

Trends in sustainable biobased packaging materials: a mini review

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ABSTRACT

Petroleum-based polymers have served the packaging industry in numerous ways as films, pouches, rigid containers, foamed containers, and other components for food, medical, and other packaging applications. However, growing concerns about environmental impact, awareness of greenhouse gas emission and their adverse effects, increased oil prices, and disposal and landfill issues are forcing researchers and the industry to develop sustainable packaging. Biobased materials, those derived from biological sources rather than petroleum sources, are ideally suited to meet these new sustainability requirements. Although biobased materials such as paper have been used for packaging extensively, packaging with increased functionality and performance is needed. Therefore, the movement toward sustainable packaging will include both improving current biobased packaging and development of new biobased materials such as biopolymers. The aim of this mini review was to offer a summary of the current state of biobased packaging as well as provide insight into current and future trends of sustainable paper- and bioplastic-based materials for packaging industry.

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1. Current global packaging market and materials

The world packaging market is continuously growing. The most recent data from industry analyst Smithers Packaging report that the global packaging market was worth \$914.7 billion in 2019, having increased by 8.4% in value terms since 2015. This market was expected to rise further but in 2020, the world faced an unprecedented global challenge in the COVID-19 pandemic, which has considerably affected the packaging market. Without considering the probable and long-term COVID-19 impact, industry experts estimated the global packaging market to be valued at \$939.9 billion in 2020 and was forecasted to grow at a compound annual growth rate of 2.3% to 2025 reaching a value of \$1.05 trillion. An additional market expansion is predicted across 2025–2030 at almost 1.8% annual growth rate, reaching a global value of over \$1.15 trillion [1]. The fastest market growth during this period is projected to occur in the emerging and developing nations of Asia, Africa, the Middle East, and Eastern Europe due the rising real incomes, growing population, demographic changes, rising urbanization, the further development of a retail infrastructure, and so on. These leading economic and demographic trends coupled with the

spread of the Internet and the ensuing rapid growth of the global e-commerce industry will result in a rapid expansion in demand for packaged goods in sectors such as food, beverages, cosmetics, and pharmaceuticals. In contrast, a slower growth is predicted for the more mature packaging markets such North America, Western Europe, and Australasia [1].

The global packaging materials market has been segmented into paper/paperboard, flexibles (almost 64% being plastics), rigid plastics, metals (steel and aluminum), glass, and others (wood, textiles, etc.) [1,2]. Paper/paperboard and plastics constitute the largest fraction of packaging materials used (78%) followed by metals, glass, and others (Fig. 1) [1].

This review will focus on paper/paperboard and both flexible and rigid plastics, which are the most widely used materials within the global packaging market, accounting for a value share of more than 70%. Among these materials, the packaging sustainability credentials for paper/paperboard continue to be strong due to its high recycling rate and the organic nature of the raw materials (trees) used to make it, which are sourced today from sustainably managed forests (e.g. Forestry Stewardship Council [FSC]—certified forests). In contrast, most common flexible and rigid plastics used in packaging are petrochemical based and under increased environmental pressure to improve their sustainability credentials because they are not sourced from renewable materials and/or biodegradable so they pose serious ecological problems [3].

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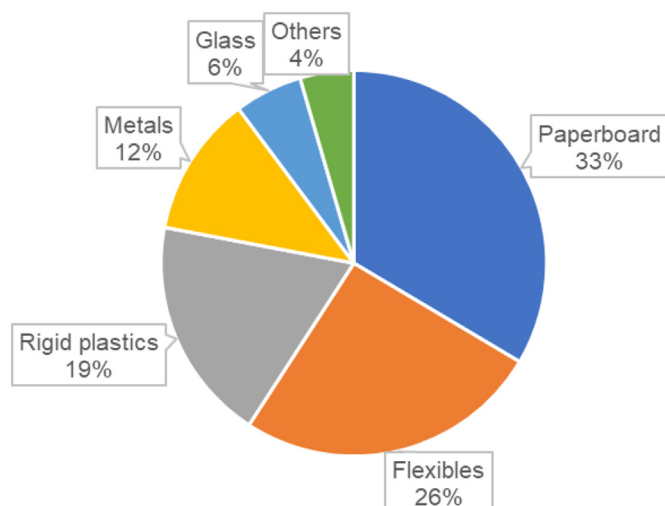


Fig. 1. Percent share in 2020 of the global packaging market by material type. Adapted from Ref. [1].

According to the US-Environmental Protection Agency, more than 68% (68.2%) of paper and paperboard and less than 9% of plastics (8.7%) were recycled in 2018 in the United States [4,5], whereas the worldwide recycling rates were estimated at approximately 70% for paper-based packaging and 14% for plastic packaging [6]. Most of these materials are easily recyclable when used as a single material in packaging formats, for example, uncoated paperboard or corrugated cardboard. Unfortunately, packaging materials are often combined in different structures such as laminates, multilayers, coated materials, and so on, making their recycling impracticable and most of the times economically not convenient. Since they are either landfilled or incinerated at the end of their lives, these packaging materials have raised serious environmental concerns [1,7].

2. Consumer preferences and industry responses

The continued global economic and population growth, demographic changes (e.g. growth of the urban consumer base, the rising life expectancy, etc.), coupled with other changes in consumer lifestyles have resulted in an increased demand for packaged convenient and single-serving foods, durable and non-durable goods, healthcare/pharmaceutical products, and so on [8]. These changes have also increased the amount of packaging materials needed to meet consumer's demand; thus, resulting in an increased generation of municipal solid waste. Packaging waste remains a growing environmental concern and there is mounting public pressure by consumers worldwide for sustainable materials due to their growing environmental awareness and desire to preserve the environment [9,10]. The environmental public pressure is being backed by stringent legislations around the world banning specific materials derived from fossil fuels (e.g. single-use plastic packaging), mandating recycling, seeking more sustainable packaging material alternatives [10–15].

In response to changing consumer preferences and emerging regulatory policies, many brands and retail chains are committing to transition away from non-recyclable and difficult to recycle multilayer flexible packaging materials in favor of more recyclable, compostable, or biodegradable materials, eco-friendly, and sustainable alternatives [10–15].

Sustainable packaging, defined by the Sustainable Packaging Coalition as a packaging that, over time, reduces its environmental impact and footprint [16], is becoming one of the fastest growing

packaging sectors and is therefore identified as a priority for both the industry and consumers. Several large brand companies and their suppliers have introduced sustainability agenda in their business plans in the past few years. For examples, in 2015, PepsiCo introduced its 2025 sustainability agenda, which includes the intent to make 100% of its packaging recoverable or recyclable. As part of this, they plan to move toward completely biodegradable snack food packaging [17]. Similarly, Kraft Heinz announced in 2018 its strategy to make 100% of its packaging globally sustainable by 2025 [18]. Likewise, McDonald's announced recently that its packaging will be 100% renewable and recycled by 2025 [19].

Sustainable packaging is also supported by the New Plastics Economy Global Commitment led and launched in October 2018, by the Ellen MacArthur Foundation in collaboration with the United Nations Environment Programme [20]. This Global Commitment unites businesses, governments, and other organizations across five continents behind a common vision of a circular economy for plastics and 2025 targets to address plastic waste and pollution at its source, starting with packaging. To deliver a world without plastic pollution, the global commitment urges the industry and policymakers to develop regulations and strategies to accelerate advanced recycling innovations that will dramatically reduce plastic waste in oceans and landfills. Moreover, major brands worldwide have started to incorporate recycled plastics in their packaging due to recent advances in recycling technologies and legislations encouraging greater recycling and use of recycled content in packaging [21].

Packaging plays an extremely crucial role in our society by not only helping to prevent food loss and waste but also reducing energy use from the transportation and shipping of goods, among others. However, concerns over the large quantity of waste materials generated by the packaging industry are rising, and sound solutions are needed from the industry and policy makers. There is no doubt that the growing consumer concern over the preservation of the environment will drive demand for not only a circular economy for plastics, in which plastics typically are reused rather than discarded, but also for more sustainable packaging, based on renewable resources; concepts that will be described in the following sections.

3. Sustainable packaging materials

3.1. Wood fiber-based materials

Cellulose is the most abundant biopolymer and therefore is a valuable, readily available resource for sustainable packaging applications. Cellulose may be derived from biomass such as wood, forestry residues, agricultural residues, algae, plants, and some bacteria. In this article, we discuss packaging materials derived from wood-based cellulose fibers. Cellulose, hemicellulose, and lignin are other primary wood components which are found in varying quantities depending upon the sourced material. The wood cell wall may be comprised of 40–50% cellulose, which must be isolated from wood for wood fiber-based packaging [22]. Methods to isolate cellulose can impact the cellulose fiber morphology and chemical composition, which results in different packaging applications [23].

Cellulose fibers can contribute to sustainable packaging in many ways ranging from 100% cellulose-based products such as paper and paperboard or less than 1% nanocellulose added to biopolymers to improve barrier properties. Paper and paperboard are among the earliest and most used sustainable packaging materials for food products and are considered a commodity market. Cellulose nanomaterials (CNs) are cellulosic fibers that are processed so that one dimension is in the nanoscale. CNs represent an emerging market and have been extensively studied for packaging and will contribute to the next generation of sustainable packaging materials [24].

3.1.1. Paper and paperboard

Packaging applications represent a large outlet for manufactured paper and paperboard. For example, in 2000, approximately 47% of total paper and paperboard produced was used for packaging applications [25]. These materials are generally considered sustainable when they are made from sustainable sourced materials, and due to their relative ease of recyclability. However, inclusions of inks and coatings can negatively impact recyclability.

Paper has been derived from plants for millennia. Today, most paper is prepared from the wood pulp of coniferous trees found in North America and Europe [25]. Wood pulping can either be a mechanical process or chemical process, which will determine pulp quality and composition. The pulp fiber slurry is then formed into sheets and pressed through a calendaring process resulting in paper. Often the pulp fiber is bleached using chemical agents to improve the brightness and whiteness of paper, increasing the cost and desirability of the paper. The standard bleaching process using chlorine, chlorine dioxide, or hydrogen peroxide may result in adverse chemicals released into the environment and can cause environmental concerns. As a result, more sustainable bleaching methods, such as using ligninolytic enzymes, are being investigated [26]. On its own, paper does not provide sufficient protection for food packaging due to poor barrier properties, low heat sealability, and strength. Impregnating the paper with additives incorporated during paper processing such as colorants, optical brighteners, sizing, or strengthening agents is a common solution to improve paper properties for packaging. Another strategy involves laminating paper with a second material, typically aluminum or plastic, to impart desired properties. Waxed paper, which is a paper coated with wax to improve barrier properties, and glassine paper, a paper produced with high density to provide grease resistance, are two examples of these types of papers. Changes to the paper processing methods can also improve its functional properties [27].

Paperboard is similar to paper and generally refers to a material with multiple layers of cellulosic fibers to create sheets of higher thickness. This is often folded into a box to contain products such as cereal and crackers. Like paper, the strength and barrier properties are poor. The product in the box is often contained in an additional package to impart shelf-life. In some packaging applications paperboard is often a component in multilayer packages. One of the most widely known is Tetra-Pak, which combined layers of paperboard, paper, as well as polyethylene (PE) and aluminum to achieve specific barrier properties.

Corrugated fiberboard consists of two or more layers of paperboard made up of a combination of flat sheets and fluted sheets. Corrugated cardboard consisting of two layers (one sheet and one fluted layer) is referred to as single face board, single wall board consists of a fluted layer sandwiched between two sheets, and double wall board consists of two fluted sheets sandwiched between flat sheets with an additional flat sheet between them. The thickness and geometries of the components and final product can change depending upon the desired mechanical properties.

Molded pulp packaging is usually a 100% biobased product manufactured from waste paper and other natural resources that are compostable and biodegradable. Interest in sustainable packaging has resulted in an increased use of molded pulp packaging. Molded pulp packaging can be used for clam-shell packages or provide protection of fruits, vegetables, eggs, and electronics during shipping.

3.1.2. Cellulose nanomaterials

Interest in CNs has grown tremendously in the past decade. The term CN encompasses a class of cellulosic particles having at least one dimension in the nanoscale. Compared with other nanoparticles they are considered low cost, light weight, and

environmentally friendly. Wood, the most important industrial source of cellulose, is also the most common source of CNs. Characteristics such as high surface area and nanoscale morphology contribute to properties such as low density, high strength, transparency, barrier properties, and low thermal expansion, which make them ideally suited for sustainable packaging applications requiring high barrier properties [24,28]. Generally, two types of CNs extracted from lignocellulosics are applicable to packaging films: cellulose nanofibrils (CNFs) and cellulose nanocrystals (CNCs), each of which exhibits different properties. Although production of each typically starts with individual cellulose fibers, CNFs are generally extracted using a mechanical process with or without biological treatment while CNCs are extracted using a chemical process through acid hydrolysis [28]. The result is different morphologies and compositions which naturally lend themselves to different types of packaging applications. The production of CNs likely has some environmental impact including use of large amounts of water and acids used during hydrolysis. Nonetheless, CNs can be used to produce films, incorporated into polymeric-based composites, or added as laminates on other substrates. Although there are currently no commercial food packaging products that contain CNs, research efforts to develop these materials are vast [24,29,30]. Additionally, efforts to determine the safety of these materials have shown no effects on toxicity paving the way for commercialization in food packaging applications [31,32].

3.1.2.1. Cellulose nanomaterial films. Compared to CNCs, CNFs have much higher aspect ratios which lend them to production of CN films directly from aqueous suspension in a process similar to papermaking. As water is removed, hydrogen bonding between CNFs and fiber entanglement results in stiff, strong, translucent films generally not redispersible in water. CNF films have been coined 'nanopaper' due to the analogous production methods with cellulosic-based paper [33]. A range of mechanical properties can arise from factors such as CNF raw materials, CNF production method, film preparation technique, and testing conditions [34–37]. CNF films can also be the starting point for impregnation with polymers, which further improve mechanical properties [36,38].

The small pores of CNF films, the strong hydrogen bonding between nanoparticles, and high crystallinity within nanoparticles can contribute to barrier properties of CNF films, making them suitable for food packaging. However, similar to mechanical properties, barrier properties of CNF films are also affected by raw material source and production method. For example, CNF films from hardwood sources may have lower water vapor transmission rate (WVTR) than CNF films from softwoods [35]. CNF treatments such as acetylation [39], or coating films with starch, beeswax, and paraffin [35], or adding non-cellulosic materials such as clay [40] improve WVTR. However, it should be considered that modification to improve physical and barrier properties could negatively impact biodegradability or recyclability. Even with these improvements, the water vapor permeability of CNF films is generally less favorable than other petroleum-based materials such as polypropylene (PP), PE, and polyethylene terephthalate (PET) [29].

The oxygen transmission rates (OTRs) of CNs compare favorably with conventional packaging materials. The low porosity of CNF films results in oxygen diffusion rather than transport, and at a sufficient thickness the pores are not interconnected which contribute to the impermeability [41]. The OTR of CNF films can be a function of treatment, production method, film thickness, and test method. For example, the OTR can be improved by increasing film thickness [42] or reducing void volume through the addition of glycerol as a plasticizer [41]. However, the hydrophilic nature of

CNF films results in increasing OTRs as humidity increases [36,41,42].

3.1.2.2. Cellulose nanomaterials in bioplastic matrices. Cellulosic fibers have been added as fillers or reinforcing agents in plastic-based composites for many years but more recently opportunities to add CNs to bioplastics for sustainable packaging applications have been identified [24,29]. Typically added at small loading levels, CNs may provide improvements in mechanical properties and barrier properties while maintaining transparency of the plastic. The strength of the composite films depends upon the properties of the matrix, the properties of the CN, the CN-matrix compatibility, and the dispersion of the CN in the matrix [43]. It is expected that nanocomposite packaging materials will provide barrier properties, high mechanical strength, thermal stability, chemical stability, recyclability, biodegradability, dimensional stability, heat resistance, and transparency [44].

Although CNs can be incorporated into petroleum-based polymers such as PE and PP, there are considerable efforts to develop sustainable packaging materials by adding CNs to biobased matrices for sustainable packaging, including polylactic acid (PLA), polyhydroxyalkanoate (PHA), polyhydroxybutyrate (PHB), starch-based polymers, and bio-PE and bio-PP. Cellulose nanocomposites containing both CNFs and CNCs have been produced. However, the smaller aspect ratio and higher crystallinity of CNCs compared with CNFs make them a more suitable reinforcement for plastic-based nanocomposites. On a commercial scale, production of cellulose nanocomposites for packaging will likely include melt-processing. One challenge of melt-processing CN composites is obtaining well-dispersed and distributed CNs in the bioplastic [45–47]. The bioplastic matrix for packaging applications is usually hydrophobic. Compatibility between the polar cellulosic nanomaterial and non-polar matrix provides a critical role in composite film properties. Poor compatibility can lead to low moisture resistance, poor barrier properties, poor dispersion, low transparency, and low mechanical properties, all of which may be undesirable in packaging applications. Efforts are underway to modify CNs to improve the nanocomposite properties, typically by imparting a non-polar surface to the CNs. Common modifications include using a surfactant, acetylation, esterification, silylation, or polymer grafting [46,48–51].

There are limited studies where CNCs are melt-processed with bioplastics. In an early study, PLA-CNC composites were manufactured in a vented extrusion system where the CNCs were fed wet. A processing aid was used in liquid form to facilitate dispersion of CNCs in PLA. This method improved thermal degradation, but not mechanical properties compared with neat PLA [48]. This method did show promise, however, and subsequent efforts have demonstrated the possibility of producing nanocomposites using commercial methods [48,49,52–60]. However, melt-processing has not solved the challenge of fully dispersing CNs in bioplastics. One new strategy to improve dispersion consists of melt-compounding aqueous suspensions of CNs with bioplastics in a process termed wet-compounding [47]. This promising technique has the advantage of improving dispersion without drying CNs before compounding, which is an energy intensive step.

3.1.2.3. Coating with cellulose nanomaterials. CNs can be added as a coating to many substrates to improve properties. For sustainable packaging this likely means coating either paper or bioplastics with CNs. For example, the surface of paper substrates may be rough and porous. Adding CNs to the paper surface as thin layers decreases the surface roughness [29]. Due to the low oxygen permeability of CN films, many research groups have added CNs as a coating to paper and plastic as a way to improve oxygen barrier properties [61–64]. CN coatings on cardboard [61] or paper [62] have not been shown

to improve water vapor barrier properties. However, oxygen permeability was improved [63]. Adding a CN layer to plastics has been shown as a promising way to improve oxygen barrier properties for packaging applications [64]. Spray-coating or dip-coating are likely to be viable methods to add CNs to a substrate surface for property improvements.

3.2. Bioplastic materials

Petroleum-based polymers have conventionally served the packaging industry. However, plastics from biological substances rather than petroleum, or bioplastics, will contribute to sustainable packaging as growing concerns about the environment, increased oil prices, disposal and landfill issues, changing consumer preferences, and emerging regulations force the industry to look for alternative sustainable materials [3,10,53–60,65–68]. The movement of the packaging industry toward the use of biobased and/or biodegradable materials and a circular economy based on plastic recycling will help the industry to meet its future sustainability needs for a wide variety of applications.

A diverse family of bioplastics with differing properties are available for packaging applications (Table 1). These bioplastics can be grouped into three main types: (1) biobased or partially biobased non-biodegradable plastics, such as biobased PE, PP, or PET; (2) plastics that are both biobased and biodegradable, such as PLA and PHA or polybutylene succinate (PBS); and (3) plastics that are based on fossil resources and are biodegradable, such as polybutylene adipate terephthalate (PBAT) [67]. Bioplastics have a smaller carbon footprint and a better compostability compared to petroleum-based plastics [65]. In addition to being sustainable, biobased plastics also have some physico-mechanical properties similar to petroleum-based polymers (Table 2), and hence are ideal alternative to the latter [66].

3.2.1. Bioplastics market

A recent market and trend report from German-based researcher nova-Institute described the year 2020 as very promising for biobased polymers [67,68]. The report indicated that the global bioplastics production capacity was about 1% of the more than 368 million tons of plastic produced annually [67]. This production capacity is expected to rise by almost 36% from around 2.11 million tons in 2020 to approximately 2.87 million tons in 2025 due

Table 1
Global production capacities of bioplastics in 2020 and forecast in 2025.

Biobased material types	Capacity (10 ³ tons)	
	2020	2025
Non-biodegradable		
PA (polyamide)	251.2	304.3
PE (polyethylene)	221.7	318.7
PTT (polytrimethylene terephthalate)	194.2	195.2
PET (polyethylene terephthalate)	164.7	94.7
PP (polypropylene)	29.6	129.2
PEF (polyethylene furanoate)	0.0	5.7
Other	23.2	23.0
Total of non-biodegradable	884.5	1,070.9
Biodegradable		
PLA (polylactic acid)	394.8	559.8
Starch blends	394.8	396.2
PBAT (polybutylene adipate terephthalate)	285.0	396.2
PBS (polybutylene succinate)	86.6	86.1
PHA (polyhydroxyalkanoate)	35.9	330.2
Other	29.6	31.6
Total of biodegradable	1,226.5	1,800.1
Total	2,111	2,871

Adapted from Ref. [67].

Table 2

Some physical, thermal, mechanical, and barrier properties of petroleum-based and bio-based polymers.

Polymers	Density (g/cm ³)	Thermal properties ^a		Tensile properties ^b			Barrier properties ^c (10 ⁻¹⁷ kg·m/m ² ·s·Pa)			References
		<i>T_m</i> (°C)	<i>T_g</i> (°C)	σ (MPa)	<i>E</i> (GPa)	ϵ (%)	<i>P_{wv}</i> (25°C)	<i>P_{O2}</i> (25°C)	<i>P_{CO2}</i> (25°C)	
PET	1.29–1.40	245–265	73–80	48–72	2.8–4.1	30–3,000	76–100	0.124–0.206	0.12–0.21	[2]
PA (Nylon 6)	1.13–1.16	210–220	48–60	41–165	—	300	756–834	0.008–0.017	0.08–0.10	[2]
PP	0.902	160–175	–10	27–42	0.6–1.7	400–900	114	2.39	—	[2,69]
HDPE	0.940–0.965	112–138	–120	17–45	0.4–1.1	10–1,200	25	0.65–1.19	4.2–5.3	[2,69]
LDPE	0.910–0.925	88–115	–120	8–32	0.05–0.5	100–965	73–97	2.66–3.48	15.8–22.3	[2,69]
PLA	1.24	150	55	53–60	2.8–3.5	6–92	1,594–3,498	0.35–1.63	2.77	[54–59]
PBAT	1.22	115–125	–32	20–40	0.08	470–690	1,620–12,776	1.41	—	[7,70,71]
PBS	1.24	102–114	–32	30	0.73	7.1	4,938	0.32	—	[70]
PHB ^d	1.18–1.26	170–180	–10 to 4	22	2.03	3.1	1,307–1,321	0.55	3.2–4.2	[72,73]
PHBV ^d	1.25	102–172	–9 to +3	22–25	2.3–2.8	2.0–2.8	319–1,108	0.11–0.38	0.2–1.7	[72,73]

The listed data are from various references and samples prepared from different methods.

^a *T_m* = melting temperature and *T_g* = glass transition temperature.^b σ = tensile strength, *E* = Young's modulus, and ϵ = elongation at break.^c *P_{wv}*, *P_{O2}*, and *P_{CO2}* are the water vapor, oxygen, and carbon dioxide permeabilities, respectively.^d PHB and PHBV are polyhydroxyalkanoates (PHAs). PHB data are for poly (3-hydroxybutyrate) (P3HB); whereas the data for PHBV are for poly (3-hydroxybutyrate)-co-poly (4-hydroxybutyrate) (P3HB-co-P4HB) and poly (3-hydroxybutyrate-hydroxybutyrate-co-3-hydroxyvalerate) (P3HB-co-P3HB).

to continuous growth and strong market diversification of bioplastics (Table 1) [67].

The large variety of bioplastics on the market makes it possible today to find a sustainable bioplastic alternative with similar performance on a particular property for almost every conventional plastic material (Table 2) and for almost any corresponding applications. Consequently, bioplastics are currently increasingly utilized in a variety of applications, but packaging is the largest market segment within the bioplastics industry having consumed 47% (0.99 million tons) of the total bioplastics produced in 2020 [67].

3.2.2. Sustainable packaging with bioplastics

The materials listed in Table 1 reveal that a broad spectrum of bioplastics products is available for sustainable packaging. Recently, the flexible and rigid plastics packaging sectors have witnessed the emergence of incorporating these biobased materials into more products. For rigid packaging for examples, Procter & Gamble uses bio-PE to package some of its cosmetic products (e.g. creams and lipsticks), whereas other well-known brands such as Vittel, Volvic, or Heinz use bio-PET for beverage bottles and other fluids, while Coca-Cola is testing the performance of bottles made from polyethylene furanoate (PEF) [67]. The use of PEF as an interesting alternative to PET in rigid plastic bottles for drinks and films for food packaging is expected to grow due to its attributes [74,75]. This new 100% plant-based plastic made from sustainably grown crops is fully degradable and enzymatically hydrolysable [76–79]. It has superior barrier properties for oxygen, carbon dioxide, and water vapor than most widely used petroleum-based packaging materials currently in the market, leading to prolong shelf-life of packaged products. Additionally, production of thinner PEF packages requiring fewer resources will be possible due to its superior strength property [78,79]. PLA is another bioplastic being used in both rigid and flexible packaging market [59]. Beverage bottles and closure products made of PHA, another entirely biodegradable biopolymer, are expected to enter the market very soon [80] and PHA use as a packaging material will significantly grow over the next years (Table 1). Moreover, three new versions of PHA resin formulations recently developed for blown-cast films, injection molding, and thermoforming have been globally launched for customer evaluations in 2021 [81]. Fresh produce such as fruits and vegetables are packaged with bioplastics-based flexible formats (e.g. films, trays, etc.). Biodegradability is an attribute sought for food packaging of these perishables due to an increased demand for packaged convenient and single-serving foods, among others, in

addition to the fact that the bioplastics extend food shelf-life in a similar manner than the existing conventional packaging, and sometimes even better [67]. The food and catering segments are also benefiting from both the flexible and rigid bioplastics packaging in applications such as cups, mugs, trays, plates, cutlery, and so on, thus providing viable sustainable packaging solutions in the single-use and reusable sectors.

3.2.3. Circular economy for plastics

Today, most of packaging plastics derived from fossil fuels are neither produced from renewable resources nor biologically degradable. Additionally, many of them are still either landfilled or incinerated at the end of their lives. These practices have raised serious environmental concerns, which, when combined with recent initiatives around the world banning the single-use plastic bags and/or limiting the use of plastic packaging formats, are becoming key issues for the global packaging industry. In response to these initiatives, several businesses, governments, and other organizations across five continents are pledging to the MacArthur Foundation's 'New Plastics Economy Global Commitment' that unites these signatories with a common vision to moving toward a circular economy for plastics. Specifically, these organizations are united behind concrete 2025 targets to address plastic waste and pollution at its source, starting with packaging [20]. Moreover, signatories have begun pledging to transition to a circular economy that promote reduction, reuse, and recycling (composting) of plastics to retain plastics in their highest value condition and reduce environmental impacts [82].

Many brand owners and retailers are already making progress on targets to reduce their overall use of plastic packaging by moving away from non-recyclable packaging materials or phasing out difficult to recycle multilayer flexible packaging materials in favor of more sustainable and eco-friendly alternatives [19–21,68]. Other companies such as Apple have committed to fully eliminate plastics in its packaging by 2025 [20] and likewise, McDonald's has also announced that its packaging will be 100% renewable and recycled by 2025 [19]. In contrast, other brand companies and their suppliers have committed to innovate in advanced recycling technologies to ease plastic package recycling; thus, increasing recycled content in the packaging materials [82]. A chemical recycling process for example, one of these advanced recycling technologies, offers the opportunity to convert waste plastics to food-grade materials by restoring the waste polymer to its monomeric feedstocks. Consequently, several global brands are not only already

incorporating advanced recycled plastics in their food grade packaging in the marketplace [21,82], but also are expanding their feedstock portfolio to include biobased and biodegradable polymers from both fossil and renewable resources [68]. Kraft Heinz announced in 2018 its strategy to make 100% of its packaging recyclable, reusable, or compostable by 2025 and increase usage of recycled materials [18]. Unilever will convert its entire global toothpaste portfolio to recyclable tubes by 2025 [83]. These fully recyclable toothpaste tubes will be available in France and India, two of Unilever's biggest oral care markets, later in 2021. They will be made of high-density polyethylene (HDPE), one of the most widely recyclable plastics globally, and will not contain an aluminum inner lining, which prevents multilayered tubes to be recycled. Additionally, the HDPE used will be the thinnest plastic material available on the toothpaste market at 220 μm , thus reducing the amount of plastic needed for each tube.

4. Sustainable packaging trends

Smithers Pira conducted a survey asking participants in the packaging value chain to rank 113 sustainable packaging topics for both the level of impact on sustainable packaging and the likelihood that these will be implemented by 2028 [84]. The top 20 are listed by category in Table 3. Technologies most related to materials include recycling, innovative materials, and design. Other trends include evaluating packaging based on the circular bioeconomy and certifications for packaging. These will be discussed in further detail later in this section.

4.1. Recycling

Recycling packaging is an important component of sustainability. Despite efforts to increase the recycling rate, challenges remain. Therefore, it is no surprise that recycling will be a large trend in sustainable packaging. Motivations for improvements in recycling include improving the quality of the waste stream and improving the economics of collection and reuse.

Recycling of paper and paperboard is routine and frees up biomass for other uses. Although the recycling rate of paper and paperboard is relatively high, it is not without drawbacks. Each recycling cycle decreases fiber length, in turn decreasing the

strength of that paper. For example, a virgin grade paper can be recycled 6–7 times before the performance of that material is inadequate [27]. Improvements in de-inking paper and paperboard will be necessary to improve recycling rates.

The recycling rate of plastic-based packaging is much lower compared with paper and paperboard. Separating plastics in the recycling stream can be challenging, and many packages consist of more than one type of material. Therefore, designing plastics for recyclability is anticipated to be a large factor moving forward. Examples of this include identifying material types on the packaging product, minimizing the number of components used, minimizing the number of materials used, and avoiding color pigments or using the smallest amount of pigment possible. Plastic packages should also avoid having paper labels or glue to avoid contamination of the waste stream. It is preferable to move to a simpler, closed plastics packaging chain by requiring the entire package to be recyclable and ensuring caps and labels are made of the same source [60,85]. In some cases, plastic-digesting bacteria which can break down polymers to monomers, and chemical recycling may contribute to sustainable packaging. Although the trend is toward producing packaging with a single material, in some cases it may be beneficial to blend polymers if it increases biodegradability.

4.2. Innovative materials

Both new and higher performing bioplastics have been identified as a disruptive technology for sustainable packaging (Table 3). This is indeed an active area of research and development. Bioplastics from bacteria and alternative cellulose-based feedstocks such as agricultural waste and other plant materials are continually being developed. For example, researchers have demonstrated that polycarbonate can be produced from a synthesis of limonene, an extract from orange peels, and carbon dioxide [86]. CNs, discussed extensively above, are likely to be one of the key new materials contributing to sustainable packaging. The flexibility of CNs to serve as a barrier film, coating, or reinforcement or additive for plastics makes them likely to be an important new packaging material. Moreover, the potential of PLA/CNC nanocomposite films as packaging materials for shelf-life extension of water-sensitive food products has been recently demonstrated [59]. Other natural

Table 3
Top 20 sustainable packaging technologies based on impact on sustainability and likelihood of adaptation between 2018 and 2028.

Category	Technology
Recycling	Near infrared process for material recovery
	De-inking of waste paperboard
	Recyclable paperboard cups
	Design for recycling
	Effective cleaning of plastic waste for reuse
	Improved separation of multipolymer constructions
Innovative materials	Plastic-digesting bacteria
	New biopolymers
	Natural barrier coatings
	Higher performing bioplastics
	Compostable packaging
Design	Mono material barrier films
	Intelligent labeling
	Light weighting existing packages
Other	Antimicrobial nanotechnology in active packaging
	Big Data analytics and blockchain
	Innovation in fixtures and closures
	Sustainable protective packaging for transit and e-commerce
	Free-market trading of packaging waste
	Expanded waste to energy schemes

Adapted from Ref. [84].

coatings are anticipated to be either easily removed during recycling, provide enhanced properties to paper cups, or provide oil resistance to paper and paperboard [84].

Another interesting innovation is packages that are intended to be edible. One research group has identified a milk protein, casein, that can polymerize and form an oxygen barrier for food. An application could be as a single serve, edible wrapper on cheese [87]. In another example, edible films based on alginate-acerola puree were reinforced with cellulose whiskers [88].

4.3. Design

Active packaging that can monitor the condition of packaged food using sensors or indicators is anticipated to grow [89]. Systems may contain tags or labels printed on or embedded within packaging. Indirect indicators do not touch the food product, but the trend is to include direct indicators. These systems provide convenience to the consumer, increase food safety, and decrease food waste. They either have direct food contact or react with the atmosphere surrounding the food to present some information relating to freshness, quality, and safety. There are many direct indicators under development; most of them provide real-time monitoring of microbial growth or release of volatile organic compounds. For example, a bromophenol blue indicator placed on a package with a cellulose membrane as a freshness indicator may change from blue to green as guavas ripen, indicating over-ripe fruit [90]. In another case a shrimp freshness indicator was developed based on a biosensor film [91]. As these indicators are developed, they need to be tested at all environments the package may be used in. Active packaging that increases shelf-life through moisture absorption, carbon dioxide scavengers, or anti-microbial is another class of smart packaging [92]. This newest trend in active packaging is development of food packaging that contain substances meant to be added into food products to extend shelf-life.

Designing for light weighting, by either removing components from packaging or foaming the packaging materials is expected to contribute to sustainable packaging. There is a natural limit to this technology as it needs to be accomplished in such a way that packaging performance is not lost. However, the result can be decreased use of raw material and decreased shipping and handling costs. The ultimate goal of all packaging design is to ensure the product reaches the consumer in prime condition.

4.4. Circular bioeconomy

The circular bioeconomy is a new way to think of sustainability and will also impact sustainable packaging. The principle of circular bioeconomy involves considering a process from a cradle-to-cradle model rather than from a material perspective only, and optimizing each step. The trends identified above including innovative materials, advances in design, and improvements in recycling are part of this [84]. In the case of cellulose-based packaging this includes sustainable biomass sourcing, use of residues and wastes, development of biobased products, prolonged use of the product, energy recovery and composting of the product, and recycling.

Much of the driving force behind the circular bioeconomy has been directed at reducing petroleum-based plastics packaging. Moving toward a circular economy for plastic packaging will necessitate an approach that is restorative and regenerative by design, meaning that the plastics must constantly flow around a 'closed loop' system, rather than being used once and then discarded [93]. The Ellen MacArthur Foundation reported that this transition will require, over time, decoupling plastic packaging materials from finite (fossil) resources [20]. The foundation proposes the following two solutions to transition to a circular

economy for plastic packaging, including (1) a drastic reduction of the need for virgin plastics through elimination, reuse, and use of recycled content and (2) a switch over time of any remaining virgin inputs to renewable feedstocks that are proven to come from responsibly managed sources and to be environmentally beneficial [20,82].

4.5. Certifications

Certification in packaging serves as a way to inform consumers of sustainability of the resource used in production of the products, and may be used by industry as a way to differentiate themselves from other products. There are many types of certifications ranging from resource-based to end-product based. For example, a packaging material may be certified as using cellulose-based components from a forest certified for healthy forest management. One example of a resource-based certification is offered by the FSC [us.fs.org]. Obtaining this certification is a voluntary process where an independent third party assesses the quality of forest management and production against a set of requirements that includes prohibiting deforestation, limiting clear-cut size to protect ecology, protecting rare, threatened, and endangered species. Once this certification is obtained the product can display the FSC logo. Another avenue for certification is the Sustainable Forestry Initiative (www.forests.org). These types of certifications are routinely found on wood-based packaging such as paper and paperboard.

The USDA Certified Biobased Products program (www.biopreferred.gov) is managed by the US Department of Agriculture to increase the use and purchase of biobased products. To meet these criteria, products must be composed in whole or in significant part of biological products including renewable forestry materials. One part of this program includes a voluntary labeling component for biobased products, with the goal of making it easy for consumers to identify biobased products. If a business meets the USDA criteria, they are allowed to display a USDA Certified Biobased label on their product. Product certification will be an important factor for packaging producers to differentiate their products, but also to allow consumers to make choices based on environmental impact.

5. Summary

Consumer demand and emerging regulations will continue to drive the movement toward sustainable packaging. Biobased materials such as wood-based paper and paperboard and bioplastics are ideally positioned to capture some of this market growth. However, challenges remain before replacement of petroleum-derived packaging by biobased packaging can be fully realized. It is anticipated that increased commercial availability of CNs and bioplastics will continue to increase the acceptance of these alternative materials in sustainable packaging. Improvements in packaging recycling, innovative new materials, and designing for sustainability, implementation of new and existing certifications will contribute to overall market acceptance. Finally, considering material choice from a circular bioeconomy perspective will allow for advancements at all stages of sustainable packaging.

CRedit authorship contribution statement

Nicole M. Stark: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing. **Laurent M. Matuana:** Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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