	Wang <i>et al.</i> 2025
Regenerated cellulose, ascorbic acid, plasma-deposited SiOx	Free-standing composite film	Soil burial at 36 °C and 50% RH; weight loss	~100 (35)	Dense surface deposition improved barrier properties but did not prevent substantial degradation	Xu <i>et al.</i> 2025
Gelatin-based bioplastic with tea polyphenolics	Free-standing film	Soil burial under controlled conditions; residual mass	~100 (28)	Soil-burial tests showed complete biodegradation in soil after 4 weeks.	Zhang <i>et al.</i> 2025
Paper surface treated with rosin and silane agent	Coated paper	Humus compost (from chicken manure)/soil burial at 25 °C, 80% RH; weight loss	~80 (180)	The dense hydrophobic coating slowed degradation compared with uncoated paper.	Zhu <i>et al.</i> 2025

Coating Composition (Table A)	Specimen Form	Test Method/Endpoint/Environment	% Biodegraded (days)	Important Findings	Citation
Rapeseed protein-chitosan with MMT and citric acid	Free-standing film	Soil burial at room temperature; weight loss	40 to 48 (30)	Weight loss was affected to a small degree by the blend ratios; the MMT/citric-acid system improved barrier and mechanical properties while remaining biodegradable.	Abookleesh <i>et al.</i> 2026
Loquat peel with Na alginate, film	Free-standing film	Soil burial: weight loss	~90 (20)	The pectin/cellulose-rich film degraded rapidly, reflecting the susceptibility of the biomass components to microbial decomposition. Pectin was the main component from the loquat peel. It was mixed with Na alginate and cast.	Chen <i>et al.</i> 2026
Hydroxypropyl or acetylated starch for kraft paper	Coated paper	Soil burial at 25 °C and 80% RH; visual observation	~100 (110)	There was no trace of the modified starch film on day 110 in soil.	Guo <i>et al.</i> 2026
Epoxidized soy oil & regenerated bamboo film	Free-standing surface-engineered film	Soil burial + ASTM D5338 aerobic CO ₂ evolution	88 to 100% (50-195)	Increasing surface-layer thickness delayed disintegration and biodegradation. The hydrophobic layer improved barrier performance but also restricted water and microbial access. The film with the epoxidized soy oil degraded more slowly (195 days to complete biodegradation) than a control specimen with the bamboo film (50 days).	Huang <i>et al.</i> 2026
Starch, fatty acid-hydrophobized silica	Coated paper	Soil burial; visual observation	~90 (40 to 50)	The coating delayed degradation relative to uncoated paper but did not prevent eventual disappearance. Photographs showed that the hydrophobic additives had a slight effect in increasing the biodegradation time.	Ma <i>et al.</i> 2026
Na alginate, soy protein, AKD, CMC nanofiber	Coated paper	Soil burial; weight loss	~85 to 95 (35)	The coating treatments moderately slowed down biodegradation. Commercial paper degraded about 50% in 35 days.	Nan <i>et al.</i> 2026

Table B. Reported Results of Compostability Studies Associated with Waterborne Barrier Coatings and their Coated Paper Packaging Materials

Specimen Type	Composting Conditions	Important Findings	Citation
Glass-like platy particles, PLA, hemicellulose & amination	58 °C aerobic compost medium	The coated films were industrially composted with manure.	Emmert <i>et al.</i> 2021
Cellulose nano-crystals & sorbitol, glycerol, maltitol, or xylitol, etc.	Aerobic, municipal compost; temperature not recorded	Biodegradability was tracked by respirometry, with the evolution of CO ₂ . The plasticizing agents promoted faster biodegradation of the cellulose.	Fernández-Santos <i>et al.</i> 2021
Silane-modified starch and starch-PLA bilayer	Controlled composting, 58 ± 2 °C: ISO 14855	Biodegradation was lower for 3-APTMS-modified starch than for untreated starch; the starch-PLA bilayer showed further reduced biodegradation.	Gürler <i>et al.</i> 2021
Poly(vinyl alcohol) modified with oxalic acid & Ca ²⁺	Simulated composting 40 °C	The modified PVOH films showed >90% biodegradation after 84 days.	Kwon et al. 2024
Carboxylated PLA	48 °C composting	Thermophilic composting (48 °C) showed delay relative to cellulose, but no plateau effect (linear CO ₂ production with time).	Hamdani <i>et al.</i> 2025

Table C. Reported Results of Repulpability Studies Associated with Waterborne Barrier Coatings and their Coated Paper Packaging Materials

Coating (Table C)	Specimen Type	Matrix Type	Test Protocol	Yield (%) or Result	Rejects/ Stickies	Coating Grammage	Recycled Pulp Quality	Citation
TEMPO-oxidized NFC, polypyrrole	Coated Paper-board	Cellulose-based	Water immersion/repulping	~80	NR	Uncoated: 45 g/m ² Coated 49 g/m ²	Coating could be stripped; paperboard fibers recovered	Bideau <i>et al.</i> 2018
Nanofibrillated cellulose	Coated paper	Cellulose-based	Spray coating followed by repulping	Repulp-able	NR	NR	No significant interference with repulpability reported	Shanmugam <i>et al.</i> 2019
Hemicellulose, aminated, glass-like units	Coated paper	Cellulose-based	Water dispersion/ redispersion	Dispersible	NR	NR	The mixture could be placed back into water and redispersed.	Emmert <i>et al.</i> 2021
Alkali-soluble resin	Coated paper	Non-cellulosic	Aqueous alkaline treatment	Substantial	NR	NR	Coating separated and could be recovered/reused	Bakker <i>et al.</i> 2022
Starch with zein protein	Coated paper	Mixed	Water soaking/mechanical blending	Repulpable	NR	Uncoated: 529.70 Rod coat: 34.13-38.65 g/m ² Dip coat: 145-170 g/m ²	Pulp recovered for recycling	Hamdani <i>et al.</i> 2022
Nanofibrillated cellulose	Coated paper	Cellulose-based	Spray coating and repulping	86 to 97	NR	Non-recycled : 60 g/m ² Recycled: 53-60 g/m ²	High fiber recovery	Nadeem <i>et al.</i> 2023a,b
Na alginate with silane polymer	Coated paper	Mixed	Warm-water repulping with acetic acid; solvent-assisted coating removal	Repulpable	NR	NR	Coating removed from paper	Weng <i>et al.</i> 2023

Coating (Table C)	Specimen Type	Matrix Type	Test Protocol	Yield (%) or Result	Rejects/ Stickies	Coating Grammage	Recycled Pulp Quality	Citation
Chitosan, with tannin extract epoxy	Coated paper	Non-cellulosic	Repulpability testing	Repulpable	NR	Uncoated: 118.4 g/m ² Coated: ~121.98 g/m ²	Coated paper could be repulped.	Zhu <i>et al.</i> 2023a
Nanofibrillated cellulose, Na alginate, <i>etc.</i>	Coated paper	Mixed	Calcium-ion crosslinking followed by repulping	Repulpable	NR	NR	Fibers recovered	Zhu <i>et al.</i> 2023b
Chitosan with cardanol glycidyl ether	Coated paper	Non-cellulosic	Acetic-acid assisted repulping	Repulpable	NR	Uncoated: 75.6 g/m ² Coat load: 2.36-4.75g/m ²	Hydrophobic coating could be removed	Tan <i>et al.</i> 2023
Quat. chitosan & Na alginate	Free-standing film	Non-cellulosic	Film dissolution/reformation	Not clear	NA	NA	Film could be stripped/reapplied	Bi <i>et al.</i> 2024
Microfibrillated cellulose & graft fatty acid	Coated paper/film	Cellulose-based	Repulping/recycling	~100	NR	Unlaminated: 195 g/m ² MFC weight: 15-25 g/m ²	High recovery reported	Bru <i>et al.</i> 2024
Aqueous poly urethane coat on paper	Coated kraft paper	Non-cellulosic	Repulping/recycling	~90	NR	NR	Coated kraft paper recyclable	Chen <i>et al.</i> 2024
Starch, gelatin, beeswax film by blowing	Free-standing film	Mixed	Water soaking, resuspension and recasting	Not clear	NA	NA	Film could be resuspended and recast	Cheng <i>et al.</i> 2024a
Ca ²⁺ poly(vinyl alcohol), oxalic acid modified	Coated paper	Non-cellulosic	Repulpability testing under alkaline conditions	~100	NR	Uncoated: 90 g/m ² Dry coat weight: 1.5 & 3 g/m ²	High fiber recovery	Kwon <i>et al.</i> 2024
Poly(vinyl alcohol), caffeic acid phenyl ether	Free-standing film	Non-cellulosic	Dissolution and recasting	Not clear	NA	NA	Film recovered and recast	Lyu <i>et al.</i> 2024

Coating (Table C)	Specimen Type	Matrix Type	Test Protocol	Yield (%) or Result	Rejects/ Stickies	Coating Grammage	Recycled Pulp Quality	Citation
PLA particles, nanocellulose, starch, chitosan	Coated paper	Mixed	Acetic-acid assisted repulping	Not clear	NR	NR	Fibers recovered after treatment	Peng <i>et al.</i> 2024
Poly(vinyl alcohol), Fe ³⁺ , TEMPO NFC	Free-standing film	Mixed	Dissolution/ reformation	NR	NA	NA	Film reformed	Ren <i>et al.</i> 2024
Poly(vinyl alcohol), arabinogalactan, vanillin	Free-standing film	Non-cellulosic	Aqueous dissolution and recasting	NR	NA	NA	Films dissolved and recast	Zhang <i>et al.</i> 2024c
Microfibrillated cellulose	Paper/handsheet	Cellulose-based	Repeated papermaking and recycling	90 to 98	NR	NR	High recovery maintained over 6 cycles	Abenghal <i>et al.</i> 2025
Poly(vinyl alcohol), MXene cast	Free-standing film	Non-cellulosic	Shredding, water dissolution and recasting	Not clear	NA	NA	Film could be reformed	Dong <i>et al.</i> 2025
Carboxylated PLA, PBAT	Coated paper/film	Non-cellulosic	Recycling/ repulpability assessment	94	NR	Uncoated: 127.6 g/m ² Coat load: 9.4-48.9 g/m ²	Higher yield than conventional bioplastic films	Hamdani <i>et al.</i> 2025
Chitosan, acrylic, rosin, hydrophobic silica/PDMS	Coated paper	Non cellulosic	Acetic acid and petroleum ether treatment followed by recycling	Repulpable	NR	NR	FTIR indicated coating removal; recycled paper had a looser fiber network but no obvious fiber damage	Lu <i>et al.</i> 2025
Microfibrillated cellulose with a latex topping and nanoclay	Coated paper	Mixed	Standardized repulpability/ screening	88 to 98	Rejects/ stickies reduced (8.5%)	Uncoated: 218.5 g/m ² Coated: 224.7-227.8 g/m ²	Improved pulp cleanliness; MFC/nanoclay reduced stickies	Upadhyay <i>et al.</i> 2025
Starch with carboxymethyl cellulose	Coated paper	Mixed	Repulping at 85 °C	Repulpable when hot	NR	NR	Recyclability dependent on elevated-	Wang <i>et al.</i> 2025

Coating (Table C)	Specimen Type	Matrix Type	Test Protocol	Yield (%) or Result	Rejects/ Stickies	Coating Grammage	Recycled Pulp Quality	Citation
							temperature treatment	
Rosin with a silane coupling agent	Coated paper	Non-cellulosic	1 M NaOH at 90 °C	Hard to repulp	NR	NR	Strong alkaline/thermal treatment required	Zhu <i>et al.</i> 2025
Protein, and chitosan	Free-standing films	Non-cellulosic	Dissolution in acetic acid and reforming	~100, by separate dissolution	NA	NA	Film regenerated; practical paper-recycling relevance unclear	Abookleesh <i>et al.</i> 2026
Loquat peel oxidation, Na alginate casting	Free-standing film	Mixed	Crushing, water dissolution and reforming	Substantial	NA	NA	Film could be reformed	Chen <i>et al.</i> 2026
Starch: acetyl, hydroxypropyl	Coated paper	Cellulose-based	1% NaOH, 45 °C, 12 h, stirring	Repulpable	NR	NR	Successful repulping reported	Guo <i>et al.</i> 2026
Suberin aqueous dispersions	Coated paper-board	Non-cellulosic	Aqueous repulping	>99	Minimal rejects 0.1-3%	Uncoated: 210 g/m ² Coat weight: 6.5-11.2%	High fiber recovery	Lyytikäinen <i>et al.</i> 2026
Starch with hydrophobic silica	Coated paper	Mixed	Ethyl-acetate washing followed by water repulping	Repulpable	NR	Uncoated: 33129, 81 g/m ² Coat weight: 3.92- 7.95 g/m ²	Solvent washing enabled subsequent repulping	Ma <i>et al.</i> 2026
Poly(vinyl alcohol), nano clays	Coated paper	Non-cellulosic	Aqueous repulping	Repulpable	NR	Uncoated: 135.12 g/m ² Coat load: 32.04-37.04 gm ² and 0.72-41.76 g/m ²	No major recycling limitation reported	Muiliya <i>et al.</i> 2026
Na alginate, soy protein, AKD	Coated paper	Mixed	Repulping after hydrophobization	Repulpable	NR	Uncoated: 200 g/m ²	Recovered pulp reported as recyclable	Nan <i>et al.</i> 2026

Coating (Table C)	Specimen Type	Matrix Type	Test Protocol	Yield (%) or Result	Rejects/ Stickies	Coating Grammage	Recycled Pulp Quality	Citation
						Coat weight: 1.18-8.62 g/m ²		
Ca ²⁺ cross-linked alginate with latex, SiO ₂	Coated paper	Mixed	Standardized repulpability testing	~99	Minimal rejects	NR	High fiber recovery and good separation	Ning <i>et al.</i> 2026

NR – not reported NA – not applicable