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Biodegradable materials: current research and applications in the food packaging sector in Europe and Colombia

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Abstract

Packaging is an essential part of the food supply chain, it is essential to transport and store food during each phase of its production until it reaches the consumer. The material most used for food packages is plastic: it's lightweight, durable, economical, and with excellent barrier and mechanical properties. Nowadays, though, plastic waste has become an ever-increasing problem, filling landfills and polluting oceans. Consumers are demanding more sustainable alternatives, and, in this picture, biodegradable materials are acquiring interest both in academics and in industries. The aim of this work is to analyse if redesigning packages with new materials can be a factual solution to this challenge: a literature review is being conducted, with a particular focus on life cycle assessments and consumer perception. Furthermore, a comparison is made between legislation in Europe and in Colombia and a few examples of research and applications is shown as well.

Keywords: history of packaging; biodegradable materials; active packaging; life cycle assessment; consumer perception; food packaging sustainability; biodegradable packaging in Colombia.

Abstract in italiano

L'imballaggio è una parte essenziale della catena di approvvigionamento alimentare, è indispensabile per trasportare e conservare gli alimenti durante ogni fase della loro produzione fino al raggiungimento del consumatore. Il materiale più utilizzato per le confezioni alimentari è la plastica: è leggera, resistente, economica e con eccellenti proprietà meccaniche e di barriera. Oggi, però, i rifiuti di plastica sono diventati un problema sempre più grave, che riempie le discariche e inquina gli oceani. I consumatori chiedono alternative più sostenibili e, in questo quadro, i materiali biodegradabili stanno acquisendo interesse sia in ambito accademico che industriale. L'obiettivo di questo lavoro è analizzare se la riprogettazione delle confezioni con nuovi materiali possa essere una soluzione concreta a questa sfida: viene condotta una revisione della letteratura, con particolare attenzione alla valutazione del ciclo di vita e alla percezione dei consumatori. Inoltre, viene fatto un confronto tra la legislazione europea e quella colombiana e vengono mostrati alcuni esempi di ricerca e applicazioni.

Parole chiave: storia degli imballaggi; materiali biodegradabili; imballaggi attivi; valutazione del ciclo di vita; percezione dei consumatori; sostenibilità degli imballaggi alimentari; imballaggi biodegradabili in Colombia.

Contents

Introduction

The packaging industry is one of the major consumers of petrol-sourced plastics, accounting for 40% of the total worldwide consumption. Traditionally, glass, metals, paper, and plastics are commonly used as packaging materials (Venkateshaiah et al., 2021). However, the use of these conventional materials is facing severe scrutiny by the public due to their contribution to global warming and bioaccumulation in the case of petroleum-based plastics and greenhouse gas production. Specifically, plastics are suitable packaging materials for food due to their cost-effectiveness, good mechanical properties, lightweight nature, and good barrier properties (Jackson-Davis et al., 2023).

Still, consumers desire to reduce the use of plastics. Trends in the food industry, in fact, suggest consumers are drawn to environmentally friendly alternatives and less synthetic chemical preservatives. Furthermore, even though the recycling rate of plastics has been increased from 0% in the 1980s to 19.5% in current projections, packaging materials, especially flexible food packaging, are largely unrecyclable. Approximately 95% of the current plastic packaging materials made from polyolefins and polyethylene terephthalate (PET) are not recycled and go to landfills after a short single-use, resulting in an $80–120 billion annual losses to the global economy (Wu et al., 2021).

Amidst growing public pressure to tackle the issue of single-use plastics, the coronavirus pandemic has brought plastic food packaging back to the center stage. Sales of packaged produce and food deliveries have skyrocketed over the initial stages of the COVID-19 pandemic, with packaging seemingly offering a form of reassurance to consumers (Kakadellis et al., 2021).

Therefore, focusing on using alternatives such as biodegradable packaging and edible coatings and films will help alleviate consumers’ concerns and impact on the environment.

A plastic material is defined as a bioplastic if it is either biobased, biodegradable, or features both properties. According to the method of production, biopolymers can be polymers directly extracted from biomass of vegetable or animal origin, such as polysaccharides, proteins, lipids, but also polymers produced by classical chemical synthesis starting from renewable bio-based monomers such as polylactic acid (PLA), or polymers produced by wild or genetically modified microorganisms, such as polyhydroxyalkanoates (PHAs), polyhydroxybutyrate (PHBs), bacterial cellulose, xanthan, gellan, pullulan (Pinto et al., 2021). Biodegradable polymers have acquired particular importance in food packaging applications as packaging waste represents a significant part of solid waste with a negative impact on the environment.

Biodegradable packages with special marks or indicators could be separated from the municipal waste stream and directed into organic recycling. This could be achieved by collecting them together with the organic waste arising from households. Thus, it is extremely important to increase consumer awareness about biodegradable polymeric materials and introduce them to the market, so biodegradable packaging will become an integral part of their lives.

In packaging materials, in addition to biodegradability, other properties are especially desired including antioxidant and antimicrobial properties (Chiloeches et al., 2022). For these reasons, practical applications of biodegradable food packaging in markets are still hampered by major challenges as we'll see in the next chapters. Techniques improving the oxygen and water barrier of biodegradable polymer systems are ideal to lead to the biodegradable packaging entering our daily lives. Notable potential modifications, such as nanocomposites fabrication, multi-layer coextrusion and coating have been adopted in the last decades, showing their promise in obtaining high oxygen/water vapor barrier biodegradable systems for food packaging (Wu et al., 2021).

The global introduction of biodegradable polymeric materials for packaging must be preceded by a number of changes, such as the development of new technology, the improvement of the infrastructure of composting, as well as the financial capacity and the appropriate policies that are required. The key to achieving success and increased presence in the bioeconomy industry is to understand both the advantages and limitations of biodegradable and biobased products (Musioł et al., 2018).

The goal of this thesis is to determine whether redesigning packaging with new materials is a viable solution to reduce plastic waste: a literature evaluation is being done, with a special emphasis on life cycle assessments and customer perception. Furthermore, a comparison of legislation in Europe and Colombia is provided, and a few examples of research and applications are given.

1. History of packaging

At the beginning of time, food was consumed where it was found. Families and villages were self-sufficient, making and catching what they used. When containers were needed, nature provided gourds, shells, and leaves to use (*A History of Packaging*, n.d.). The origins of packaging can be traced back to prehistoric times. Early humans fashioned containers from natural materials such as hollowed logs, sticks, stones, woven grasses, animal organs and clay to store food (*The History Of Packaging: From Ancient Times To The Future*, n.d.).

Figure 1: wallaby-skin water carrier (Australian Museum, n.d.)

1.1. Glass

It is estimated that glass packaging is being used for around 5000 years. The first glass objects for holding food are believed to have appeared around 3000 B.C. in Egypt. The production of glass containers involves heating a mixture of silica (the glass former), sodium carbonate (the melting agent), and limestone/calcium carbonate and alumina (stabilizers) to high temperatures until the materials melt into a thick liquid mass that is then poured into moulds. Because it is odourless and chemically inert with virtually all food products, glass has several advantages for food-packaging applications: it is impermeable to gases and vapours, so it maintains product freshness for a long period of time without impairing taste or flavour. The ability to withstand high processing temperatures makes glass useful for heat sterilization of both low- and high-acid foods. Glass is rigid, provides good insulation, and can be produced in numerous different shapes. The transparency of glass allows consumers to see the product, yet variations in glass colour can protect light-sensitive contents *(Robertson, 2013).* The basic nomenclature used for glass containers is shown in *Figure 2.*

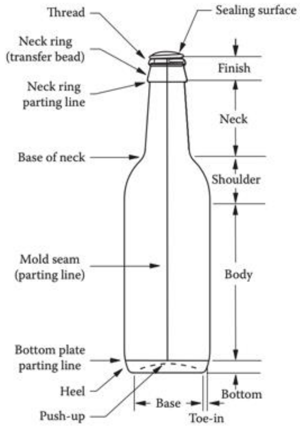

Figure 2: glass container nomenclature (Robertson, 2013)

Finally, glass packaging benefits the environment because it is reusable and recyclable (Marsh & Bugusu, 2007), although its recycling involves high costs.

1.2. Metal

Since ancient times, metal packaging, seen in gold and silver boxes and strong alloys and coverings, is today being used to protect many products. The production of the tin sheet was invented in Bohemia in 1200 A.C. Afterwards, at the beginning of 14th century, tinned food cans have started to be used. This technology was kept a secret since the 1600s and has been replaced by better quality and easier-produced steel after William Underwood forwarded the process to the USA (*History of Packaging*, n.d.-a). Military requirements have helped to accelerate or precipitate some key packaging developments: food canning was invented when Napoleon Bonaparte said he would award twelve thousand franks to whomever comes up with a method to protect the army's food supply (Robertson, 2013).

Metal is the most versatile of all packaging forms. It offers a combination of excellent physical protection and barrier properties, formability and decorative potential, recyclability, and consumer acceptance. The two metals most predominantly used in packaging are aluminium and steel (Coles, 2003). Most commercial uses of aluminium require special properties that the pure metal cannot provide. Therefore, alloying agents are added to impart strength, improve formability characteristics, and influence corrosion characteristics. Depending on the container design and fabrication, a wide range of aluminium alloys is commercially available for packaging applications. The chemical composition and typical usage of some of the more commonly used aluminium alloys (the aluminium is at least 99% pure) are shown in *Table 1.*

Table 1: some aluminium alloy composition limits (% weight) and applications (Robertson, 2013)

Alloy	Typical Application	Si	Fe	Cu	Mn	Mg	Cr	Zn	It
1050	Foils and flexible tubes	0.25	0.4	0.05	0.05	0.05	0.05	0.03	0.03
3104	Beverage can ends and D&I can bodies	0.60	0.7	0.25	1.4	1.3	-	0.25	0.10
5042	Full panel EOE and DRD can bodies	0.20	0.35	0.15	0.5	4.0	0.10	0.25	0.10
5182	Easy-open beverage can ends and tabs	0.20	0.35	0.15	0.5	5.0	0.10	0.25	0.10
8011	Pilfer-proof caps	0.90	1.00	0.20	0.20	0.05	0.05	0.10	0.08
8079	Foil for lamination	0.30	1.3	0.05	-	-	-	0.10	-

The general effect of several alloying elements on the corrosion behaviour of aluminium is as follows:

- copper reduces the corrosion resistance of aluminium more than any other alloying element and leads to a higher rate of general corrosion.
- manganese slightly increases corrosion resistance.
- magnesium has a beneficial influence and Al–Mg alloys have good corrosion resistance.
- zinc has only a small influence on corrosion resistance in most environments, tending to reduce the resistance of alloys to acid media and increase their resistance to alkalis.
- silicon slightly decreases corrosion resistance, depending on its form and location in the alloy microstructure.
- chromium increases corrosion resistance in the usual amounts added to alloys.
- iron reduces corrosion resistance and is probably the most common cause of pitting in aluminium alloys; a high iron content increases the bursting strength but reduces the corrosion resistance.
- titanium has little influence on corrosion resistance of aluminium alloys.

A technology that has been developing in recent years in various metal packaging applications is the coating of steel bands with synthetic polymers (polymer-coated steel), mainly polyester (PET) and polypropylene (PP). Steel cans and drums, coated with synthetic resins, have always found applications in the packaging of paints and other chemical products, but some high-performance solutions have also become of interest for food packaging; for these, the combination of the characteristic properties of steel with those of thermoplastic polymers is successfully exploited. The plastic coating offers high guarantees of inertia regarding the risk of corrosion in wet conditions or following scratches or abrasions, avoids the need for seals in certain situations (aerosols), is readily decorated and colourable, and makes it possible to use metal objects in microwave ovens (Piergiovanni & Limbo, 2010).

1.3. Paper

Ancient China is credited for inventing flexible packaging due to their innovations in developing paper. Historians believe that in the first or second centuries, the Chinese began to use treated mulberry bark to wrap foods. In later centuries, when the Chinese perfected their paper-making techniques, paper also began to be used for packaging items such as medicine and parcels of tea (*History of Packaging*, n.d.-b). Nevertheless, these first papers were somewhat different from those used today. Early paper was made from flax fibres and later old linen rags. It was not until 1867 that paper originating from wood pulp was developed. Although commercial paper bags were first manufactured in Bristol, England, in 1844, Francis Wolle invented the bag making machine in 1852 in the United States. Further advancements during the 1870s included glued paper sacks and the gusset design. After the turn of the century (1905), the machinery was invented to automatically produce in-line printed paper bags (*A History of Packaging*, n.d.).

Paper is divided into two broad categories: (1) fine papers, generally made of bleached pulp, and typically used for writing paper, bond, ledger, book, and cover papers, and (2) coarse papers, generally made of unbleached kraft softwood pulps and used for packaging. Most properties of paper depend on direction. The paper has a definite grain caused by the greater orientation of fibres in the direction of travel of the paper machine, and the greater strength orientation that results partly from the greater fibre alignment and partly from the greater tension exerted on the paper in this direction during drying (Robertson, 2013).

The first commercial cardboard box was produced in England in 1817, more than 200 years after the Chinese invented cardboard. The corrugated paper appeared in the 1850s; in about 1900, shipping cartons of faced corrugated paperboard began to replace self-made wooden crates and boxes used for trade. As with many innovations, the development of the carton was accidental. Robert Gair was a Brooklyn printer and paper-bag maker during the 1870s. While he was printing an order of seed bags, a metal rule normally used to crease bags shifted in position and cut the bag. Gair concluded that cutting and creasing paperboard in one operation would have advantages; the first automatically made carton, now referred to as "semi-flexible packaging", was created (*A History of Packaging*, n.d.).

The first records of paper being used to carry liquids on a commercial scale are found in reports, dated 1908 by Rd. Winslow of Seattle. He remarked on paper milk containers invented and sold in San Francisco and Los Angeles by G.W. Maxwell as early as 1906. Paraffin wax was used to moisture-proof the paper but achieving a liquid-tight bond at the joins was more difficult. In 1915, John Van Wormer, owner of a toy factory in Toledo, Ohio was granted a U.S. patent for a "paper bottle" (a folded blank box) for milk that he called Pure-Pak. The crucial and unique feature was that this box would be delivered flat to be folded, glued, filled, and sealed at the dairy. This offered significant savings in delivery and storage compared to glass bottles, then the predominant package for milk, which was introduced in 1889 (Robertson, 2013).

1.4. Plastic

Although the chemical nature of polymers was not understood until well into the mid-twentieth century, the materials themselves, and the industry based on them, existed long before that. (Andrady & Neal, 2009). The first synthetic polymer was invented in 1869 by John Wesley Hyatt: by treating cellulose, derived from cotton fibre, with camphor, Hyatt discovered a plastic that could be crafted into various shapes and made to imitate natural substances like tortoiseshell, horn, linen, and ivory. This discovery was revolutionary. For the first time human manufacturing was not constrained by the limits of nature. Nature only supplied so much wood, metal, stone, bone, tusk, and horn. However, now humans could create new materials (Science History Institute, n.d.).

World War II necessitated a great expansion of the plastics industry in the United States: nylon, invented by Wallace Carothers in 1935 as a synthetic silk, was used during the war for parachutes, ropes, body armour, helmet liners, and more. In addition, plexiglass provided an alternative to glass for aircraft windows. A Time magazine article noted that because of the war, *"plastics have been turned to new uses and the adaptability of plastics demonstrated all over again."* (Aswell, 1942). During World War II plastic production in the United States increased of 300% (Science History Institute, n.d.).

The properties of plastics are determined by the chemical and physical nature of the polymers used in their manufacture; the properties of polymers are determined by their molecular structure, molecular weight, degree of crystallinity and chemical composition. Examples of different structures of polymers are shown in *Figures 3-4-5*.

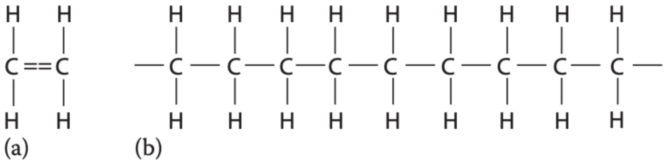

Figure 3: (a) the monomer ethylene and (b) the polymer PE.

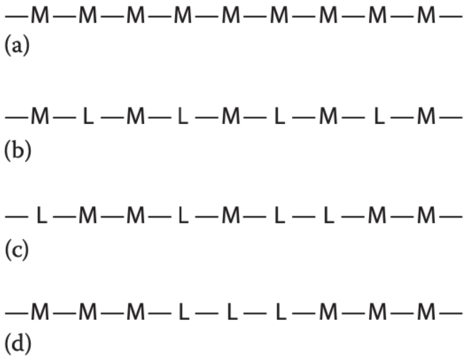

Figure 4: copolymers made with different structures. L and M are any monomers. (a) linear polymer, (b) alternating copolymer, (c) random copolymer and (d) block copolymer.

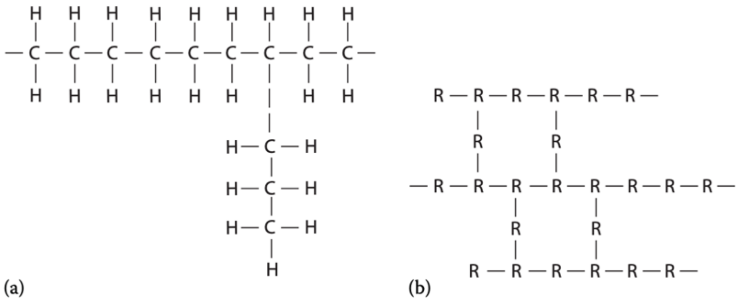

Figure 5: (a) branched PE and (b) cross-linked polymer.

Since there are so many different plastics and new plastic polymers are synthesised all the time, various classification criteria are commonly used to indicate and describe them, to which it is useful to refer. *Table 2* shows the main criteria used to classify plastics.

Table 2: some classification criteria for plastics (Piergiovanni & Limbo, 2010)

Classification criteria	**Characteristics**
Nature of the raw materials	Natural, synthetic, and partially synthetic
Mechanism of polymerisation	Addition, condensation
Tacticity	Isotactic, atactic, syndiotactic polymers
Molecular weight	Mono- and polydisperse polymers
Heat behaviour	Thermoplastics and thermosets
Glass transition temperature	Rubbery and glassy polymers
Morphology	Amorphous, crystalline, semi-crystalline polymers
Structural organisation	Homo- and copolymers, blends, and alloys

The most widespread polymers are described in the following paragraphs, represented by both the cheaper polymers and those with the greatest aptitude for making structural materials; some of their chemical-physical properties of interest are shown in *Table 3*.

Table 3: main characteristics of the most common polymers (indicative values) (Pier Giovanni & Limbo, 2010)

	LDPE	**HDPE**	**PP**	**PS**	**PVC platst.**	**PET**	**EVA**	**PVDC**	**EVOH**
Bulk density [g*cm^{-3}]	0.91-0.94	0-94-0.96	0.88-0.91	1.05-1.2	1.2-1.4	1.34-1.39	0.951	1.675	1.1-1.2
Melting temperature [°C]	110	137	176	-	150	265	69	436	156-195
Glass transition temperature [°C]	-25	-125	-20	94	40-50	69	-33	253	50-63
Breaking strength [MPa]	8-30	22-30	30-40	36-57	20-40	50-60	7.58-31.7	25-110	37-317
Elongation at break [%]	100-950	10	100	1	100	50	800	30-80	730
Permeance O_2 per 25 µm [cm^3*24h^{-1}*m^{-2}*bar^{-1}]	7000	2800	2300	3800	6000	45	21.220	0.001-0.030	0.15-0.71
Water vapour transmission rate per 25 µm [g*m^{-2}*24h^{-1}] at 38°C and 90% ΔHR	15-25	5	4-10	100-155	70-450	15-20	6.673-17.118	1.161	1000-2500

1.4.1 Low density polyethylene (LDPE)

Polyethylene is structurally the simplest plastic and is made by the addition polymerization of ethylene gas in a high-temperature and pressure reactor. Polyethylenes are readily heat-sealable. They can be made into strong, tough films, with a good moisture and water vapor barrier. They are not a particularly high barrier to oils and fats or gases such as carbon dioxide and oxygen, but they have good tensile strength, burst strength, impact resistance, and tear strength, retaining its strength down to - 60°C, even tough when simultaneously exposed to both stress and a chemical medium, there is a dramatic reduction in the time to failure (Coles, 2003).

1.4.2 High-density polyethylene (HDPE)

Addition polymer of ethylene obtained by polymerisation at low temperature and low pressure using specific catalysts (called low-pressure polyethylene). It has a linear structure with few branches and long chains, hence high crystallinity (> 60%). The temperature range of use varies from -25 to +120 °C. Flexible to rigid depending on density. It has very low permeability to water and rather high permeability to oxide. It has excellent electrical insulation properties. Resistant to acids, alkalis, oils, alcohols, and stress cracking. Not resistant to oxidizing agents and organic hot solvents. Low cost, no food suitability problems. It can be processed using all known techniques (Piergiovanni & Limbo, 2010).

1.4.3 Polypropylene (PP)

Propylene is an addition polymer with an ordered, isotactic structure and high crystallinity. The upper thermal limit of use at 110-130 °C. It has the lowest density of the most common polymers (0.9 $g*cm^{-3}$). It is quite rigid and resistant. It has very low permeability to water, but high to oxygen. Excellent electrical insulation characteristics. Resistant to acids, alkalis, oils, alcohols, and stress cracking. Not resistant to oxidising agents and hot organic solvents. It lends itself effectively to bi-orientation, with considerable improvement in mechanical and optical properties. Convertible with all known techniques. The isotactic homopolymer is very crystalline and not very transparent; 1.7% ethylene as comonomer gives rise to the random ethylene propylene copolymer, which is widely used in the industry because it is very transparent (Piergiovanni & Limbo, 2010).

1.4.4 Polystyrene (PS)

Amorphous styrene addition polymer with atactic structure. The upper thermal limit of use at 70-80°C. Rather rigid and very brittle. Very low permeability to water, medium to oxygen. Excellent electrical and thermal insulation characteristics. Transparent and shiny. Resistant to acids, alkalis, oils, and lower alcohols. Not resistant to oxidising agents, organic solvents, stress cracking and UV. Can be processed using all known techniques, very suitable for thermoforming and injection moulding. As a homopolymer, it is also known as crystal PS (brittle and transparent), but formulas containing other comonomers (butadiene) are mainly used to increase mechanical strength (HIPS, high impact polystyrene). Also widely used in expanded form (EPS, expanded polystyrene) (Piergiovanni & Limbo, 2010).

1.4.5 Polyvinyl chloride (PVC)

Addition polymer of vinyl chloride, with amorphous, atactic structure. The upper thermal limit of use ranges from 70 to 100 °C depending on the formulation; it tends to decompose at high temperatures. It has generally low permeability to water and oxygen and is transparent. Very versatile, with characteristics that vary greatly depending on the formulation (rigid PVC/plasticised PVC). It resists diluted acids and alkalis, non-polar solvents, oils and greases, petrol. It is not resistant to polar solvents, concentrated acids, chlorinated hydrocarbons, and aromatics. It presents problems in extrusion processing but has excellent behaviour in blow moulding and thermoforming. Its use has raised many concerns in the past due to the residue of the dangerous monomer (VCM, vinyl chloride monomer), the possibility that it could release dioxins during thermal destruction, and the presence of potentially migratory and dangerous additives (especially phthalate plasticisers and heat stabilisers containing heavy metals). However, due to the presence of chlorine, which makes up more than 50% of its mass, it represents one of the best opportunities to fix a problematic by-product of some important chemical syntheses (chlorine from the Solvay soda process); it is the least "petroleum" and most "mineral" of the plastic polymers (Piergiovanni & Limbo, 2010).

1.4.6 Polyethylene terephthalate (PET)

A polycondensation polymer of monomers produced by esterification of terephthalic acid with ethylene glycol (the monomer is formed with the liberation of water), or by trans-esterification between ethylene glycol and dimethyl terephthalate (with the liberation of methanol); however, the monomer is always polymerised with the liberation of ethylene glycol, which is reused in the synthesis.

It has an amorphous (APET) or crystalline (CPET) structure depending on the speed of crystallisation. It has low permeability to water and oxygen, high hardness, and rigidity. The thermal limit is a function of the degree of crystallisation: it varies from 80 °C for amorphous to over 200 °C for CPET. It is practically not heat-sealable. Resistant to hydrocarbons including aromatic hydrocarbons, fats, oils, dilute acids, and alkalis. Not resistant to halogenated hydrocarbons, acetone, concentrated acids, and alkalis. Processing by injection moulding, extrusion, blow moulding and thermoforming. The addition of a second glycol component makes it possible to lower the density and obtain a material (PETG) that is easy to use in thermoforming and less brittle (Piergiovanni & Limbo, 2010).

1.4.7 Ethylene-vinyl acetate (EVA)

It is a family of copolymers obtained through the polymerisation of ethylene and vinyl acetate. The different proportions of the two comonomers influence all the final plastic pre-stations, which are however quite like those of LDPE. Due to their high coefficients of friction and high adhesiveness, EVA films are used almost exclusively as a sealing layer. They are also used as stretch films, due to their high elasticity, even without plasticiser additives, and in co-extrusion processes for the preparation of multilayer materials and as hot melt adhesives (Piergiovanni & Limbo, 2010).

1.4.8 Ionomers

Ionomers are polymers formed from metallic salts of acid copolymers and possess interchange ionic crosslinks which provide the characteristic properties of this family of plastics. The best known in food packaging applications is Surlyn®, from Dupont, where the metallic ions are zinc or sodium, and the copolymer is based on ethylene and methacrylic acid. Surlyn® is related to PE. It is clear, has excellent oil and fat resistance, and it's tougher than PE, having high puncture strength, strong and flexible but not unbreakable (Coles, 2003).

1.4.9 Polyvinylidene chloride (PVDC)

When vinylidene chloride co-polymerised with PVC (5 to 20%), it is a soft film that is very impermeable to oxygen and water vapour and has been well known and marketed for over 50 years under the name Saran. In addition to excellent gas and water vapour barrier properties, it has good thermal characteristics (withstands sterilisation) and excellent resistance to grease and numerous chemicals. PVC/PVDC copolymers are semi-crystalline resins that are available in a water-soluble form or in organic solvents; they therefore have great versatility of use, also as a waterproofing lacquer, which has also been used in the past on regenerated cellulose films (cellophane). Its monomer, like that of PVC, is subject to strict specific migration limits (Piergiovanni & Limbo, 2010).

1.4.10 Ethylene-vinyl alcohol (EVOH)

It is obtained by hydrolysis of EVA. As the vinyl fraction increases, permeability to water vapour increases and permeability to oxygen decreases; the opposite occurs if the ethylene fraction prevails, normally between 25 and 48%. In any case, the copolymer is typically hydrophilic and, therefore, very sensitive to moisture: if used in humid environments and not adequately protected, it loses its oxygen barrier characteristics. It is a highly crystalline polymer with good mechanical and thermal performance; it can also be processed using many different techniques. It has progressively replaced PVDC in many applications, as it is considered safer (Piergiovanni & Limbo, 2010).

2. Plastic and environment

Since 1950, plastic production output has been steadily increasing. In 2019, 368 Mt of plastic was produced and predicted to reach 8300 Mt between 1950 and 2015, with a total quantity of plastic waste of 6300 Mt. (Ali et al., 2021). If current trends continue, it is estimated that ~12,000 Mt of plastic waste will be in landfills or the natural environment by 2050 (Geyer et al., 2017).

After a stagnation in 2020 due to the Covid-19 pandemic, (*Plastic Europe*, n.d.) reports that the global plastics production increased to 390.7 Mt in 2021 and of this quantity just a small amount was post-consumer recycled plastics and bio-based/bio-attributed plastics, as shown in *Figure 6*.

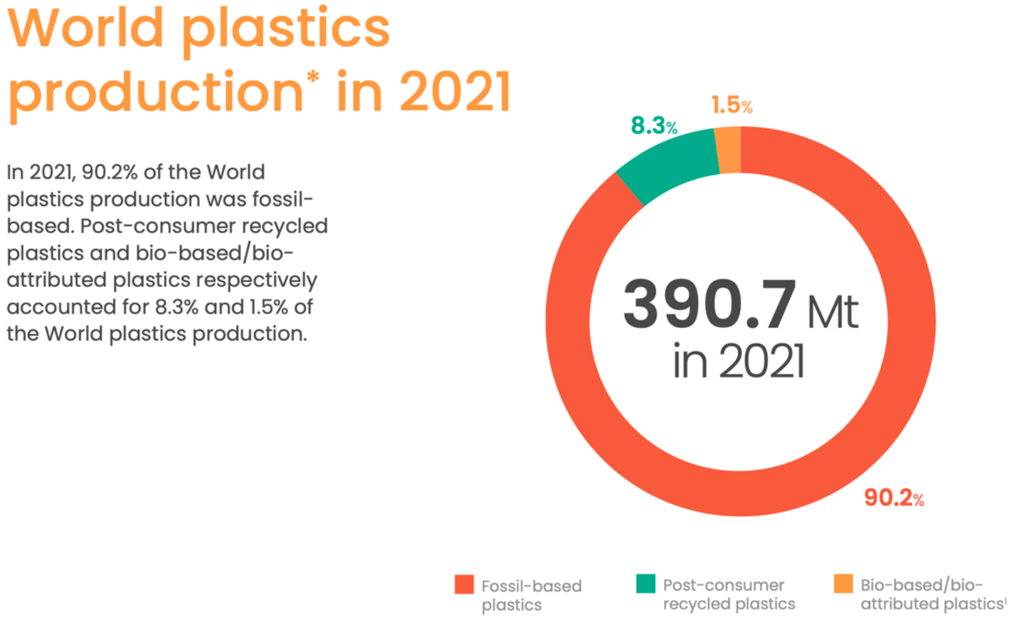

Figure 6: world plastics production in 2021. Polymers that are not used in the conversion of plastic parts and products (i.e. for textiles, adhesives, sealants, coatings, etc.) are not included. (Plastic Europe, 2022)

Strong, inexpensive, lightweight, and versatile plastics are used in thousands of products that add comfort, convenience, and safety to our everyday lives. In particular, packaging is the largest end-use market segment, accounting for just over 40% of total plastic usage (Dedieu et al., 2022).

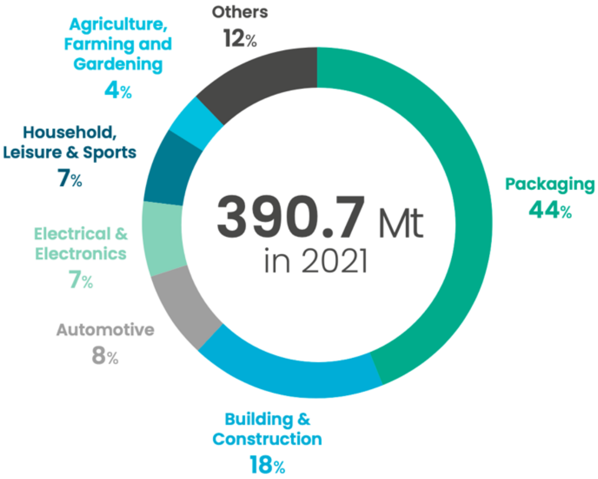

Figure 7: distribution of the global plastics use by application (Plastic Europe, 2022)

Plastics also contributes in several different positive ways for the environment: for instance, plastic packaging materials save energy by reducing transportation fuel consumption due to their light weight compared to metal and glass packaging and containment materials (Eslami et al., 2022). Nonetheless, the long-time degradation of food packaging plastic material has become a major environmental concern, since they have half-lives ranging from 2 to more than 2500 years (Amin et al., 2022).

In particular, according to the estimates, the ocean's surface presently contains more than 150 Mt of floating plastic waste (Tripathi et al., 2021). An area of certain concern is the abundance of small plastic fragments or microplastics. Fragments as small as 1.6mm have been identified in some marine habitats, and it seems likely there will be even smaller pieces below current levels of detection (Thompson et al., 2009). Marine species and humans are being harmed since the plastic waste enters the human food chain through fish consumption (Smith et al., 2018).

An interest study by (Okeke et al., 2022) uncover the microplastic burden in Africa, which is ranked second after Asia as an indiscernible consumer of plastics that break down into microplastic. Of the vast number of plastics produced in Africa, a higher percentage ends up in water bodies due to the low/zero recycling habit, hence keeping Africa upfront in microplastics pollution. Their research has shown that microplastics affect enzyme activity, the immune response, and, most significantly, reproductive function impairment. In addition, microplastics contain a vast range of potentially toxic chemicals, such as polychlorinated biphenyl (PCBs), octadecyl-trichlorosilane (ODTs), and bisphenols (BPA), which have been shown to cause physiological alterations. They also reported that most aquatic lives, such as crabs, shrimp, fish, etc., further used for processing feeds for other aquaculture, may be contaminated with MPs. In fact, studies have shown that plastic debris has been detected in some kinds of seafood marketed for human consumption, including fish and shellfish (Okeke et al., 2022).

Moreover, another important drawback of plastic packaging is that chemicals used to improve the packaging material properties can also migrate into foods during processing and storage. Probable chemical migrants include plasticizers, antioxidants, light stabilizers, heat stabilizers, lubricants, slip compounds, antistatic agents, and monomers. Studies on the chemicals associated with plastic packaging show that at least 148 compounds have hazardous properties such as carcinogenic, endocrine-disrupting, persistent, bio accumulative and toxic, mutagenic, or reprotoxic (Sid et al., 2021). Workers directly involved in the plastic industries are severely affected. Different diseases, i.e., liver cancer, genotoxicity, and neurological dysfunction, were observed due to exposure to styrene monomer and vinyl chloride monomer (Christensen et al., 2017).

To address these problems, at the start of 2018, the European Commission communicated *"a European Strategy for Plastics in a Circular Economy"*, emphasizing improved design and production of plastics and plastic products to facilitate reuse, repair, and recycling (European Commission. Joint Research Centre., 2017). It also noted the need to decouple plastic production from fossil resources and reduce greenhouse gas (GHG) emissions in line with the commitments under the Paris Agreement on Climate Change (*The Paris Agreement*, n.d.). Since then, several policy measures and voluntary actions have been launched by public and private bodies to address the problems caused by plastic food packages. These actions include policies and regulations to reduce or ban single-use plastics (*EUR-Lex - 32019L0904 - EN - EUR-Lex*, n.d.) and voluntary measures, like collaborative commitments (*Global Commitment 2022*, n.d.), and pacts (*European Plastic Pact*, n.d.) to foster the circular economy of plastics.

The vision of a circular economy for plastics has six key points (*Ellen MacArthur Foundation*, n.d.-a):

1. elimination of problematic or unnecessary plastic packaging through redesign, innovation, and new delivery models is a priority.
2. reuse.
3. models are applied where relevant, reducing the need for single-use packaging.
4. all plastic packaging is 100% reusable, recyclable, or compostable.

5. all plastic packaging is reused, recycled, or composted in practice.
6. the use of plastic is fully decoupled from the consumption of finite resources.
7. all plastic packaging is free of hazardous chemicals, and the health, safety, and rights of all people involved are respected.

2.1 End of life

The European Commission lays down some basic waste management principles (*Waste Framework Directive*, n.d.). It requires that waste must be managed:

- without endangering human health and harming the environment
- without risk to water, air, soil, plants, or animals
- without causing a nuisance through noise or odours
- and without adversely affecting the countryside or places of special interest

The main end-of-life options for plastics are recycling, incineration, and landfilling (Civancik-Uslu et al., 2019) with incineration with energy recovery the most common method in the EU (*Plastic Waste and Recycling in the EU: Facts and Figures*, n.d.). Combustion of plastic fractions requires a lot of energy as well its combustion causes the release of several dangerous gaseous products that can cause serious impacts on human health and the environment. Gases released as a by-product of combustion of plastic wastes are highly dangerous and their exposure to living beings can result in several breathing disorders and can even cause cancer. Disposal of plastic wastes in sanitary landfills and open dumps results in the generation of toxic leachate due to the interaction of plastics with groundwater and moisture-rich substances present in the dump, which is of hazardous nature (Moharir & Kumar, 2019).

One of the best treatment options is recycling: it provides opportunities to reduce oil usage, carbon dioxide emissions and the quantities of waste requiring disposal. It is possible in theory to closed-loop recycle most thermoplastics, however, plastic packaging frequently uses a wide variety of different polymers and other materials such as metals, paper, pigments, inks and adhesives that increases the difficulty (Hopewell et al., 2009). There are two main techniques of plastic recycling: mechanical or chemical.

Mechanical recycling is the most common and economical method available for recycling postconsumer plastic waste, and involves sorting, grinding, washing, and extrusion of the material. Given that the process results in varying degrees of polymer degradation, mechanical recycling is limited by the number of reprocessing cycles. Mechanical recycling is operated in two modes: primary and secondary recycling. Primary or closed-loop recycling implies reprocessing of the plastic back to the product used for the same purpose as the original plastic; the process makes use of almost clean waste or postconsumer waste of known origin (Hatti-Kaul et al., 2020).

Chemical recycling technologies, degrading the plastic into chemical feedstock or monomers, are suggested as potential alternative recycling methods for materials that are not suitable for mechanical recycling (Mendes & Pedersen, 2021).

Even though recycling is the preferred option of plastic waste, it's important to highlight that mechanical and chemical recycling of postconsumer single-use food packaging plastic is not always techno-economically feasible (Jayasekara et al., 2022). Secondly, recycling is an energy and time-consuming practice, which may increase the product's carbon footprint, and therefore, not favourable (Shlush & Davidovich-Pinhas, 2022).

2.2 Upstream innovation: new material selection

In a circular economy, upstream innovation is about tracing a problem back to its root cause and tackling it there. It means that rather than working out how to deal with a pile of waste, we prevent it from being created in the first place (*Ellen MacArthur Foundation*, n.d.-b). In the past decades, there's been a growing interest for biodegradable materials both in academics and in industrial applications. (Moshood et al., 2022) show how the appearance of papers on bio-based plastics and biodegradable plastics began in 1990 and continued to develop steadily until 2014 but there has been an exponential increase since 2014 and continues until now. Furthermore, the trend line shows an upward tendency, implying that the literature on bio-based and biodegradable polymers is continually expanding.

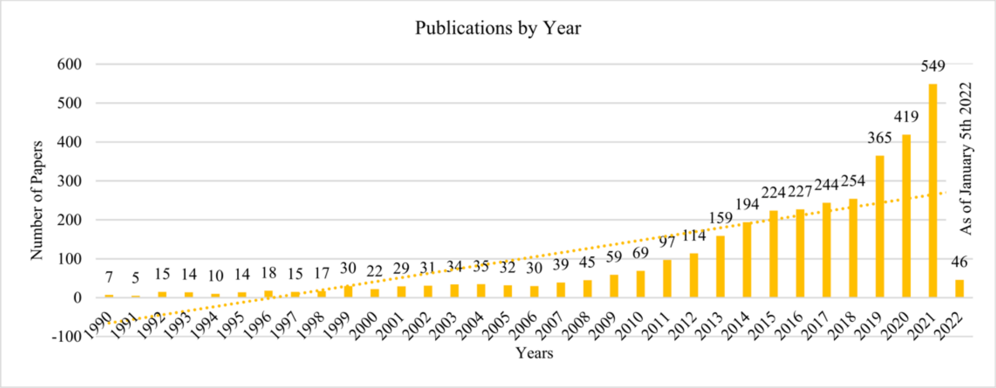

Figure 8: publications on bio-based and biodegradable plastics by year (Moshood et al., 2022)

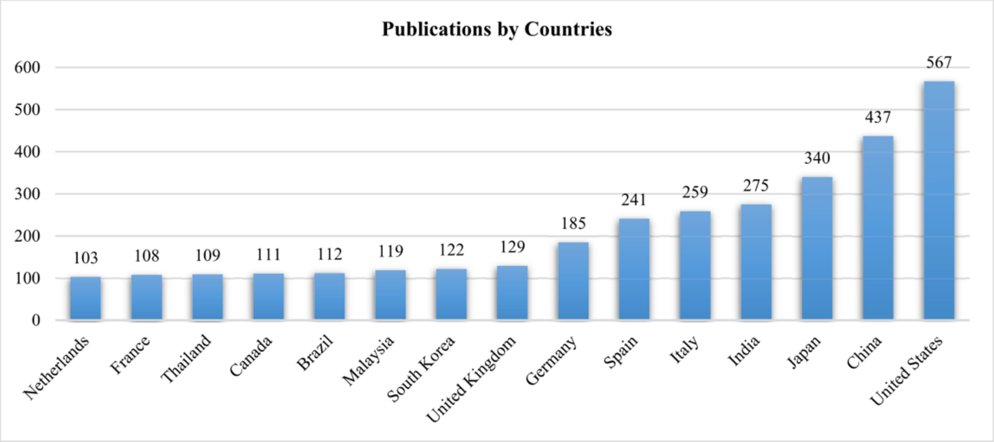

Figure 9: top fifteen countries that contributed to bio-based and biodegradable plastics literature (Moshood et al., 2022)

At the same time, 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 (*PepsiCo: Agenda de Sustentabilidad Para 2025*, n.d.). Similarly, Kraft Heinz announced in 2018 its strategy to make 100% of its packaging globally sustainable by 2025 (*KraftHeinz*, n.d.). Likewise, McDonald's announced recently that its packaging will be 100% renewable and recycled by 2025 (*McDonald's*, n.d.).

Even though the growing popularity of bio-based materials, the terms *biopolymers* and *bioplastics* are susceptible to misunderstanding and thus inappropriate for standardization purposes. When associated with plastics, the prefix "bio" can be perceived by consumers as an indication of biodegradability or of full natural origin.

However, polymers and plastics derived from biomass can be either biodegradable or non-biodegradable whereas there are different fossil-based plastics that are biodegradable according to the relevant standards (Pellis et al., 2021), as shown in *Figure 10*.

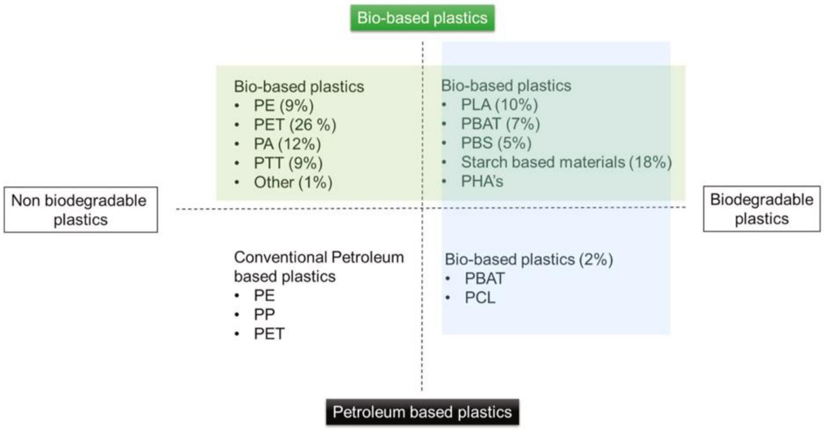

Figure 10: characterization of common plastic materials used in packaging according to their feedstock origin and biodegradability properties, market shares in brackets for bio-based plastics (Mendes & Pedersen, 2021)

Table 4 reports a schematic overview of the relevant standards and definitions as published by (*European Bioplastics*, n.d.).

Table 4: definitions regarding the concepts of bio-based polymers and biodegradability (Pellis et al., 2021)

Bio-based (material or product)	Fully or partly derived from biomass (plants). Bio-based carbon content is the variable describing the amount of bio-based carbon (in relation to fossil-based carbon) contained in a material or product and is measured via the 14C method
Biodegradation	Chemical process during which microorganisms available in the environment convert materials into natural substances such as water, CO_2, and compost (artificial additives are not needed to accelerate degradation). This process depends on the surrounding environmental conditions (e.g. location or temperature), on the material and on the application.
Biodegradable plastic	Bio-based or oil-based plastics that meet standards for biodegradability and compostability. If a material or product is advertised to be biodegradable, further information about the timeframe, the level of biodegradation, and the required surrounding conditions should be provided and a timeframe for biodegradation must be set in order to make claims measurable and comparable. This is regulated in the applicable standards.

Compostable plastic	Bioplastic that has proven its compostability according to international standards and can be treated in industrial composting plants (see details above). Plastic products can provide proof of their compostability by successfully meeting the harmonized European standards (ISO 17088, EN 13432 / 14995 or ASTM 6400 or 6868), a certification, and an according label (seedling label via Vinçotte or DIN CERTCO, OK compost label via Vinçotte).
Degradable or oxo-degradable plastics	Plastics to which additives have been added to enhance the degradation, but do not meet biodegradability and compostability standards. Oxo-biodegradable plastic do not fulfil the requirements of EN 13432 on industrial compostability, and are therefore not allowed to carry the seedling label
Bio-based, non-biodegradable technical/performance polymers	Polymers such as bio-based polyamides (PA), polyesters (e.g., PTT, PBT), polyurethanes (PUR) and polyepoxides used in technical applications like textile fibers (seat covers, carpets) or automotive applications (foams for seating, casings, cables, hoses), etc. Their operating life lasts several years (durable plastics) and, therefore, biodegradability is not desired.
Bio-based, biodegradable plastics	Include starch blends made of thermo- plastically modified starch and other biodegradable polymers as well as polyesters such as polylactic acid (PLA) or polyhydroxyalkanoates (PHAs). Unlike cellulose, materials such as regenerate- cellulose or cellulose-acetate have been available on an industrial scale only for the past few years and primarily used for short- lived products. Yet this large innovative area of the plastics industry continues to grow due to the introduction of new bio-based monomers and polymers.
Fossil-based, biodegradable plastics	Biodegradable plastics currently still made in petrochemical production processes. Mainly used in combination with starch or other bioplastics because the latter improve the biodegradability and mechanical properties. Partially bio-based versions of these materials are already being developed.

Currently, bioplastics still represent less than one percent of the more than 390 million tonnes of plastic produced annually, but according to the latest market data compiled by European Bioplastics in cooperation with the nova-Institute, global bioplastics production capacities are set to increase from around 2.23 million tonnes in 2022 to approximately 6.3 million tonnes in 2027 (*Bioplastics Market Data*, n.d.).

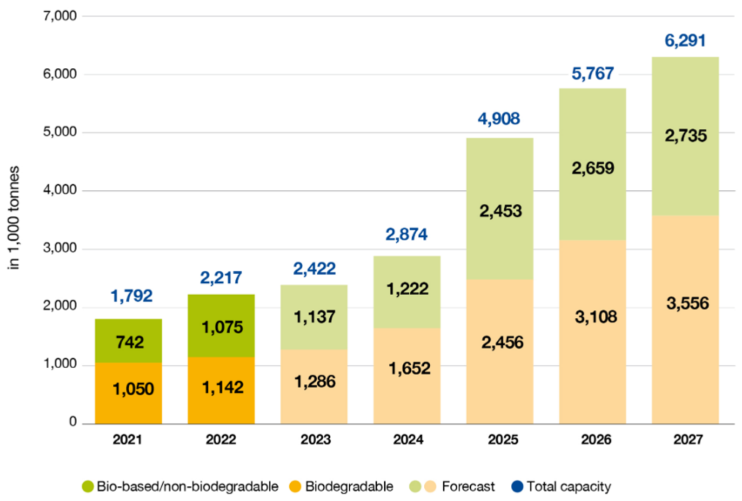

Figure 11: global production capacities of bioplastics (Bioplastics Market Data, *n.d.)*

Bioplastics are used in an increasing number of markets, from packaging, catering products, consumer electronics, automotive, agriculture/horticulture, and toys to textiles and several other segments. Packaging remains the largest market segment for bioplastics with 48 percent (almost 1.1 Mt) of the total bioplastics market in 2022 (*Bioplastics Market Data*, n.d.).

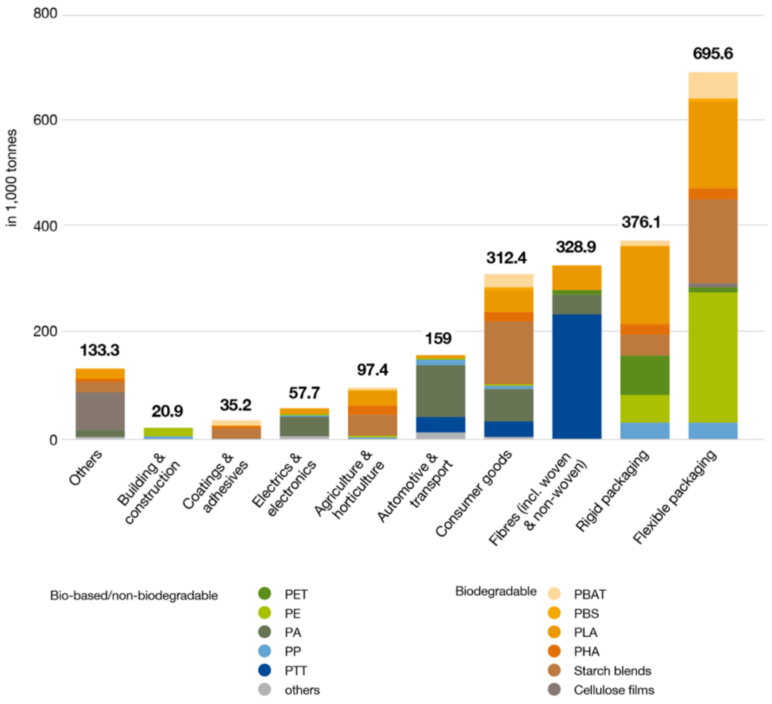

Figure 12: global production capacities of bioplastics 2022 (by market segment) (Bioplastics Market Data, *n.d.)*

Presently, just over a quarter of the production capacity is still located in Europe, with Asia being the first producer of bioplastics. In South America the production of bioplastics is still limited (*Bioplastics Market Data*, n.d.).

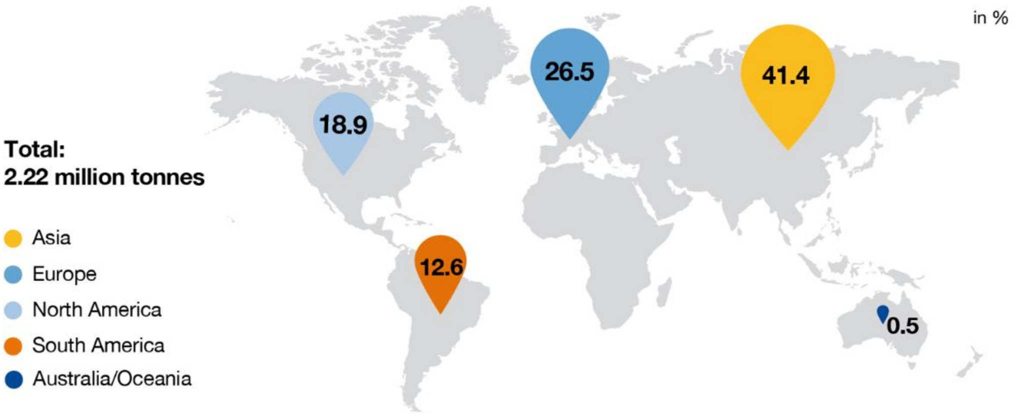

Figure 13: global production capacities of bioplastics in 2022 (by region) (Bioplastics Market Data, *n.d.)*

3. Biodegradable materials

The most prevalent criterion used to classify biodegradable materials is the source of raw materials and their synthesis process: biodegradable compounds are divided into three groups based on this classification, as shown in *Figure 14*.

Polymers made from natural materials, mainly plants, are known as natural polymers. Natural polymers include polysaccharides such as starch and cellulose. Polymers generated from microorganisms or genetically modified bacteria are known as microbial polymers. Polyhydroxyalkanoates are a famous example of microbial polymers in the energy substrate function. Finally, synthetic polymers are made chemically from renewable polymers, such as poly acetate from lactic acid monomers. (Yuvaraj et al., 2021).

Another group of synthetic biopolymers, such as biobased polyethylene (PE) and polyethylene terephthalate (PET), has recently attracted much attention from the industry. These biopolymers are bioderived, but they are non-biodegradable and are chemically identical to the conventional polymers derived from oil and therefore have the same chemical and physical characteristics. It is worth noting that biopolymers like polycaprolactone, a fossil fuel–derived and biodegradable, are typically excluded from biobased polymers (DeGruson, 2016). Therefore, for the reasons just explained above, these two groups of biopolymers will not be considered in this analysis.

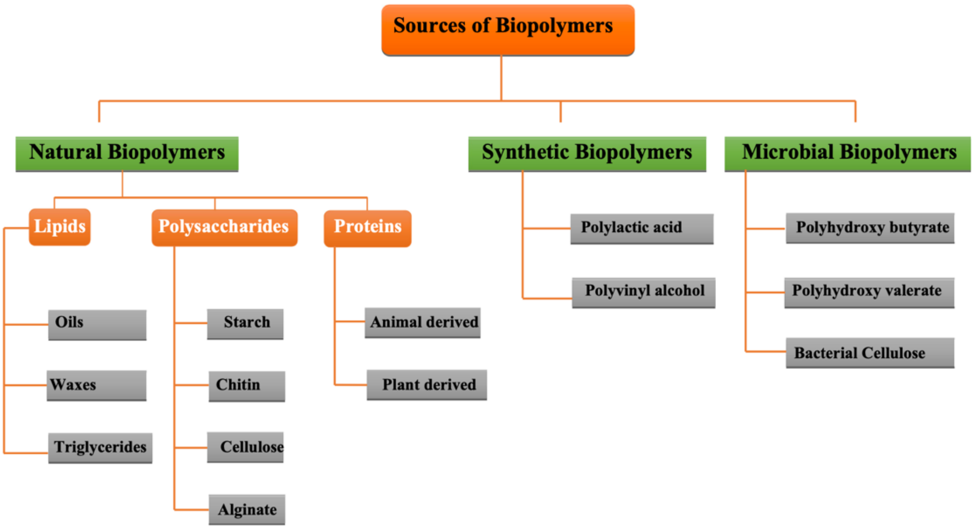

Figure 14: source of biopolymers (Yuvaraj et al., 2021)

3.1. Natural Biopolymers

Natural polymers, typically known as bio-derived compounds, can be obtained through physical or chemical means by extracting them from their natural environments. These polymers have been extensively used in various industrial sectors, including food, textiles, papers, wood, adhesives, and pharmacy. Natural polymers outperform synthetic polymers in terms of biodegradability, toxicity, and biocompatibility. They also have several advantageous properties such as incorporated antioxidant and antimicrobial properties, which enhances nutritional value of food, they’re comparatively cheap, and they have no detrimental environmental effect like inorganic plastic materials (Gupta et al., 2022).

3.1.1. Lipids

The utilization of lipids is presently in the spotlight of food industry as they are one of novel renewable and sustainable raw materials. Lipids derived materials are considered as a promising alternate to petrol-based polymers as they are sustainable, bio-renewable, biodegradable, and environmentally benign. These unique attributes draw the attention of scientific community for the use of lipids in food packaging applications with a potential to compete with fossil fuel derived polymers. In particular, lipid derived plasticizers from bio-resources (vegetable oil, waste cooking oil) have shown great potential to be used as an effective bio-plasticizer. The compatibility of these plasticizers with different polymer matrices and their influence on the thermal and mechanical characteristics is richly discussed in the literature (Zubair et al., 2021).

3.1.1.1. Oils

Plant oils have been actively pursued for their ability to yield various satisfactory chemicals and polymers (Sousa & Silvestre, 2022). Biobased polyamides, notably commercially available Nylon 11 (PA 11), synthesized via polycondensation reaction of 11-aminoundecanoic acid (obtained by castor oil pyrolysis), are an important example of the use of vegetable oils at the service of engineering plastics used for multiple applications from textile fibers and packaging to electronic devices (Meier, 2019). Furthermore, there is a strong track record of using vegetable oil polyols to synthesize linear or crosslinked polyurethanes via the isocyanate root (Sousa & Silvestre, 2022).

3.1.1.2. Waxes

Waxes are generally nonpolar lipid and are solid at ambient temperature. The waxes have no solubility in bulk water. They are highly hydrophobic and are soluble in typical organic solvents. Different types of natural waxes from plant and animal sources are produced and derived from petroleum resources. Waxes are esters (monoesters and diesters) of alcohols and long fatty acid chains with variety of functional groups such as acids, alcohols, ketones, and esters of fatty acids. Moreover, the waxes from synthetic sources are mainly comprised of long chain of aliphatic hydrocarbons (Zubair et al., 2021).

3.1.1.3. Triglycerides

Triglycerides can be obtained from a great diversity of sources: vegetable oils, microalgae, animal fats (tallow, lard, butter, etc.). They are esters of glycerol and fatty acids, the structure of which is depending on the source. Fatty acids are constituted of long hydrocarbon chains generally comprised between 14 and 24 carbons, which can present several active groups. The chemical structure of the fatty acids offer plenty of opportunities for chemical modifications, making them one the most employed biobased resource for polymer synthesis (Lucherelli et al., 2022).

3.1.2. Polysaccharides

Polysaccharides represent the bulky molecules in the biosphere and are the main structural elements of plants. The polysaccharide-based films have excellent gas permeability properties, thus contributing to improve the product life without creating anaerobic conditions, unlike fat-based films, which create an anaerobic environment and thus increase the risk of contamination (Zubkiewicz et al., 2022). These polysaccharide-based biofilms are hydrophilic and have low water barrier properties, high mechanical strength, high gas (CO_2 and O_2) barrier properties (Bianco, n.d.).

3.1.2.1. Starch

Starch is a kind of polysaccharide, which is a long chain of glucose molecules. Starch has two kinds of glucose chains. The first is a basic chain known as amylose, while the second is a complicated branching form known as amylopectin. Starch is the most abundant carbohydrate reserve in plant tubers and seed endosperm, where it is found in the form of granules (Baranwal et al., 2022).

Corn is the most widely produced starchy crop for human and animal feed globally; it is the source of 80% of the starch produced worldwide and is the main source of starch for bioplastics but the study of non-conventional starch sources to produce edible films is an ongoing trend in food science and technology (Henning et al., 2022).

Starch films are tasteless, colorless, and odorless. They present good oxygen barrier properties, nutritional value, edibility, and others. However, due to their hydrophilic nature, starch films have some disadvantages, mainly related to their low water vapor barrier capacity and mechanical properties (Teixeira-Costa & Andrade, 2021).

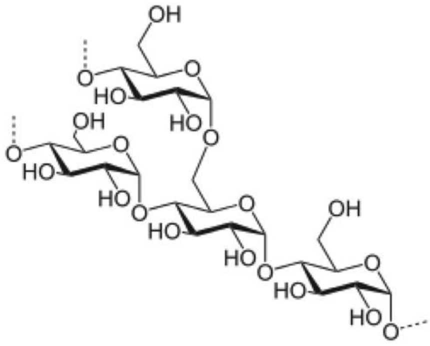

Figure 15: chemical structure of starch (Yuvaraj et al., 2021)

3.1.2.2. Chitin/Chitosan

Chitin is also an abundant biopolymer on earth after cellulose. It mainly originates from the exoskeleton of marine invertebrates and insects or the cell wall of some fungi. The process of obtaining chitin from the shells of crab or shrimp starts with the extraction of proteins followed by treatment with calcium carbonate for dissolution of shells. The chitin obtained from this process is then deacetylated with 40% sodium hydroxide for 1–3 h at 120 ◦ C. This yields a 70% deacetylated chitosan (Reddy et al., 2013). Chitosan is a cationic biopolymer, which can be produced by deacetylation of chitin (J. Wang et al., 2022). Chitosan has amino and hydroxyl group in its structure, which enabled the antimicrobial activities against gram-positive and gram-negative bacteria: for this reason, chitosan films showed good antimicrobial and antioxidant activities for food packaging (Kumar et al., 2020).

Chitosan has also been blended with other biopolymers (polysaccharides and proteins), some synthetic polymers (polyvinyl alcohol and polylactic acid), some functional extracts (such as beeswax, honeysuckle flower extract) and nanomaterials (such as metal and metal oxide nanomaterials, graphene oxide, montmorillonite, silica) to adjust the mechanical, thermal and barrier properties for food packaging (H. Wang et al., 2018).

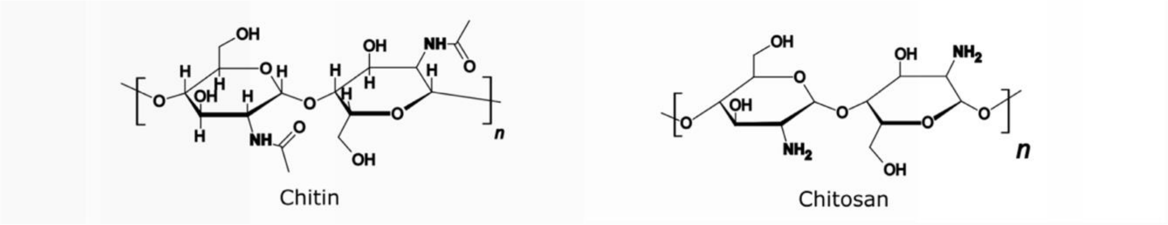

Figure 16: chemical structure of chitin and chitosan (V et al., 2022)

3.1.2.3. Cellulose

Cellulose is the world's most abundant source of natural polysaccharide. Presently, cellulose has a production capacity of 10^{11}-10^{12} tons globally annually (Foroughi et al., 2021). In general, the various types of cellulose have some commonality, including adaptable hydroxyl groups within the glucopyranose units, which contributes to many desirable properties including, hydrophilicity, chirality, biodegradability, and versatility of attaching various functional groups. Consequently, cellulose is a fascinating candidate for sustainable and renewable starting point for the development of various functional materials such as hydrogels, films, membrane, and coatings. (Sugiarto et al., 2022).

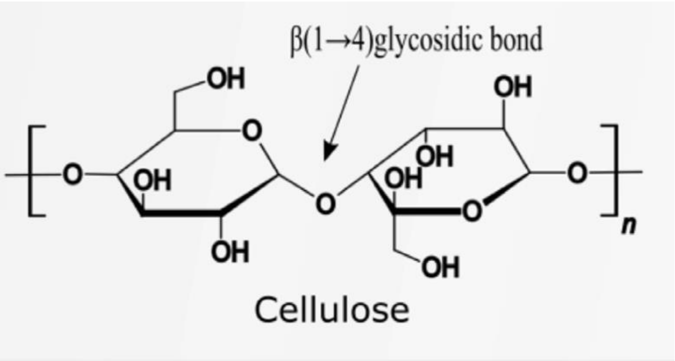

Figure 17: chemical structure of cellulose (V et al., 2022)

Cellophane, made from regenerated cellulose, has been widely used for food packaging in real life. Cellophane films are transparent and mechanically stiff with excellent stability of dimensions. They are well known as candy wrappings, and also the packaging for cheese, cookies, coffee and chocolates (J. Wang et al., 2022).

During cellulose isolation through pulping process, it can also be extracted lignin: the encrusting material in which the cellulose microfibrils are embedded, byproduct of the delignification process in the papermaking industry. Utilization of lignin in the food packaging sector is a growing topic of interest mostly driven by (1) its natural properties as antioxidant, anti-microbial, and UV-resistance, (2) aim to enhance the material properties to be at least equal with conventional plastics in terms of performance, and (3) use of sustainable resources by valorization of lignin which is a huge agro-industrial waste (Basbasan et al., 2022).

3.1.2.4. Alginate

Alginate is a natural polysaccharide present in the cell wall of various brown algae. It contains β-D-mannuronic acid (M) joined to α-L-guluronic acid (G) joined through α-1,4-glycoside linkage. The properties of alginate depend on the source and the ratio of M and G units in the polysaccharide chain (Nadi et al., 2019).

Alginate is already in use in the food industry as a stabilizer, thickening, and gelling agent. As biodegradable polymers are widely utilized to prepare edible films (EFs) due to their novel properties as gel and film formation. Alginate films have good resistance to oil and fats transfer but they are poor water barriers because alginates are water-soluble polymers; nevertheless, calcium limit the water vapor permeability of these films and make them water insoluble (Atta et al., 2022).

Recently, EFs are prepared on the way to achieve the term *active packaging* through the inclusion of specific compounds as antioxidants and anti- microbial materials. These active EFs undergo some additional functions, beside their packaging role, as carrier for antioxidants, antimicrobial agents and other components and consequently extend the shelf-life of the food (Abdel Aziz et al., 2018).

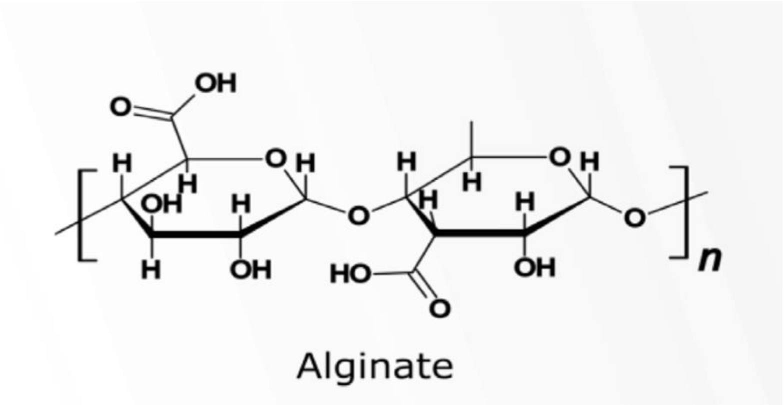

Figure 18: chemical structure of alginate (V et al., 2022)

3.1.3. Proteins

Proteins are biopolymers with complex compositions and structures. The high intermolecular binding ability of proteins makes them suitable for multiple functions and applications. Protein-based film packaging exhibits extraordinary mechanical and barrier properties, especially to oxygen and carbon dioxide gases, when compared to polysaccharides (Teixeira-Costa & Andrade, 2021).

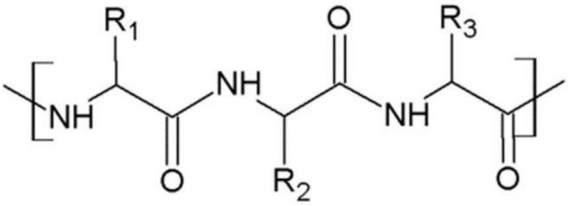

Figure 19: chemical structure of proteins (Gupta et al., 2022)

3.1.3.1. Animal-derived

Collagen and gelatin are examples of proteins obtained from animal sources. Collagen is the most abundant protein in nature. In animal, it constitutes about 20–25% of total body mass. Its structure consists of three cross-linked α-chains while denatured collagen derivative is called gelatin, composed of many polypeptides and proteins. Collagen is rich in methionine, hydroxyproline/proline, and glycine amino acids. Collagen-based bioplastics are synthesized by the extrusion process and comprises various applications, while films production using gelatin requires wet process by the formation of film forming solution. Collagen-based bioplastic films comprise good mechanical properties: hydrolyzed collagen films have been reported to possess excellent tensile strength. However, gelatin films possess poor mechanical and barrier properties which shows its hydrophilic nature (Asgher et al., 2020).

3.1.3.2. Plant-derived

Plant-derived proteins have gained remarkable attention of food manufactures and consumers in the search for natural food resources and alternative materials for vegetarian, vegan, and food allergy diet restrictions (Teixeira-Costa & Andrade, 2021). In this review, among the many choices of possible plant-derived proteins, it's discussed soy protein.

Soy protein has become one of the important proteins for food packaging applications due to its worldwide abundance. They are an appealing alternative for food packaging applications due to their great film-forming ability and low cost. The soy protein-based films provide excellent oxygen barrier properties at low relative humidity, which is critical for preventing the oxidative deterioration of food quality within the packaging material (Umaraw & Verma, 2017).

Moreover, these films are economical, sustainable, clear, biodegradable, and biocompatible. However, the soy protein-based films are usually brittle and have insufficient moisture barrier characteristics. Glycerol is frequently used to plasticize the soy protein films, which increases their flexibility but lowers their moisture resistance further due to their hydrophilic nature (Rani & Kumar, 2019).

3.2. Synthetic biopolymers

This class of biopolymers is produced by "classical" chemical synthesis from renewable bio-derived monomers (Petersen et al., 1999). Polylactic acid (PLA) belongs to this class, considered one of the most promising to produce sustainable and green packaging materials (Singh et al., 2020).

3.2.1. Polylactic acid (PLA)

PLA is a type of aliphatic polyester obtained by ring-opening polymerization of lactide monomer. The lactic acid monomers are usually obtained from the fermentation of renewable materials like corn, sugar, and other feedstocks. It is recyclable, compostable, and degradable within a short life span having a high molecular weight and has high transparency (Shaikh et al., 2021).

The properties of PLA, such as thermal stability and impact resistance, are inferior to those of conventional polymers used for thermoplastic applications. Therefore, PLA is not ideally suited to compete against the conventional polymers. The applications of PLA can be widened by improving its properties: considerable research is being carried out to develop and study modified PLA, PLA-based copolymers, and PLA-based composites (Reddy et al., 2013). The manufacturing cost of PLA has dwindled due to the advances in obtaining glucose from corn using bacterial fermentation. Today it is easily available and cost-competitive with most of commodity polymers. PLA-target markets include packaging, textiles and biomedical applications (Bordes et al., 2009).

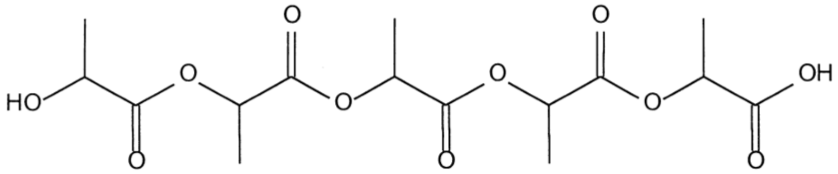

Figure 20: chemical structure of PLA (Petersen et al., 1999)

3.2.2. Polyvinyl alcohol (PVA)

Also known as PVOH, and sometimes PVAL, it is obtained by hydrolysis, usually alkaline, of polyvinyl acetate. It is completely soluble in water and insoluble in organic solvents. It has an atactic structure with high crystallinity. When anhydrous, it has very low gas permeability. It is used both as a film and, more often, as a barrier lacquer. It has good resistance to oils, greases, and solvents; it is odourless, non-toxic, and flexible but has good mechanical strength. PVA has a melting point between 180 and 240 °C (Piergiovanni & Limbo, 2010).

3.3. Microbial polymers

The third route to produce bio-based polymers is their direct synthesis by microorganisms. Examples of such polymers include polyhydroxyalkanoates (PHA) and bacterial cellulose (BC) (Amulya et al., 2021).

3.3.1. Polyhydroxyalkanoates

Polyhydroxyalkanoates (PHAs) comprises a broad group of biobased polymers. PHAs can also be thermally transformed as PLA and are synthesized by renewable raw materials (such as fatty acids, maltose, glucose) via biotechnological conversion by action of different microorganisms (Kawaguchi et al., 2016).

Different types of PHAs have been produced including polyhydroxy butyrate (PHB) and its copolymer 3-hydroxybutyrate-co-3-hydroxyvalerate (PHBV). Their applications range from packaging industries to medicinal implants and textile sectors. There has not been significant application of PHAs as bioplastics and possible cause could be the high production and recovery cost of PHAs. Scientists are searching for the replacement with cost effective feedstocks for PHA production. For example, the use of wood-based raw material containing hemicelluloses which can be used for the development of bacterial PHAs (Asgher et al., 2020).

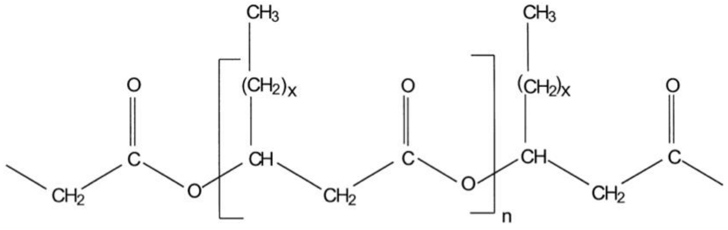

Figure 21: chemical structure of polyhydroxyalkanoate (Petersen et al., 1999)

3.3.2. Bacterial cellulose

Bacterial cellulose (BC) is a material that is emerging as a potential alternative to plastic materials to apply as food packaging because of its excellent properties and the various alternatives of use that it offers. BC is well-known in some Asian countries as raw material for some food products with a long and ancient tradition: for example, in Philippines, BC is used to prepare the famous dessert *Nata de Coco*, which is basically BC fermented in coconut water and later seasoned (Azeredo et al., 2019).

The BC is a linear polysaccharide composed of β-d-glucopyranose monomers linked by β-1,4-glycosidic linkages, forming molecules of cellobiose. Unlike plant cellulose, BC is synthesized in a pure way, free of other vegetable molecule remains, such as lignin, hemicellulose, or pectin. The purity of BC is an advantage over vegetable cellulose, since it does not require expensive extraction and purification processes and the use of environmentally hazardous chemicals (Huang et al., 2014).

Moreover, toxicological experiments have shown that the consumption of BC had no reproductive toxicity, embryotoxic and teratogenic effects. Therefore, BC has been classified as generally recognized as safe (GRAS) by the USA Food and Drug Administration since 1992 (Lin et al., 2020). The main drawback of BC is the high cost of production, which is considered a limiting factor.

The most widespread and studied application of BC for films is its use as disassembled BC. It can be easily processed into microfibrils (BCMFs), nanofibrils (BCNFs) and nanocrystals (BCNCs) in suspension or powder form. It can be physically incorporated into various polymeric matrices as reinforcing agent to form polymeric composites. In the literature, there are multiple examples of edible polysaccharide-based films reinforced with BC fibers to improve mainly their mechanical, water interaction and thermal properties (Cazón & Vázquez, 2021).

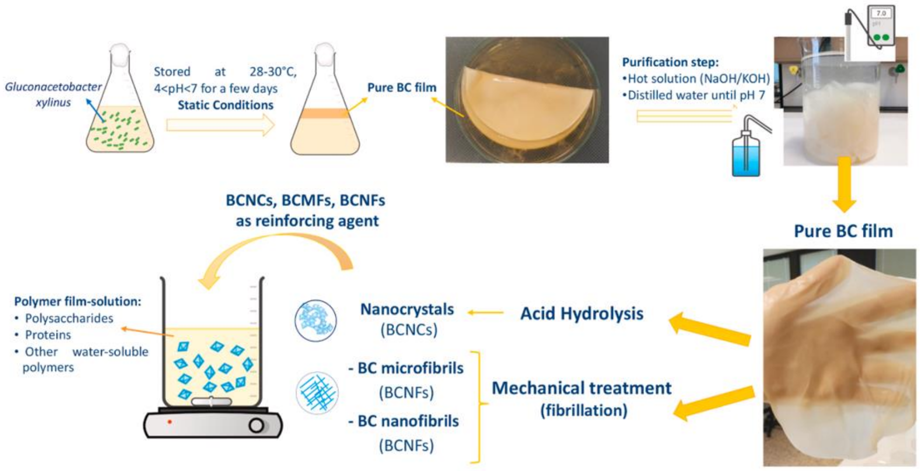

Figure 22: schematic process to obtain microfibrils, nanofibrils and nanocrystals from bacterial cellulose (Cazón & Vázquez, 2021)

4. Life cycle assessment review

Life cycle assessment (LCA) is a well-established method used to quantify the environmental impacts of products and processes. The International Organization for Standardization (ISO) defines LCA and its applications in ISO-14040 and ISO-14044 (Klüppel, 2005). The LCA framework as defined by ISO includes an iterative process of (Hottle et al., 2013):

1. Goal and Scope Definition: defines the extent of the analysis including the goals and the system boundaries. The functional unit for the LCA is defined within this step. The functional unit describes a reference for what is being studied and how much or over what time frame.

2. Inventory Analysis: documents material and energy flows that occur within the system boundaries, often referred to as Life Cycle Inventory (LCI).

3. Impact Analysis: characterizes and assesses the environmental effects using the data obtained from the inventory, often Life Cycle Impact Assessment (LCIA). LCIA expresses the LCI data in common terms, usually with respect to an equivalency factor, such as CO_2-equivients for greenhouse gas emissions. Common LCIA categories include global warming potential, non-renewable resource depletion, eutrophication, ecotoxicity, acidification, ozone depletion, smog formation, and human health (e.g., carcinogens, respiratory impacts, and non-carcinogens).

4. Interpretation: reviews the results of the LCA, identifies opportunities to reduce the environmental burden throughout the product's life, and provides conclusions and recommendations.

Previous LCAs and environmental assessments of biopolymers are largely limited to global warming potential and fossil fuel depletion impact categories which may favor biopolymers because of the inherent properties of plastics made from biogenic carbon, which is carbon that was recently captured from the atmosphere through the biological process of photosynthesis by plants, compared to fossil based plastics and may miss the potential environmental tradeoffs that can occur when shifting to agriculturally produced feedstocks. Additionally, few past LCAs of biopolymers address end of life (EOL). When waste scenarios are included in biopolymer LCAs, findings vary widely based on the chosen EOL scenarios (e.g., landfilling, recycling, incinerating, composting) which are not always based on realistically available disposal methods (Hottle et al., 2017). It is important not to overlook the method of bioplastics disposal, their impact on microplastic formation in the environment and marine life. Therefore, the life cycle assessment studies of these polymeric materials are important before bringing them into the industrial chain (Pandey et al., 2021).

Many studies, such as (Firoozi Nejad et al., 2021), where is assessed the carbon and energy impact of high-value food trays and lidding films used in meat, fish, and poultry packaging, show how the largest impact on the environmental footprint is due to the raw materials and the end-of-life of the products. These stages, in terms of life cycle assessment, are the most relevant in justifying the benefits of one packaging material over another.

It is important to recognize that there is no such thing as *"The ONE Life Cycle Assessment of ALL bioplastics"*. An LCA applies to a specific product or service, not to bioplastics in general or all products available. Parameters of an LCA can vary decisively from product to product, e.g., the type of bioplastics used, the raw materials used, the production and conversion technology, means of transport, as well as available recovery and recycling system(s). Even though LCA is the currently best tool we must assess the environmental impact of biobased products, the possibility of making sound substantiated comparisons between two LCAs, however, is limited (*European Bioplastics, Environment*, n.d.).

Moreover, when doing a comparative analysis of conventional plastics and bioplastics, LCA boundaries need to be broadened to encompass all environmental impacts, including those associated with food production and food waste. Since food waste dominates food packaging, assessing any measure to reduce the former, even to a small extent, can reduce the overall environmental profile of the food product-food packaging system (Kakadellis & Harris, 2020).

4.1. Raw material extraction

Agricultural crops used in the production of bio-based plastics are often grown and harvested using a significant number of resources (such as land, water, fertilizers and pesticides, and energy). In 2018, it was anticipated that 0.81 million hectares of land were used for the manufacturing of bio-based plastics, and by 2023, that number is expected to increase by 25%. Between 30 to 219 million hectares, or almost nine times the area of the United Kingdom, might experience a change in land use if bio-based alternatives were to replace conventional plastics globally (Gerassimidou et al., 2021).

(Escobar et al., 2018) report that the replacement of 5% of global plastic consumption with bio-based plastics could lead to such an increase in the land use change that could take 22 years to offset the carbon emissions released.

Furthermore, the increased agricultural production processes required to support the replacement of conventional plastics with bio-based plastics can be associated with the use of significant amounts of water and chemicals, such as pesticides and artificial fertilizers, as well as genetically modified organisms (GMOs)(Álvarez-Chávez et al., 2012). Additionally, it's critical to keep in mind that the competition between food and bio-based plastics feedstock can have an impact on food access, availability, and cost (Storz & Vorlop, 2013). This has implications for regional food security.

4.2. Production

A study of a range of products with and without biopolymers concluded that there is a significant decrease in energy consumption (25%–75%) and GHG emissions (20%–80%) when switching to many biopolymers (Patel et al., n.d.). The focus of this paragraph is on polylactic acid (PLA), which is the most common biodegradable plastic on the market, owing to its low cost.

(Bishop et al., 2021) examine the environmental impact of using PLA instead of petrochemical plastic packaging for fresh fruits and vegetables. The results show that PLA production can have a high impact when compared to petrochemical plastic production in many impact categories; however, diverting PLA and food waste to be organically recycled, via anaerobic digestion, or potentially insect feed in the future, can compensate for this, dramatically improving the overall environmental performance of bioplastic packaging.

The impact categories for which bioplastic scenarios outperformed petrochemical plastic use included effects on human health, climate change, freshwater eutrophication, ionizing radiation, photochemical ozone formation, resource use (energy carriers), and respiratory inorganics, as shown in *Figures 23* and *24*. The burdens of ozone depletion, water scarcity, terrestrial and freshwater acidification, and terrestrial and marine eutrophication, on the other hand, were increased by bioplastic plastic scenarios. Sensitivity analysis showed that increased energy efficiency in PLA synthesis offered a considerable improvement potential for bioplastics.

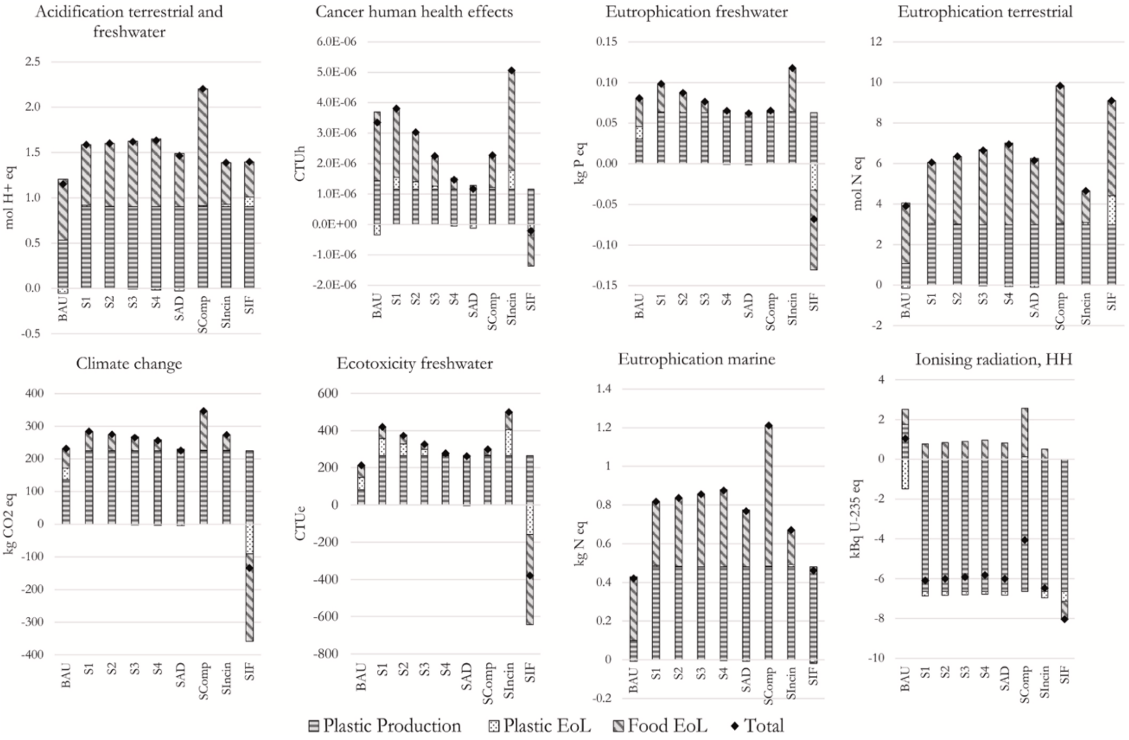

Figure 23: contribution analysis for the LCIA of the eight bioplastic and food waste scenarios, and the business-as-usual (BAU) petrochemical plastic and food waste scenario, across eight of the 16 impact categories assessed. Horizontal stripes represent burdens from plastic production, dotted bars represent burdens from plastic end-of-life, diagonal stripes represent burdens from food end-of-life. Black diamonds represent the total results for each scenario with each impact category. BAU: business-as-usual (20% separation); S1: scenario 1 (20% separation); S2: scenario 2 (40% separation); S3: scenario 3 (60% separation); S4: scenario 4 (80% sepa- ration); SAD: scenario anaerobic digestion (100% separation); SComp: scenario composting (100% separation); SIncin: scenario incineration (100% separation); SIF: scenario insect feed (100% separation) (Bishop et al., 2021).

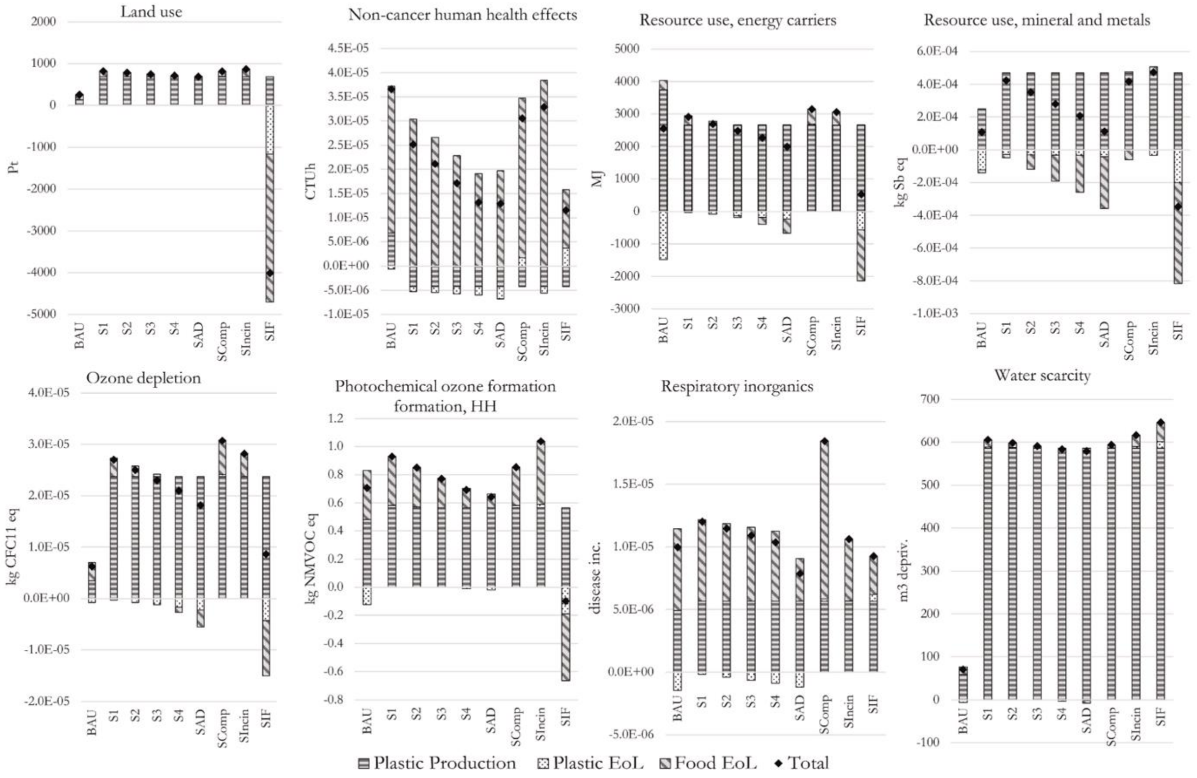

Figure 24: contribution analysis for the LCIA of the eight bioplastic and food waste scenarios, and the business-as-usual (BAU) petrochemical plastic and food waste scenario, across the remaining eight of 16 impact categories assessed. Horizontal stripes represent burdens from plastic production, dotted bars represent burdens from plastic end-of-life, diagonal stripes represent burdens from food end-of-life. Black diamonds represent the total results for each scenario with each impact category. BAU: business-as-usual (20% separation); S1: scenario 1 (20% separation); S2: scenario 2 (40% separation); S3: scenario 3 (60% separation); S4: scenario 4 (80% separation); SAD: scenario anaerobic digestion (100% separation); SComp: scenario composting (100% separation); SIncin: scenario incineration (100% separation); SIF: scenario insect feed (100% separation) (Bishop et al., 2021).

Similar results can be drawn from other studies present in the literature. (Hottle et al., 2013) give an account of the comparative life-cycle environmental impacts from existing databases for petro- and biopolymers (shown in *Figure 25* and *26*) reported directly from ecoinvent and TRACI with no modifications. These figures present a simplified analysis of the ecoinvent data using TRACI to demonstrate life cycle methodology and can provide a baseline for the environmental impacts of PLA and TPS with commonly used data and tools. The results reported from ecoinvent represent a cradle to granule (i.e., gate) system boundary to produce 1 kg of granules for the five common petroleum-based plastics and PLA. Since TPS is not formed into granules, the functional unit for TPS was 1 kg of processed starch.

Figures 25 and *26* make it impossible to tell whether there is a substantial difference in the cradle to gate production of biopolymers and fossil-based polymers. Some LCAs attempt to answer this question by normalizing the impact categories to determine whether they are significant. When compared to petroleum polymers, biopolymers do not show a clear win or loss across any of the environmental indicators with ecoinvent system boundaries only from cradle to granulate (or kg of starch in the case of TPS). PLA and TPS are not clearly "better" or "worse" in the acidification, smog production, ecotoxicity, carcinogen, or respiratory categories. PLA's ecotoxicity affects range from three times those of PP to just 1.2 times that of PET. However, PLA and TPS have a greater impact on eutrophication and ozone depletion than their petroleum counterparts.

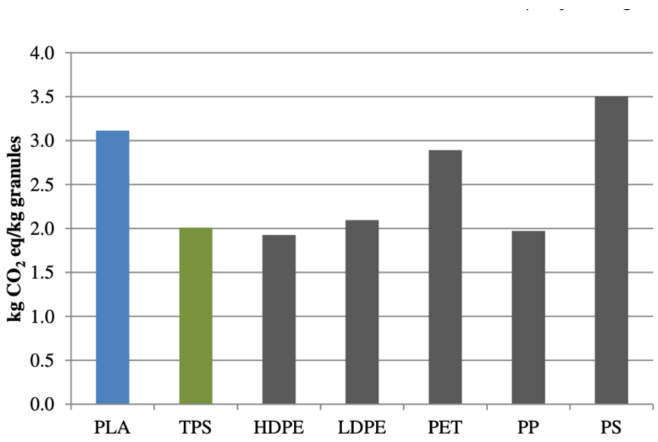

Figure 25: global warming potential for cradle to granule (gate) of PLA and TPS compared to five common petroleum-based plastics. Data taken from ecoinvent v2.2 and TRACI v2.00. PLA = polylactic acid, TPS = thermoplastic starch, HDPE = high density polyethylene, LDPE = low density polyethylene, PET = polyethylene terephthalate, PP = polypropylene, PS = polystyrene (Hottle et al., 2013)

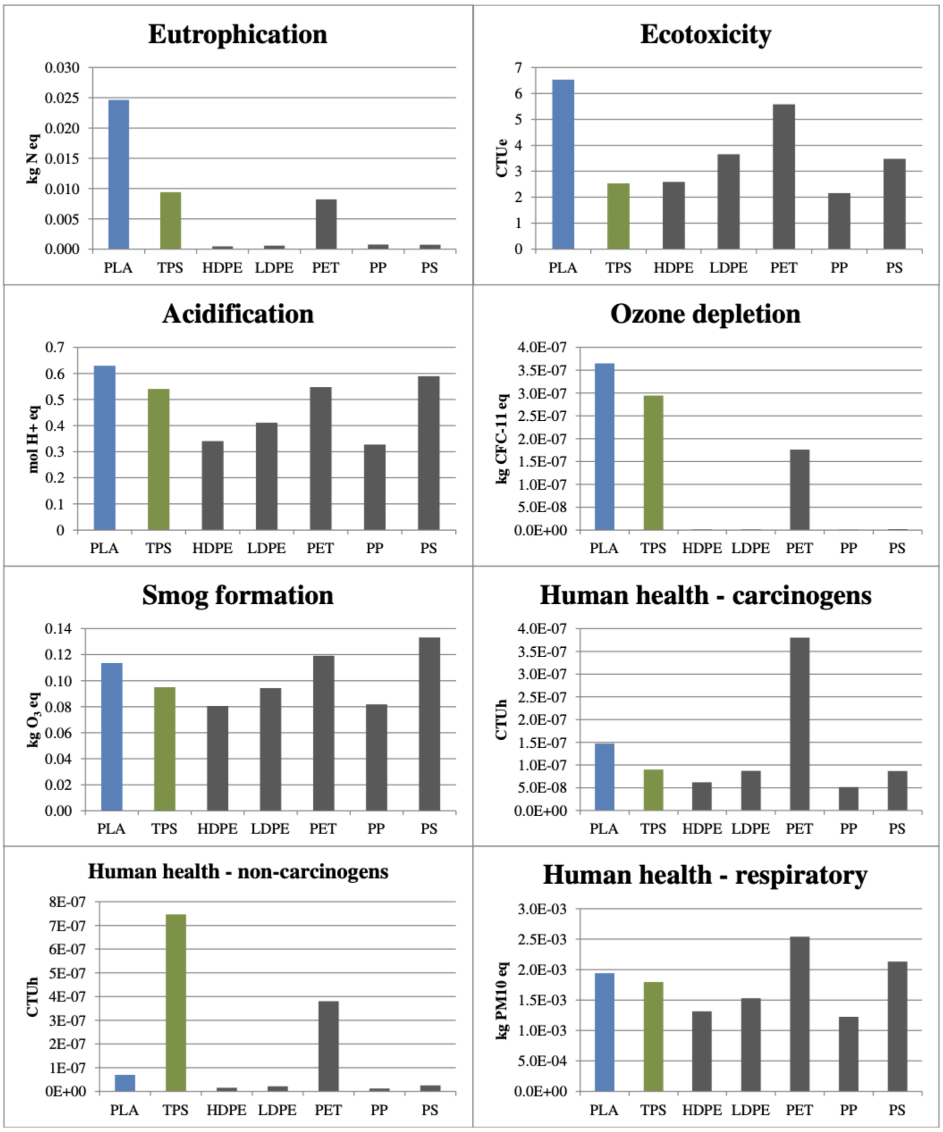

Figure 26: life cycle environmental impacts of PLA and TPS compared to petroleum-based polymers per kg of granule (starch). Data taken from ecoinvent v2.2 and TRACI v2.00. PLA = polylactic acid, TPS = thermoplastic starch, HDPE = high density polyethylene, LDPE = low density polyethylene, PET = polyethylene terephthalate, PP = polypropylene, PS = polystyrene. CTUe = Comparative Toxic Unit ecosystem, CTUh = Comparative Toxic Unit human health (Hottle et al., 2013)

4.3. End of life

The best end-of-life option for any waste product depends on the material, its volume on the market, and available collection and processing infrastructure. As mentioned in *chapter 2*, according to the European Directive on waste management, waste should be managed according to a precise hierarchy indicating a priority order in the legislation and policy for waste prevention and management: (1) prevention; (2) preparing for re-use; (3) recycling; (4) other recovery, e.g., energy recovery; and (5) disposal.

Figure 27: waste hierarchy of the European Directive on waste management (Fredi & Dorigato, 2021)

Since recycling is the second-best option for waste management after preparing for reuse, the life cycle of every plastic material is sustainable only if its disposal options include recycling. While everyone agrees on the convenience of recycling non-biodegradable plastics, be they bioderived or not, for biodegradable plastics biodegradation is often seen as the only appropriate end-of-life option. Although biodegradation can be regarded as a recycling option, and it is sometimes called "organic recycling", it is normally not aimed at recovering plastic materials or monomers to be reintroduced in the life cycle of plastic products.

Biological waste treatments are unique to biodegradable plastic and can be conducted aerobically (with oxygen, for example, composting) or anaerobically (without oxygen, for example, anaerobic digestion). Fungi, bacteria, and actinomycetes compost at either a moderate temperature (35 °C for home composting) or a high temperature (50-60 °C for industrial composting). Similarly, bacteria, not fungi, execute anaerobic digestion at either a low temperature (35 °C for mesophilic digestion) or a high temperature (50-60 °C for thermophilic digestion). The rate of biodegradation is highly dependent on the degradation technique and environment, with compost being the fastest, followed by soil, fresh water, marine water, and finally landfill, because biodegradation occurs at higher temperatures and in the presence of fungi, which are only active in compost and soil environments. Furthermore, not all biodegradable plastics degrade in all biological degradation environments, so the appropriate biodegradation route for each type of biodegradable bioplastic must be chosen (Fredi & Dorigato, 2021).

Nonetheless, it should not be a priori assumed that biodegradation is always the best end-of-life option for biodegradable plastic waste, but all available recycling strategies should be explored, to maximize the environmental benefits of these materials. In the specific case of PLA, (D'Adamo et al., 2020) analyze the different routes for biodegradable plastic waste and rank them on the basis of socio-economic indicators (i.e., waste disposal cost, resource efficiency, end of life responsibility) as shown in *Figure 29*.

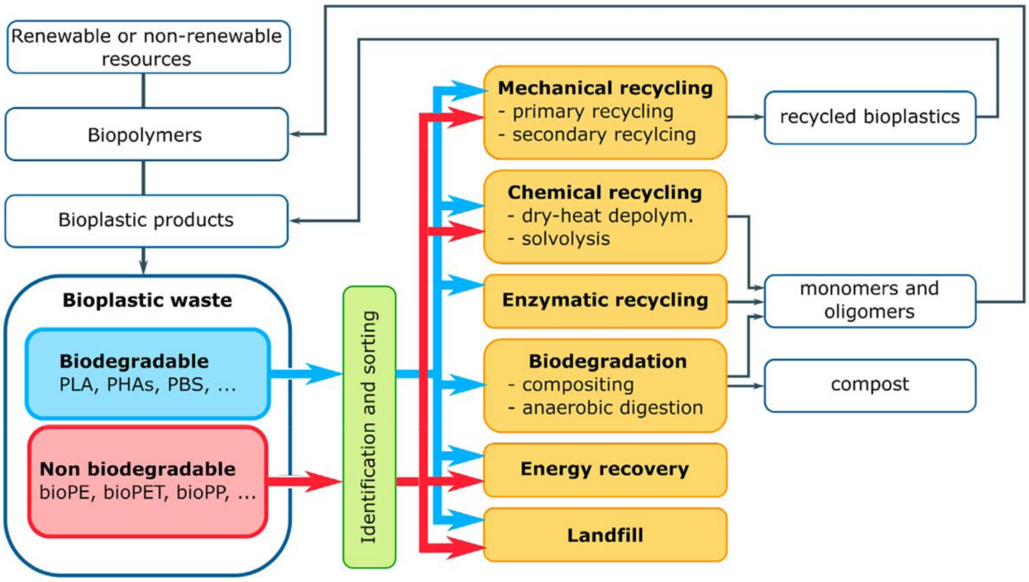

Figure 28: end of life routes for biodegradable and non-biodegradable bioplastic waste (Fredi & Dorigato, 2021)

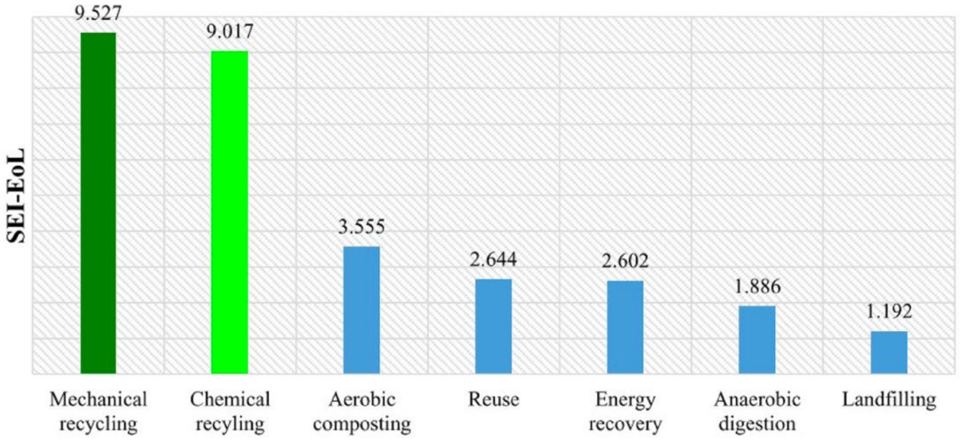

Figure 29: ranking of end of life (EoL) strategies for PLA-based film packaging on the basis of a socio-economic indicator (SEI) (D'Adamo et al., 2020)

As we see from the graph above, mechanical recycling of PLA is the best option among the waste valorization methods for this polymer. When the material quality decreases under a certain threshold, it could be chemically recycled to recover valuable monomers that could be used as building blocks for new polymers or valuable chemicals. Finally, only when the material shows low quality, PLA waste could be biodegraded, when possible, and/or recycled via incineration (D'Adamo et al., 2020).

In the same way as plastic waste, recycling biodegradable packaging can entail a great economic effort: likely in the future, we'll see differences in recycling technologies and treatment efficiency between high-income and low-income nations. Additionally, to increase recyclability, it's needed more integration and transparency amongst all actors in the packaging value chain. This means joint efforts from various stakeholders regarding waste management actors, governments, packaging industry, research institutions, brand-owners, and consumers, towards a more harmonic system. Challenges such as the heterogeneity of local waste management systems and the differences of regulations increase the difficulties to achieve a transparent circular economy in this industry (Lahtela et al., 2020).

5. Consumer perception

Global brands increasingly attempt to differentiate themselves based on adding bio-based materials to their products. Despite this growing popularity of the use of bio-based materials among companies, only a handful of studies focuses on consumer evaluations of bio-based products. Is full use of bio-based materials leading consumer to stronger purchasing intentions? And partial use of bio-based materials? The results depend on several variables and may vary from private to global brand: private label brands that partially use bio-based materials are more positively evaluated than private label brands that do not use bio-based materials; for global brands, this is not necessarily the case.

(Reinders et al., 2017) show that incorporating bio-based product features may help boost the value of both global and private label brands, for example, by differentiating or repositioning a product. At the same time, launching a product that just comprises a portion of bio-based components does not necessarily result in a higher brand rating. This is significant since it is sometimes not technically or financially possible to adopt the usage of bio-based products all at once. If future studies confirm the findings of this study and show that consumers are willing to pay more for products made entirely of bio-based materials as opposed to 30% bio-based materials or products made entirely of non-bio-based materials, brand managers will have compelling reasons to consider using bio-based materials in their brands.

The production of bioplastics is typically hampered by high capital and production costs, far from being competitive with those of fossil-based plastics (such as PET or PP) which cost 1–1.5 euros per kg. In most cases the technology is still experimental, a significant initial investment is necessary. (Tassinari et al., 2023) sustain that the trade-off between reducing transportation costs and economizing on fixed costs is a core element for a biorefinery's production organization. Establishing fewer plants to produce this bioplastic film pays off only when large plant scales are achieved, in the order of 9–18 kt per year. Alternatively, minimizing transport distances by developing many small plants is more cost-efficient.

To overcome these obstacles, quantitative assessment of this disposition to pay should accompany future bioplastics developments to establish a benchmark selling price. This, however, requires experts, companies, and governments to agree and share standards (based on consistent criteria, metrics, and methods) that ensure a correct and effective sustainability assessment. Furthermore, brand managers should ensure that their bio-based brands are presented clearly and easily to customers who are unfamiliar with them. (Herbes et al., 2018) found limited consumer familiarity and knowledge of biobased products, yet even so, consumers demonstrated a willingness-to-pay a premium for bioplastics over plastics from fossil resources.

It's important to highlight that what consumer considers *"green"* or *"eco-friendly"* is different from country to country. (Herbes et al., 2018), answering to how do consumers rate different packaging materials in terms of environmental friendliness and why, underline how in Germany, the packaging options perceived as most environmentally friendly are based on reusable materials; while in France and the U.S., the highest ranking goes to packaging based on recyclable materials. This shows that consumers base their evaluation of the environmental friendliness of a packaging on different criteria: some rank more positively the use of recycled material during the production phase, others give more importance at the post-use phase, that is if the material is recyclable, biodegradable, or compostable.

In addition, while product developers are willing to switch to bioplastics, they often refrain from bringing products to the mass market due to uncertainties of customer receptiveness and fears of greenwashing allegations. This brings the influence of ecolabels and third-party certifications to the center of the debate. To overcome these concerns about greenwashing, companies often disclose environmental information through an independent third-party certifier, ensuring it is more accurate, reliable, and trusted, and hence overcomes consumer skepticism about environmental claims (Testa et al., 2021).

The purchase of food products is directly connected to the five sensory cues: sight, sound, smell, taste, and touch. The touch and sound of the packaging have as well the highest impact on the buying behavior. The visual appeal is more important than the qualitative aspects of the packaging, consumers rate the packaging sustainability also by the design: natural looking packaging materials are such as important as the supposed recyclability (Otto et al., 2021). Packaging material affects consumer expectations of the product and their willingness to buy, so it's essential to find the right balance between taking the technology right and satisfying consumers expectations before implementing any adjustments to achieve a higher level of sustainability (Soares et al., 2022).

6. Applications in Colombia

Colombia, like many other countries, is increasingly recognizing the importance of adopting sustainable practices, including the use of biodegradable materials for food packaging. In 2018, National Circular Economy Strategy was launched. A key early action was establishing a multi-stakeholder committee to help implement the National Plan of Sustainable Management of Single-Use Plastics (*Plan Nacional Para La Gestion Sostenible De Plasticos Un Solo Uso*, n.d.), consisting of twenty-two members from the public, private and academic sector. The Plan contains six strategic actions and ten transversal activities with Action One being the "Gradual replacement of single-use plastic products".

In 2019, single-use plastic products were prohibited and/or restricted in protected areas in Colombia covering some 17,466,974 hectares, which corresponds to 8.4% of the national territory. At the end of 2020, the Ministry of Environment and Sustainable Development presented the regulatory instrument for the sustainable management of plastics that included the prohibition of these products from January 2022 (*Addressing Single-Use Plastic Products Pollution Using a Life Cycle Approach*, n.d.).

This regulation emphasizes factors to consider, such as extended producer responsibility, which includes eco-design and life cycle analysis (LCA). In specifically, the problem of implementing "eco-labeling" as an alternative to transmitting necessary information to the user via digital tools in order to decrease the energy and material expenditure for such labeling. This, in turn, encourages the use of intelligent packaging. However, it is stated that the maximum duration for replacing the plastic parts described in article 5 is between 2 and 8 years (depending on the product). Given this, as well as the fact that the deadline begins to apply on the day the rule enters into effect (July 7, 2022), the necessity to construct a substitute or acceptable method in a very short period of time emerges. Nonetheless, factors such as the prohibition on the use of plastic point-of-sale bags (framed in a two-year period) have been observed throughout the nation for some time, raising the probability that the measures will be implemented on time.

It should be noted that the goal of 100% substitution of single-use plastics enshrined in Article 5 by 2030 seems, perhaps from a pessimistic point of view, not very achievable. Finally, aspects such as the extent of the population dedicated to recycling work, as well as the incentive to promote the use of recyclable materials, such as the use of recyclable materials in the production and distribution of products, are also important. Recycling, as well as the promotion of awareness campaigns through different entities, offer positive perspectives for other sectors of society.

Nonetheless, similarly to the regulation to ban single use-plastic in Europe, several specific features of the rule are vulnerable. In the first place, given the minimal percentages of domestic recycled material used by companies, there is a risk of counterfeiting or mediocrity in the absence of effective regulating organizations. At the same time, the introduction of new materials within the context of sustainability, although better choices than the single-use plastics already in use, will imply a new set of difficulties that must be addressed. Production costs and demand satisfaction stand out as important considerations.

On the 14th of February of last year, Virginijus Sinkeviius, Commissioner for Environment, Oceans, and Fisheries, and Colombian Environment Minister Carlos Eduardo Correa signed the EU-Colombia Joint Declaration on Environment, Climate Action, and Sustainable Development. The Declaration focuses on major common goals such as climate action, biodiversity and ecosystem protection, disaster risk reduction, deforestation, the circular economy, the sustainable blue economy, and plastic pollution. President Ursula von der Leyen said: *"Colombia is an indispensable partner in the fight against climate change and in our action for the environment. The EU and Colombia will work hand in hand on our green agenda and today's declaration is another important step in that direction"* (*Environmental Diplomacy EU-Colombia*, n.d.).

And even if this declaration is an important signal that Europe can't challenge alone the environmental crisis with a global green transition, it is necessary to consider that comparing Europe with Colombia is somewhat disproportionate because Europe has different needs, social, political, and economic conditions than ours. In addition, it should be considered that population density is a factor that can be significant in the recycling issue. In Colombia, the best recycled materials are paper and cardboard, while plastic is the material with the lowest recycling percentages. This is because the efforts, technologies, and budgets to recycle plastic are high. Although plastic recycling in this country is so low, this can be an opportunity to work in this area because alternatives can be found to solve the problem of poor disposal of waste. In Colombia, 56% of plastics production is directed to the packaging sector, and the materials most used for its production are polyethene (36%), propylene (20%), polyvinyl chloride (18%) and PET (13%) (*Acoplásticos, 2017*, n.d.). Simultaneously, it can be stated that Colombians, through their behavior, tend to care for natural systems, and in this way contribute to the mitigation of climate change (Guzmán Rincón et al., 2021).

Nonetheless, redesign products utilizing different materials, which are biodegradable or compostable, is an important tool to reach the goal of circular economy and reduce the plastic wastage. In the following paragraphs are reported several research in this direction, using local natural source and valorizing residues from the agri-food industry.

The first example is the case study by (Bohórqu & Ingenie, 2021): the objective of the present study was to evaluate the physicochemical and morphological properties of biodegradable materials obtained from thermoplastic yam starch (TPS), and polylactic acid (PLA) improved with the addition of epoxidized sesame oil (ESO). The blends were made by extrusion, and the films were made by compression molding. The addition the ESO on the TPS/PLA polymeric matrix caused a decrease in moisture content, surface wettability and lower permeability to water vapor. Furthermore, when adding ESO at 3%, elastic modulus and the tensile strength increased approximately double and the deformation capacity of a TPS/PLA interface without marked separation and smoother surfaces. The materials obtained show promising properties for the development of food packaging with low moisture content.

There are many ways to obtain biomaterials from the most variety of sources, one case is from fish scales: in fact, they can be used in many applications such as filling material for paper, biomass for energy generation, or removing heavy metals. However, fish scales are discarded because they are considered waste produced on a large scale, constituting 1 wt.% of whole weight in fish, which makes it one of the major sources of contamination in riverine regions in many parts of the world. *Prochilodus magdalenae*, commonly called "bocachico" in Colombia, is an endemic species grown naturally mainly in the Magdalena River and Cauca River and can be used as a source to obtain scales to extract chitosan. "Bocachico" is highly commercialized informally by street vendors because it constitutes an important food source for riverine populations. (Molina-Ramírez et al., 2021) extracted chitosan for application as an antibacterial agent integrated into starch-based films from the scales of *Prochilodus magdalenae*. The process is showed in *Figure 30*.

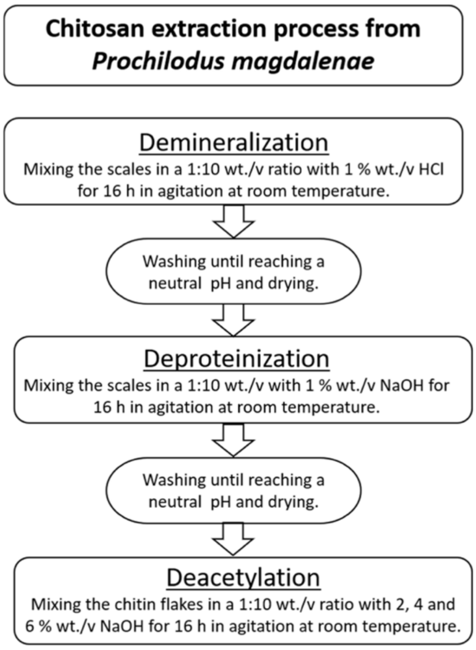

Figure 30: chitosan extraction process from P. magdalenae scales (Molina-Ramírez et al., 2021).

The importance of using local sources to obtain chitosan is due to the significant effect on its properties such as solubility, reactivity, affinity for solvents, and swelling. These films made from this novel source showed a high potential to produce biodegradable food packaging.

A case of repurpose of waste is illustrated by (Guancha-Chalapud et al., 2022) where cellulose nanofibers were obtained from pineapple leaves, a large solid waste in South America. Colombia is one of the ten pineapple-producing countries in the world. Colombian pineapple production has increased at an annual rate of 12%, reaching over 1.2 million tons in 2021. Pineapple leaves are an abundant waste during pineapple transformation since leaves represent between 65% and 80% of the total crop; most of these come from the crown (leaves from the upper part of the fruit) and the stem. A pineapple plant in the harvested state contains 25 to 30 leaves, with diameters ranging from 45 µm to 205 µm. These leaves contain 2% to 3% fiber and are composed of approximately 70–80% cellulose, 17% hemicellulose, and 5% lignin.

Due to the morphology and characteristic physical properties of the obtained materials, cellulose nanofiber produced in this work could be a promising material for use in a wealth of fields and applications such as filter material, high gas barrier packaging material, electronic devices, foods, medicine, construction, cosmetics, pharmacy, and health care. Specifically for the food packaging, cellulose nanofibers are a great barrier against oxygen (due to their > 40% crystallinity) and have low thermal expansion, properties that give them potential for use in food production and preservation since cellulose nanofibers could act as gas barrier films to reduce air flow and to maintain food freshness, thus acting as biodegradable packaging.

On the same wavelength of the case study cited above, (Orqueda et al., 2022) used red chilto waste to produce active biobased films for the protection of salmon fillets. In Colombia, about 120,000 tons of chilto are produced per year on 6500 ha, of which the majority is consumed locally. The pulp, seed and peel represent 51.5, 39.4 and 9.1% of the total weight of the fresh fruit, respectively. Therefore, approximately half of the weight of the fruit (49%) is considered waste material. These wastes are a source of natural antioxidants such as phenolic compounds, anthocyanins, and carotenoids.

First, the chemical composition and antioxidant activity of polyphenolic and anthocyanin enriched extracts from seeds and peels of red chilto were compared. Also, the film-forming properties of pectin-enriched extracts from red chilto peel were evaluated. Finally, the effectiveness of the obtained films for reducing the oxidation of salmon fillets during storage was analyzed. The active properties of the films proved a high antioxidant capacity and good mechanical and physicochemical properties. Films based on polysaccharides and polyphenols of red chilto peel are interesting as edible coatings to replace non-biodegradable plastics and extend the shelf-life of fish foods. In view of a potential commercialization, it will be necessary to evaluate a sensory analysis through a panel of tasters to analyze possible changes in the organoleptic characteristics of the salmon samples for their acceptability.

The development of biodegradable films based on agro-industrial plant products and by-products is an excellent opportunity to add value to these residues and reduce waste accumulation leading to positive impacts on the environment and the studies citied in this work are the first examples in this path in Colombia.

If reducing the use of plastic materials is a key step to achieve a more sustainable future, on the other hand, the circular economy seeks to eliminate waste and reduce environmental impact through the reduction, reuse, and recycling of materials. In the context of food packaging, this include not only designing packaging with recycled and recyclable materials, but as well implementing collection and recycling systems to recover and reuse packaging materials. In Colombia, what is best recycled is paper and cardboard, while plastic is the material with the worst recycling percentages: 690,000 tons of waste were recycled in the country for 2018, with plastic recycling accounting for approximately 7% of total waste. This is due to the fact that the efforts, technologies, and budgets to recycle plastic are high. Although plastic recycling in the country is so low, this can be an opportunity to work in this area because alternatives can be found to solve the problem of poor disposal of waste (*Empaques de Alimnetos y Sostenibilidad*, n.d.). It is necessary to consider that comparing Europe with Colombia is somewhat disproportionate because Europe has different needs, and social, political, and economic conditions than theirs. In addition, it is necessary to consider that population density is a factor that can be really significant in the recycling issue.

From a manufacturing perspective, the first steps have been moving also in Colombia. In pursuit of eliminating single-use plastic, many companies are focusing on producing products like straws, bags, and plates in alternative materials.

PROMOCIONES FANTASTICAS S.A.S. produce oxo-biodegradable straws, which the manufacturer claims they are biodegrade in 36 months when in contact with oxygen from the environment and sunlight, and PLA straws (*Promociones Fantasticas S.A.S.*, n.d.).

Natpacking is the first company to offer 100% organic packaging in Latin America and the product combines both innovation and sustainable development. *"We use renewable raw materials that allow us to generate a positive impact on the planet and provide an alternative option for homes and businesses in the region"* the company said (*Natpacking*, n.d.). Natpacking, a company led by a team of researchers headed by Jovany Perez, has developed a range of bags made from cassava, which they claim it takes just 180 days to biodegrade and are the ideal replacement for traditional plastic bags.

Papelyco by Lifepack offers an alternative, sustainable solution to using disposable plates made from non-biodegradable foams and plastics that wind up in landfills, streams and oceans after use, since these products are harmful to wildlife and the environment as they may never biodegrade (*Papelyco*, n.d.). These sustainable, disposable, biodegradable paper goods are manufactured from pineapple tops and maize husks, agricultural waste byproducts that minimize both pollution and carbon emissions from polymer plate usage. The product is not just recyclable; because it contains seeds, customers may plant the package after use. This implies that a plate will have a second life as a plant or flower, bringing more oxygen and, eventually, more life to the earth. If you do not want to plant it, you can simply throw it away with your usual waste, where it will biodegrade in the landfill in a couple of weeks.

In terms of food packaging, there's even now very little available since these materials are still being studied and the effects on food organoleptic properties in many cases is not yet known. An example in this sector is Alico (*Alico*, n.d.). They are working on barrier packaging commercialization for small and medium runs at a national level and are recognized as one of the best in Latin America. Their first experimental product with alternative material is called *Alicompost*: as the name suggests, it is a type of compostable food packaging. This packaging is manufactured with resins from renewable sources certified by the relevant international bodies TUV Austria, as suitable for home composting, which aims to be integrated into the soil 12 months after use. The websites warns that because this packaging comes from renewable sources, it may generate some characteristic colours and odours.

Along with this bag and other biodegradable material, place the organic waste generated in your home in a container. After you have filled the container with organic waste and biodegradable packaging, put it to the composter together with dry material such as sawdust, shavings, paper, or dry leaves. You can utilize composter containers designed for this operation. You can remove the compost placed at the bottom of the composter 30 days after loading the compost mix into the composter; but, if you leave it longer, you will have superior quality compost. Once the compost has been removed, it must be exposed to the outdoors for 30 days in a container with holes to allow air to enter the compost. After 30 days of maturity, you may use the compost in your garden or on your plants.

These innovative products address important environmental issues and show how Colombian entrepreneurs have creativity in their DNA: Latin America can be pioneer in new and world-changing solutions, environmentally friendly and economical effective, that can help reduce the use of plastics worldwide.

7. Future perspectives

While the aim of traditional food packaging was simply to protect the food it contained, the current trend is to develop active packaging capable of interacting with the packaged food or its environment to extend the shelf life and maintain the quality, safety, and sensory properties of the food (Cheikh et al., 2022).

In the previous chapters, we've seen the potential benefits of food packaging with biodegradable materials. It can be a way to reduce both the exploitation of fossil resources and the accumulation of plastic waste, thus preventing the environmental and health problems that result from this. But, in addition, this biodegradable packaging should also be able to preserve the quality of food and extend its shelf life in order to reduce food waste and prevent food-borne diseases. Oxidation is one of the major food degradations. It is responsible for structural alterations, producing off-flavors, discoloration and loss of nutritional quality and safety due to the formation of potentially toxic secondary compounds (lipid and protein oxidation), thus making foods unsuitable for consumption (di Giuseppe et al., 2022).

To overcome it, researchers have examined active food packaging systems and edible films with antimicrobial and antioxidant properties. Remarkable innovation in the sector of packaging materials has been boosted in recent years by advancements in the fields of nanotechnology and biotechnology.

7.1. Active packaging

Active packaging, an emerging technology compared with traditional "inert packaging", incorporates active components such as oxygen scavengers, antioxidants, and antimicrobial agents. They release or absorb substances into or from the packaged food or the environment surrounding the food (Yildirim et al., 2018). The study of active packaging has gone through three stages: (1) packaging with only in situ antioxidant or antibacterial activity, (2) active packaging with release behavior, (3) packaging with controlled release characteristics matching the food deterioration process. By regulating the release rate, active substances on the food surface can maintain the optimal concentration to inhibit microorganism growth or prevent food oxidation to ensure food quality and safety to the maximum extent (Kuai et al., 2021).

Presently, antioxidant packaging is being developed which is based on the addition of antioxidant in the packaging material to improve stability of oxidation-sensitive ingredients. For this purpose, the use of natural antioxidants has been widely studied, particularly plant essential oils (EO) (Asgher et al., 2020). Essential oils exhibit excellent antioxidant and antimicrobial properties. Although food applications of the EO have been successful, the loss of EO due to its volatile nature needs to be considered. Appropriate methods such as encapsulation and electrospinning may be helpful in preventing the loss of EO in the fabrication stage. Such encapsulations are necessary to ensure long term activities of the oil. To get the full benefit of these technologies, a thorough understanding of the EO, and their release mechanism and kinetics is needed. The use of EO is currently limited in the food industry due to their intense aroma and toxicity issues, when used beyond a specific limit. A well-maintained balance between the amount of EO loading and toxicity is important. Hence, more studies on the potential side effects of EO should be done before its widespread industrial applications. It is important to point out that the antibacterial mechanism of the EO is still not well understood (Varghese et al., 2020).

Since the utilization of essential oils as food preservatives is restricted due to stronger flavor, to overcome this problem, experimental packaging is made with bioactive agents to induce desired functionality. Examples are shown in *Figure 31*.

Figure 31: bioactive agents for smart food packaging applications (Vilela et al., 2018)

Several companies are already commercializing active packaging systems in the form of sachets and pads, or films and coatings with active functions such as antimicrobial and antioxidant agents, oxygen and ethylene scavengers, and carbon dioxide emitters. The active agents vary depending on the food characteristics with, for instance, antioxidant agents being quite relevant for lipid food products, and ethylene scavengers for fruits and vegetables. The major hurdle for active packaging is indubitably to design active materials capable of preserving their original mechanical and barrier properties, and simultaneously ensuring the activity of the active agents during the entire process of shipping, storage, and handling as food packaging materials. Further key obstacles include technology transfer, manufacturing process scale up, regulatory requirements for safety, environmental concerns, and consumer acceptance (Vilela et al., 2018).

7.2. Edible packaging

Edible packaging is regarded as a sustainable and biodegradable alternative in active food packaging field and provides food-quality optimization compared to the conventional packaging. Edible packaging materials are a subgroup of bio-based and biodegradable materials and have been extensively studied as an alternative to the traditional food packaging from the aspect of their film-formation properties. The materials of the food packaging are derived from edible ingredients such as natural polymers that can directly be consumed by humans without any potential health risk. These materials can be transformed into different forms of films and coatings without specific differences in their material composition but rather by changes in their thicknesses. Films are generally used in the production of wraps, pouches, bags, capsules, and casings, while coatings are applied directly in the food surface (Abdel Aziz et al., 2018).

Particularly, protein films are characterized by their non-toxicity, biodegradability and good barrier properties to oxygen, lipids, and flavorings: legume seeds are a cheap source of protein with high nutritional value, which makes them an interesting raw material for use in the manufacture of bio-based materials for the packaging sector due to their sustainability.

(Rojas-Lema et al., 2021) developed a faba bean protein film reinforced with cellulose nanocrystals as edible food packaging material, obtaining good mechanical, thermal and barrier properties, and low water susceptibility. In the same way, (Abdel Aziz et al., 2018) studied the preparation of edible films from alginate and castor oil. The study reported that thermal stability was improved after castor oil addition. Addition of castor oil to alginate also resulted in better mechanical properties when compared with neat alginate. The water vapor permeability was significantly reduced while the total color difference was not significantly changed after castor oil incorporation. The antibacterial study proved a significant inhibitory effect of the films towards Gram-positive bacteria while no effect was observed for Gram-negative bacteria. And these are just two of the many experimental studies found in literature on the matter.

7.3. Nanotechnology

Nanotechnology is a powerful interdisciplinary tool for the development of innovative products. It has been predicted that nanotechnology will impact at least $3 trillion across the global economy by 2020, creating a demand of 6 million employers in various industries. In 2008, the global nanotechnology-related food packaging was US$4.13 billion, which has been projected to at about 12% compound annual growth rate (Mihindukulasuriya & Lim, 2014).

Amongst the various existing nanotechnologies available, the one that has attracted more attention in the bioplastics field is the nanoclay-based nanocomposites. There are various types of nanoclays (montmorillonite, halloysite nanotubes, etc.) available, among which, halloysite nanotubes (HNT) are the most promising in the field of active food packaging due to its non-toxic, low cost and biocompatible nature (Boro & Moholkar, 2022). Nanoclays are categorized as generally recognized as safe (GRAS) material, while organomodified clay viz. octadecylamine and amino-propyltriethoxysilane exhibited toxicity. The U.S. FDA (Food and Drug Administration) and EFSA (European Food Safety Authority) have made guidelines regarding the migration of nanoparticles from packaging materials (He et al., 2014).

Because of their superior dispersion and strain-induced alignment within the polymer matrix, nanoclays are better reinforcing materials. With the addition of nanoclay fillers, the inherent hydrophilicity and brittleness of polysaccharide and protein-based films were successfully enhanced. For generating new biocomposites with required properties, nanoclays are the superior option. Nano-clay fillers used in the production of biocomposite films make them impermeable to water vapor and gases, which is an important need for food packaging materials. When interacting with biopolymers, homogeneous dispersion and strong interaction are desirable properties of filler materials. The addition of nanoclays at low concentrations, even less than 5%, to biocomposites can have dramatic impacts on their moisture barrier and mechanical characteristics (Dharini et al., 2022).

Nanoparticles are mostly useful for intelligent packaging applications. This new typology can indicate the quality of food by providing additional information about the food such as microbial contamination, gas leakage, freshness, etc. These indicators include sensors, freshness indicators, integrity indicators, temperature monitors, and radiofrequency identification tags (Sharma et al., 2022).

The shelf-life and keeping quality of food substances can be improved with smart solutions, such as time-temperature devices, CO2/O2 indicators and biosensors. *Figure 32* depicts the innovative solutions to the food packaging system. There is an essential need to upgrade the food packaging system to benefit the food products and consumers at the same time.

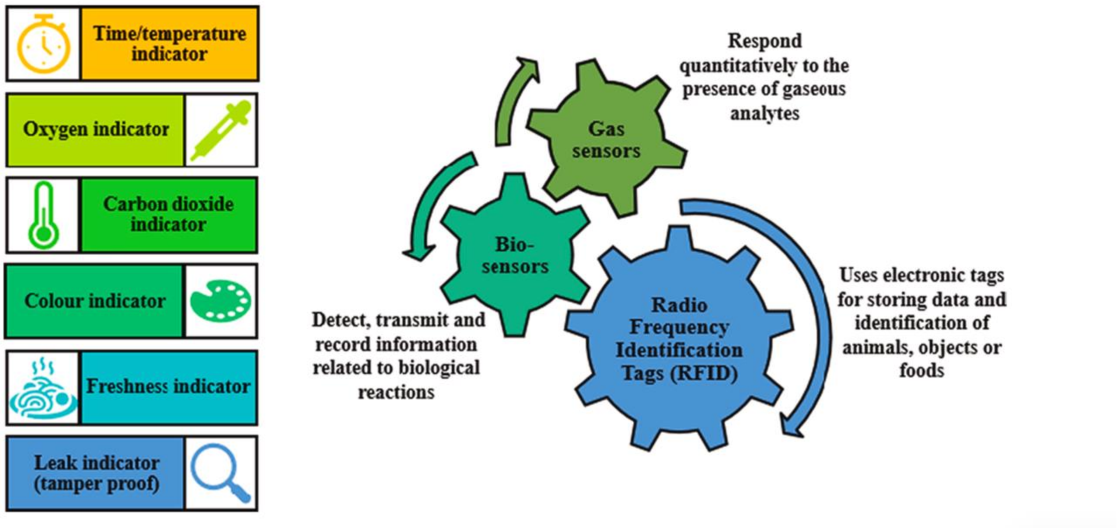

Figure 32: innovative Solutions to the Food Packaging System (Dharini et al., 2022)

Conclusion

Since the beginning of time, packaging is a necessary component of everyday life. If in prehistoric times men used natural materials to package food and beverages, the discovery of plastic was the opportunity to create synthetically what the nature offers. Plastic is lightweight, convenient, durable, with excellent mechanical and barrier properties, allows to keep the food safe through all the phases of the supply chain. In the past decades the production of plastics grew exponentially, with packaging being the first sector in which is utilized. And, often, discarded after one single use. Even with improvement in the recycling rate since 1950s, the plastic waste has become one of the most critical man-made problems: reports of presence of microplastics in the oceans, leakage in landfills, toxic fumes during incineration. All these issues discussed in this work incentive us to rethink food packaging and try to redesign these products with new materials, to tackle the problem from the font and try not to produce plastic waste in the first place.

Biodegradable materials can be a solution in this direction, and they've been a topic of interest both in academic research and for several brands not only in Europe but also in South America. They can be produced from natural sources, such as starch or cellulose, or chemically synthesized, like PLA, or derived by microorganism, for example bacterial cellulose. Production on large scale still requires a large initial investment for a company, in most cases the technology applied is experimental and not standardized. Trends in food industry show that consumer prefer more eco-friendly and natural products, but more research should be made to how much are willing to pay more for packaging made fully or partially from biobased plastic so to be able to determine a baseline for the price. Surveys also show that there's little or no knowledge from consumers about the difference in definitions among biodegradable, biobased, compostable and a campaign of education can be beneficial and can allow to make conscious choices when shopping. This campaign though shouldn't come from the companies itself, since it can bring allegations of greenwashing, due to this, together with a requirement of standardization in terms and parameters, there's also a need of certifications and a third-party agency that can guarantee the actual sustainability of a particular package. In parallel, the legislation is trying to keep up with this new trend of new materials: Europa and Colombia are allied for fighting climate challenge and they have introduced similar regulation to end the utilization of plastic of single use.

In this review, it was tried to also highlight the limitation of packaging made by biodegradable materials. Especially if compared with fossil-based plastic, their barrier and mechanical properties fall short. A great amount of research is done to overcome these defects: creating new blends from materials of different sources, plasticizers can be added, or antioxidant or antimicrobial agents. Progresses in nanotechnology and the outgrowing of conventional packaging in favour of active or intelligent packaging can help these materials to enter in large scale the market. These aspects are the most important to consider when studying the sustainability of these materials, because what we gain in GHG emissions and energy use reduction, can be lost in a decrease of shelf-life and food loss. If it's true that during the production, LCAs show advantageous biodegradable materials, we need to broaden the boundaries to include food waste. As well, more research is needed on the impacts to allocates land and resource to produce crops earmarked only to become polymers.

It's important to remember that every different material has different impact on the environment and it's impossible to generalize and make a comparison with traditional materials. Before replacing plastic as a material, we need to remember that packaging has also a crucial role in marketing: finding the right trade-off between sustainability and consumers' necessities is of the most importance before implementing any changes to the package design. For these reasons, designing new packaging with new materials must be done in parallel with improving of recycling techniques and educating the consumers, if we want to create a long-term impact on the environment and achieve the sustainability goals.

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References

A History of Packaging. (n.d.). Retrieved February 22, 2023, from https://ohioline.osu.edu/factsheet/cdfs-133

Abdel Aziz, M. S., Salama, H. E., & Sabaa, M. W. (2018). Biobased alginate/castor oil edible films for active food packaging. *LWT*, *96*, 455–460. https://doi.org/10.1016/j.lwt.2018.05.049

Acoplásticos, 2017. (n.d.). Retrieved May 13, 2023, from https://www.acoplasticos.org/index.php/mnu-noti/135-ns-170809

Addressing single-use plastic products pollution using a life cycle approach. (n.d.).

Ali, S. S., Al-Tohamy, R., Koutra, E., Kornaros, M., Khalil, M., Elsamahy, T., El-Shetehy, M., & Sun, J. (2021). Coupling azo dye degradation and biodiesel production by manganese-dependent peroxidase producing oleaginous yeasts isolated from wood-feeding termite gut symbionts. *Biotechnology for Biofuels*, *14*(1), 61. https://doi.org/10.1186/s13068-021-01906-0

Alico. (n.d.). Retrieved May 19, 2023, from https://alico-sa.com/

Álvarez-Chávez, C. R., Edwards, S., Moure-Eraso, R., & Geiser, K. (2012). Sustainability of bio-based plastics: General comparative analysis and recommendations for improvement. *Journal of Cleaner Production*, *23*(1), 47–56. https://doi.org/10.1016/j.jclepro.2011.10.003

Amin, U., Khan, M. K. I., Maan, A. A., Nazir, A., Riaz, S., Khan, M. U., Sultan, M., Munekata, P. E. S., & Lorenzo, J. M. (2022). Biodegradable active, intelligent, and smart packaging materials for food applications. *Food Packaging and Shelf Life*, *33*, 100903. https://doi.org/10.1016/j.fpsl.2022.100903

Amulya, K., Katakojwala, R., Ramakrishna, S., & Venkata Mohan, S. (2021). Low carbon biodegradable polymer matrices for sustainable future. *Composites Part C: Open Access*, *4*, 100111. https://doi.org/10.1016/j.jcomc.2021.100111

Andrady, A. L., & Neal, M. A. (2009). Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 1977–

1984. https://doi.org/10.1098/rstb.2008.0304

Asgher, M., Qamar, S. A., Bilal, M., & Iqbal, H. M. N. (2020). Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials. *Food Research International*, *137*, 109625. https://doi.org/10.1016/j.foodres.2020.109625

Aswell, E. C. (1942). The case of the ten nazi spies. *Harper's Magazine*, *185*. https://archive.org/details/harpersmagazine185junalde/mode/1up

Atta, O. M., Manan, S., Shahzad, A., Ul-Islam, M., Ullah, M. W., & Yang, G. (2022). Biobased materials for active food packaging: A review. *Food Hydrocolloids*, *125*, 107419. https://doi.org/10.1016/j.foodhyd.2021.107419

Australian Museum. (n.d.). Retrieved February 22, 2023, from https://australian.museum/learn/cultures/atsi-collection/cultural-objects/wallaby-skin-water-carrier-pre-1885/

Azeredo, H. M. C., Barud, H., Farinas, C. S., Vasconcellos, V. M., & Claro, A. M. (2019). Bacterial Cellulose as a Raw Material for Food and Food Packaging Applications. *Frontiers in Sustainable Food Systems*, *3*, 7. https://doi.org/10.3389/fsufs.2019.00007

Baranwal, J., Barse, B., Fais, A., Delogu, G. L., & Kumar, A. (2022). Biopolymer: A Sustainable Material for Food and Medical Applications. *Polymers*, *14*(5), 983. https://doi.org/10.3390/polym14050983

Basbasan, A. J., Hararak, B., Winotapun, C., Wanmolee, W., Leelaphiwat, P., Boonruang, K., Chinsirikul, W., & Chonhenchob, V. (2022). Emerging challenges on viability and commercialization of lignin in biobased polymers for food packaging: A review. *Food Packaging and Shelf Life*, *34*, 100969. https://doi.org/10.1016/j.fpsl.2022.100969

Bianco, D. (n.d.). *Biodegradable packaging and EDIBLE COATING for fresh-cut fruits and vegetables (2015) Italian Journal of Food Science, 27 (1), pp. 1-20. Cited 57 times.*

Bioplastics market data. (n.d.). Retrieved March 13, 2023, from https://www.european-bioplastics.org/market/

Bishop, G., Styles, D., & Lens, P. N. L. (2021). Environmental performance of bioplastic packaging on fresh food produce: A consequential life cycle assessment. *Journal of Cleaner Production*, *317*, 128377. https://doi.org/10.1016/j.jclepro.2021.128377

Bohórqu, M., & Ingenie, de I. (2021). *Application of modified vegetable oil for improvement of biodegradable materials based on thermoplastic starch and polylactic acid*. *20*(1).

Bordes, P., Pollet, E., & Averous, L. (2009). Nano-biocomposites: Biodegradable polyester/nanoclay systems. *Progress in Polymer Science*, *34*(2), 125–155. https://doi.org/10.1016/j.progpolymsci.2008.10.002

Boro, U., & Moholkar, V. S. (2022). Antimicrobial bionanocomposites of poly(lactic acid)/ZnO deposited halloysite nanotubes for potential food packaging applications. *Materials Today Communications*, *33*, 104787. https://doi.org/10.1016/j.mtcomm.2022.104787

Cazón, P., & Vázquez, M. (2021). Bacterial cellulose as a biodegradable food packaging material: A review. *Food Hydrocolloids*, *113*, 106530. https://doi.org/10.1016/j.foodhyd.2020.106530

Cheikh, D., Majdoub, H., & Darder, M. (2022). An overview of clay-polymer nanocomposites containing bioactive compounds for food packaging applications. *Applied Clay Science*, *216*, 106335. https://doi.org/10.1016/j.clay.2021.106335

Chiloeches, A., Cuervo-Rodríguez, R., López-Fabal, F., Fernández-García, M., Echeverría, C., & Muñoz-Bonilla, A. (2022). Antibacterial and compostable polymers derived from biobased itaconic acid as environmentally friendly additives for biopolymers. *Polymer Testing*, *109*, 107541. https://doi.org/10.1016/j.polymertesting.2022.107541

Christensen, M. S., Hansen, J., Ramlau-Hansen, C. H., Toft, G., & Kolstad, H. (2017). Cancer Incidence in Workers Exposed to Styrene in the Danish-reinforced Plastics Industry, 1968–2012: *Epidemiology*, *28*(2), 300–310. https://doi.org/10.1097/EDE.0000000000000608

Civancik-Uslu, D., Puig, R., Ferrer, L., & Fullana-i-Palmer, P. (2019). Influence of end-of-life allocation, credits and other methodological issues in LCA of compounds: An in-company circular economy case study on packaging. *Journal of Cleaner Production*, *212*, 925–940. https://doi.org/10.1016/j.jclepro.2018.12.076

Coles, R. (Ed.). (2003). *Food packaging technology*. Blackwell Publ. [u.a.].

D'Adamo, I., Falcone, P. M., Imbert, E., & Morone, P. (2020). A Socio-economic Indicator for EoL Strategies for Bio-based Products. *Ecological Economics*, *178*, 106794. https://doi.org/10.1016/j.ecolecon.2020.106794

Dedieu, I., Peyron, S., Gontard, N., & Aouf, C. (2022). The thermo-mechanical recyclability potential of biodegradable biopolyesters: Perspectives and limits for food packaging application. *Polymer Testing*, *111*, 107620. https://doi.org/10.1016/j.polymertesting.2022.107620

DeGruson, M. L. (2016). Biobased Polymer Packaging. In *Reference Module in Food Science* (p. B9780081005965033000). Elsevier. https://doi.org/10.1016/B978-0-08-100596-5.03373-4

Dharini, V., Periyar Selvam, S., Jayaramudu, J., & Sadiku Emmanuel, R. (2022). Functional properties of clay nanofillers used in the biopolymer-based composite films for active food packaging applications—Review. *Applied Clay Science*, *226*, 106555. https://doi.org/10.1016/j.clay.2022.106555

di Giuseppe, F., Coffigniez, F., Aouf, C., Guillard, V., & Torrieri, E. (2022). Activated gallic acid as radical and oxygen scavenger in biodegradable packaging film. *Food Packaging and Shelf Life*, *31*, 100811. https://doi.org/10.1016/j.fpsl.2022.100811

Ellen MacArthur Foundation. (n.d.-a). Retrieved March 13, 2023, from https://ellenmacarthurfoundation.org/plastics-vision

Ellen MacArthur Foundation. (n.d.-b). Retrieved March 13, 2023, from https://ellenmacarthurfoundation.org/upstream-innovation/overview

Empaques de Alimnetos y Sostenibilidad. (n.d.). Retrieved May 13, 2023, from https://bloqueneon.uniandes.edu.co/content/enforced/176248-UN_202310_IQYA_IMEC_001/Empaques%20de%20Alimentos%20y%20Sostenibilidad.pdf?_&d2lSessionVal=14QfcpxHskYRXUUxelHhkRK7

Environmental diplomacy EU-Colombia. (n.d.). Retrieved June 5, 2023, from https://environment.ec.europa.eu/news/environmental-diplomacy-eu-and-colombia-step-cooperation-nature-climate-and-sustainable-development-2022-02-14_en

Escobar, N., Haddad, S., Börner, J., & Britz, W. (2018). Land use mediated GHG emissions and spillovers from increased consumption of bioplastics. *Environmental Research Letters*, *13*(12), 125005. https://doi.org/10.1088/1748-9326/aaeafb

Eslami, H., Grady, M., & Mekonnen, T. H. (2022). Biobased and compostable trilayer thermoplastic films based on poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) and thermoplastic starch (TPS). *International Journal of Biological Macromolecules*, *220*, 385–394. https://doi.org/10.1016/j.ijbiomac.2022.08.079

EUR-Lex—32019L0904—EN - EUR-Lex. (n.d.).

European Bioplastics. (n.d.). Retrieved March 13, 2023, from https://www.european-bioplastics.org/

European Bioplastics—Environment. (n.d.). Retrieved April 29, 2023, from https://www.european-bioplastics.org/bioplastics/environment/

European Commission. Joint Research Centre. (2017). *Critical raw materials and the circular economy: Background report.* Publications Office. https://data.europa.eu/doi/10.2760/378123

European plastic pact. (n.d.). Retrieved March 12, 2023, from https://europeanplasticspact.org/

Firoozi Nejad, B., Smyth, B., Bolaji, I., Mehta, N., Billham, M., & Cunningham, E. (2021). Carbon and energy footprints of high-value food trays and lidding films made of common bio-based and conventional packaging materials. *Cleaner Environmental Systems*, *3*, 100058. https://doi.org/10.1016/j.cesys.2021.100058

Foroughi, F., Rezvani Ghomi, E., Morshedi Dehaghi, F., Borayek, R., & Ramakrishna, S. (2021). A Review on the Life Cycle Assessment of Cellulose: From Properties to the Potential of Making It a Low Carbon Material. *Materials*, *14*(4), 714. https://doi.org/10.3390/ma14040714

Fredi, G., & Dorigato, A. (2021). Recycling of bioplastic waste: A review. *Advanced Industrial and Engineering Polymer Research*, *4*(3), 159–177. https://doi.org/10.1016/j.aiepr.2021.06.006

Gerassimidou, S., Martin, O. V., Chapman, S. P., Hahladakis, J. N., & Iacovidou, E.

(2021). Development of an integrated sustainability matrix to depict challenges and trade-offs of introducing bio-based plastics in the food packaging value chain. *Journal of Cleaner Production*, *286*, 125378. https://doi.org/10.1016/j.jclepro.2020.125378

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, *3*(7), e1700782. https://doi.org/10.1126/sciadv.1700782

Global commitment 2022. (n.d.). Retrieved March 12, 2023, from https://ellenmacarthurfoundation.org/global-commitment-2022/overview

Guancha-Chalapud, M. A., Serna-Cock, L., & Tirado, D. F. (2022). Valorization of Pineapple Residues from the Colombian Agroindustry to Produce Cellulose Nanofibers. *Applied Sciences*, *12*(14), 6956. https://doi.org/10.3390/app12146956

Gupta, R. K., Guha, P., & Srivastav, P. P. (2022). Natural polymers in bio-degradable/edible film: A review on environmental concerns, cold plasma technology and nanotechnology application on food packaging- A recent trends. *Food Chemistry Advances*, *1*, 100135. https://doi.org/10.1016/j.focha.2022.100135

Guzmán Rincón, A., Carrillo Barbosa, R. L., Martín-Caro Álamo, E., & Rodríguez-Cánovas, B. (2021). Sustainable Consumption Behaviour in Colombia: An Exploratory Analysis. *Sustainability*, *13*(2), 802. https://doi.org/10.3390/su13020802

Hatti-Kaul, R., Nilsson, L. J., Zhang, B., Rehnberg, N., & Lundmark, S. (2020). Designing Biobased Recyclable Polymers for Plastics. *Trends in Biotechnology*, *38*(1), 50–67. https://doi.org/10.1016/j.tibtech.2019.04.011

He, X., Aker, W. G., Leszczynski, J., & Hwang, H.-M. (2014). Using a holistic approach to assess the impact of engineered nanomaterials inducing toxicity in aquatic systems. *Journal of Food and Drug Analysis*, *22*(1), 128–146. https://doi.org/10.1016/j.jfda.2014.01.011

Henning, F. G., Ito, V. C., Demiate, I. M., & Lacerda, L. G. (2022). Non-conventional starches for biodegradable films: A review focussing on characterisation and recent applications in food packaging. *Carbohydrate Polymer Technologies and Applications*, *4*, 100157. https://doi.org/10.1016/j.carpta.2021.100157

Herbes, C., Beuthner, C., & Ramme, I. (2018). Consumer attitudes towards biobased packaging – A cross-cultural comparative study. *Journal of Cleaner Production*, *194*, 203–218. https://doi.org/10.1016/j.jclepro.2018.05.106

History of Packaging. (n.d.-a). Retrieved February 22, 2023, from https://ambalaj.org.tr/en/environment-history-of-packaging

History of Packaging. (n.d.-b). Retrieved February 22, 2023, from https://crawfordpackaging.com/learn/history-of-packaging/

Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastics recycling: Challenges and opportunities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 2115–2126. https://doi.org/10.1098/rstb.2008.0311

Hottle, T. A., Bilec, M. M., & Landis, A. E. (2013). Sustainability assessments of bio-based polymers. *Polymer Degradation and Stability*, *98*(9), 1898–1907. https://doi.org/10.1016/j.polymdegradstab.2013.06.016

Hottle, T. A., Bilec, M. M., & Landis, A. E. (2017). Biopolymer production and end of life comparisons using life cycle assessment. *Resources, Conservation and Recycling*, *122*, 295–306. https://doi.org/10.1016/j.resconrec.2017.03.002

Huang, Y., Zhu, C., Yang, J., Nie, Y., Chen, C., & Sun, D. (2014). Recent advances in bacterial cellulose. *Cellulose*, *21*(1), 1–30. https://doi.org/10.1007/s10570-013-0088-z

Jackson-Davis, A., White, S., Kassama, L. S., Coleman, S., Shaw, A., Mendonca, A., Cooper, B., Thomas-Popo, E., Gordon, K., & London, L. (2023). A Review of Regulatory Standards and Advances in Essential Oils as Antimicrobials in Foods. *Journal of Food Protection*, *86*(2), 100025. https://doi.org/10.1016/j.jfp.2022.100025

Jayasekara, S., Dissanayake, L., & Jayakody, L. N. (2022). Opportunities in the microbial valorization of sugar industrial organic waste to biodegradable smart food packaging materials. *International Journal of Food Microbiology*, *377*, 109785. https://doi.org/10.1016/j.ijfoodmicro.2022.109785

Kakadellis, S., & Harris, Z. M. (2020). Don't scrap the waste: The need for broader system boundaries in bioplastic food packaging life-cycle assessment – A critical review. *Journal of Cleaner Production*, *274*, 122831. https://doi.org/10.1016/j.jclepro.2020.122831

Kakadellis, S., Woods, J., & Harris, Z. M. (2021). Friend or foe: Stakeholder attitudes towards biodegradable plastic packaging in food waste anaerobic digestion. *Resources, Conservation and Recycling*, *169*, 105529. https://doi.org/10.1016/j.resconrec.2021.105529

Kawaguchi, H., Hasunuma, T., Ogino, C., & Kondo, A. (2016). Bioprocessing of bio-based chemicals produced from lignocellulosic feedstocks. *Current Opinion in Biotechnology*, *42*, 30–39. https://doi.org/10.1016/j.copbio.2016.02.031

Klüppel, H.-J. (2005). The Revision of ISO Standards 14040-3 - ISO 14040: Environmental management Life cycle assessment Principles and framework - ISO 14044: Environmental management Life cycle assessment Requirements and guidelines. *The International Journal of Life Cycle Assessment*, *10*(3), 165–165. https://doi.org/10.1065/lca2005.03.001

KraftHeinz. (n.d.). Retrieved March 12, 2023, from https://www.businesswire.com/news/home/20180731005285/en/Kraft-Heinz-Expands-Environmental-Commitments-to-Include-Sustainable-Packaging-and-Carbon-Reduction

Kuai, L., Liu, F., Chiou, B.-S., Avena-Bustillos, R. J., McHugh, T. H., & Zhong, F. (2021). Controlled release of antioxidants from active food packaging: A review. *Food Hydrocolloids*, *120*, 106992. https://doi.org/10.1016/j.foodhyd.2021.106992

Kumar, S., Mukherjee, A., & Dutta, J. (2020). Chitosan based nanocomposite films and coatings: Emerging antimicrobial food packaging alternatives. *Trends in Food Science & Technology*, *97*, 196–209. https://doi.org/10.1016/j.tifs.2020.01.002

Lahtela, V., Silwal, S., & Kärki, T. (2020). Re-Processing of Multilayer Plastic Materials as a Part of the Recycling Process: The Features of Processed Multilayer Materials. *Polymers*, *12*(11), 2517. https://doi.org/10.3390/polym12112517

Lin, D., Liu, Z., Shen, R., Chen, S., & Yang, X. (2020). Bacterial cellulose in food industry: Current research and future prospects. *International Journal of Biological Macromolecules*, *158*, 1007–1019. https://doi.org/10.1016/j.ijbiomac.2020.04.230

Lucherelli, M. A., Duval, A., & Avérous, L. (2022). Biobased vitrimers: Towards sustainable and adaptable performing polymer materials. *Progress in Polymer Science*, *127*, 101515. https://doi.org/10.1016/j.progpolymsci.2022.101515

Marsh, K., & Bugusu, B. (2007). Food Packaging? Roles, Materials, and Environmental Issues. *Journal of Food Science*, *72*(3), R39–R55. https://doi.org/10.1111/j.1750-3841.2007.00301.x

McDonald's. (n.d.). Retrieved March 12, 2023, from https://corporate.mcdonalds.com/corpmcd/our-stories/article/renewable_packaging.html

Meier, M. A. R. (2019). Plant-Oil-Based Polyamides and Polyurethanes: Toward Sustainable Nitrogen-Containing Thermoplastic Materials. *Macromolecular Rapid Communications*, *40*(1), 1800524. https://doi.org/10.1002/marc.201800524

Mendes, A. C., & Pedersen, G. A. (2021). Perspectives on sustainable food packaging:– is bio-based plastics a solution? *Trends in Food Science & Technology*, *112*, 839–846. https://doi.org/10.1016/j.tifs.2021.03.049

Mihindukulasuriya, S. D. F., & Lim, L.-T. (2014). Nanotechnology development in food packaging: A review. *Trends in Food Science & Technology*, *40*(2), 149–167. https://doi.org/10.1016/j.tifs.2014.09.009

Moharir, R. V., & Kumar, S. (2019). Challenges associated with plastic waste disposal and allied microbial routes for its effective degradation: A comprehensive review. *Journal of Cleaner Production*, *208*, 65–76. https://doi.org/10.1016/j.jclepro.2018.10.059

Molina-Ramírez, C., Mazo, P., Zuluaga, R., Gañán, P., & Álvarez-Caballero, J. (2021). Characterization of Chitosan Extracted from Fish Scales of the Colombian Endemic Species Prochilodus magdalenae as a Novel Source for Antibacterial Starch-Based Films. *Polymers*, *13*(13), 2079. https://doi.org/10.3390/polym13132079

Moshood, T. D., Nawanir, G., Mahmud, F., Mohamad, F., Ahmad, M. H., & AbdulGhani, A. (2022). Sustainability of biodegradable plastics: New problem or solution to solve the global plastic pollution? *Current Research in Green and Sustainable Chemistry*, *5*, 100273. https://doi.org/10.1016/j.crgsc.2022.100273

Musioł, M., Sikorska, W., Janeczek, H., Wałach, W., Hercog, A., Johnston, B., & Rydz, J. (2018). (Bio)degradable polymeric materials for a sustainable future – part 1. Organic recycling of PLA/PBAT blends in the form of prototype packages with long shelf-life. *Waste Management*, *77*, 447–454. https://doi.org/10.1016/j.wasman.2018.04.030

Nadi, I., Belattmania, Z., Sabour, B., Reani, A., Sahibed-dine, A., Jama, C., & Bentiss, F. (2019). Sargassum muticum extract based on alginate biopolymer as a new efficient biological corrosion inhibitor for carbon steel in hydrochloric acid pickling environment: Gravimetric, electrochemical and surface studies. *International Journal of Biological Macromolecules*, *141*, 137–149. https://doi.org/10.1016/j.ijbiomac.2019.08.253

Natpacking. (n.d.). Retrieved May 19, 2023, from https://natpacking.com/

Okeke, E. S., Olagbaju, O. A., Okoye, C. O., Addey, C. I., Chukwudozie, K. I., Okoro, J. O., Deme, G. G., Ewusi-Mensah, D., Igun, E., Ejeromedoghene, O., Odii, E. C., Oderinde, O., Iloh, V. C., & Abesa, S. (2022). Microplastic burden in Africa: A review of occurrence, impacts, and sustainability potential of bioplastics. *Chemical Engineering Journal Advances*, *12*, 100402. https://doi.org/10.1016/j.ceja.2022.100402

Orqueda, M. E., Méndez, D. A., Martínez-Abad, A., Zampini, C., Torres, S., Isla, M. I., López-Rubio, A., & Fabra, M. J. (2022). Feasibility of active biobased films produced using red chilto wastes to improve the protection of fresh salmon fillets via a circular economy approach. *Food Hydrocolloids*, *133*, 107888. https://doi.org/10.1016/j.foodhyd.2022.107888

Otto, S., Strenger, M., Maier-Nöth, A., & Schmid, M. (2021). Food packaging and sustainability – Consumer perception vs. correlated scientific facts: A review. *Journal of Cleaner Production*, *298*, 126733. https://doi.org/10.1016/j.jclepro.2021.126733

Pandey, S., Dumont, M.-J., Orsat, V., & Rodrigue, D. (2021). Biobased 2,5-furandicarboxylic acid (FDCA) and its emerging copolyesters' properties for packaging applications. *European Polymer Journal*, *160*, 110778. https://doi.org/10.1016/j.eurpolymj.2021.110778

Papelyco. (n.d.). Retrieved May 19, 2023, from https://www.indiegogo.com/projects/papelyco-by-lifepack-plantable-plates#/

Patel, D. M., Bastioli, D. C., & Marini, D. L. (n.d.). *Environmental assessment of bio-based polymers and natural fibres*.

Pellis, A., Malinconico, M., Guarneri, A., & Gardossi, L. (2021). Renewable polymers and plastics: Performance beyond the green. *New Biotechnology*, *60*, 146–158. https://doi.org/10.1016/j.nbt.2020.10.003

PepsiCo: Agenda de sustentabilidad para 2025. (n.d.). Retrieved March 12, 2023, from https://www.pepsicoargentina.com/newsroom/press-release/pepsico-lanza-su-agenda-de-sustentabilidad-para-2025-dise%C3%B1ada-para-satisfacer-las-necesidades-cambiantes-de-los-consumidores-y-la-sociedad

Petersen, K., Væggemose Nielsen, P., Bertelsen, G., Lawther, M., Olsen, M. B., Nilsson, N. H., & Mortensen, G. (1999). Potential of biobased materials for food packaging. *Trends in Food Science & Technology*, *10*(2), 52–68. https://doi.org/10.1016/S0924-2244(99)00019-9

Piergiovanni, L., & Limbo, S. (2010). *Food packaging*. Springer Milan. https://doi.org/10.1007/978-88-470-1457-2

Pinto, L., Bonifacio, M. A., De Giglio, E., Santovito, E., Cometa, S., Bevilacqua, A., & Baruzzi, F. (2021). Biopolymer hybrid materials: Development, characterization, and food packaging applications. *Food Packaging and Shelf Life*, *28*, 100676. https://doi.org/10.1016/j.fpsl.2021.100676

Plan Nacional Para La Gestion Sostenible De Plasticos Un Solo Uso. (n.d.). Retrieved June 11, 2023, from https://www.minambiente.gov.co/wp-content/uploads/2022/02/plan-nacional-para-la-gestion-sostenible-de-plasticos-un-solo-uso-minambiente.pdf

Plastic Europe. (n.d.). Retrieved March 12, 2023, from https://plasticseurope.org/

Plastic Europe. (2022). *Plastics—The Facts*. 81.

Plastic waste and recycling in the EU: facts and figures. (n.d.). Retrieved March 12, 2023, from https://www.europarl.europa.eu/news/en/headlines/society/20181212STO21610/plastic-waste-and-recycling-in-the-eu-facts-and-figures

Promociones Fantasticas S.A.S. (n.d.). Retrieved May 19, 2023, from https://b2bmarketplace.procolombia.co/en/packaging/plastic-packaging/colored-biodegradable-straws-industrial-use-14370

Rani, S., & Kumar, R. (2019). A Review on Material and Antimicrobial Properties of Soy Protein Isolate Film. *Journal of Polymers and the Environment*, *27*(8), 1613–1628. https://doi.org/10.1007/s10924-019-01456-5

Reddy, M. M., Vivekanandhan, S., Misra, M., Bhatia, S. K., & Mohanty, A. K. (2013). Biobased plastics and bionanocomposites: Current status and future opportunities. *Progress in Polymer Science*, *38*(10–11), 1653–1689. https://doi.org/10.1016/j.progpolymsci.2013.05.006

Reinders, M. J., Onwezen, M. C., & Meeusen, M. J. G. (2017). Can bio-based attributes upgrade a brand? How partial and full use of bio-based materials affects the purchase intention of brands. *Journal of Cleaner Production*, *162*, 1169–1179. https://doi.org/10.1016/j.jclepro.2017.06.126

Robertson, G. L. (2013). *Food Packaging—Principles and Practice* (3rd ed.).

Rojas-Lema, S., Nilsson, K., Trifol, J., Langton, M., Gomez-Caturla, J., Balart, R., Garcia-Garcia, D., & Moriana, R. (2021). "Faba bean protein films reinforced with cellulose nanocrystals as edible food packaging material." *Food Hydrocolloids*, *121*, 107019. https://doi.org/10.1016/j.foodhyd.2021.107019

Science History Institute. (n.d.). *History and future of plastics*. https://www.sciencehistory.org/the-history-and-future-of-plastics

Shaikh, S., Yaqoob, M., & Aggarwal, P. (2021). An overview of biodegradable packaging in food industry. *Current Research in Food Science*, *4*, 503–520. https://doi.org/10.1016/j.crfs.2021.07.005

Sharma, V. K., Sharma, M., Usmani, Z., Pandey, A., Singh, B. N., Tabatabaei, M., & Gupta, V. K. (2022). Tailored enzymes as next-generation food-packaging tools. *Trends in Biotechnology*, *40*(8), 1004–1017. https://doi.org/10.1016/j.tibtech.2022.01.009

Shlush, E., & Davidovich-Pinhas, M. (2022). Bioplastics for food packaging. *Trends in Food Science & Technology*, *125*, 66–80. https://doi.org/10.1016/j.tifs.2022.04.026
Sid, S., Mor, R. S., Kishore, A., & Sharanagat, V. S. (2021). Bio-sourced polymers as alternatives to conventional food packaging materials: A review. *Trends in Food Science & Technology*, *115*, 87–104. https://doi.org/10.1016/j.tifs.2021.06.026

Singh, A. A., Sharma, S., Srivastava, M., & Majumdar, A. (2020). Modulating the properties of polylactic acid for packaging applications using biobased plasticizers and naturally obtained fillers. *International Journal of Biological Macromolecules*, *153*, 1165–1175. https://doi.org/10.1016/j.ijbiomac.2019.10.246

Smith, M., Love, D. C., Rochman, C. M., & Neff, R. A. (2018). Microplastics in Seafood and the Implications for Human Health. *Current Environmental Health Reports*, *5*(3), 375–386. https://doi.org/10.1007/s40572-018-0206-z

Soares, C. T. de M., Ek, M., Östmark, E., Gällstedt, M., & Karlsson, S. (2022). Recycling of multi-material multilayer plastic packaging: Current trends and future scenarios. *Resources, Conservation and Recycling*, *176*, 105905. https://doi.org/10.1016/j.resconrec.2021.105905

Sousa, A. F., & Silvestre, A. J. D. (2022). Plastics from renewable sources as green and sustainable alternatives. *Current Opinion in Green and Sustainable Chemistry*, *33*, 100557. https://doi.org/10.1016/j.cogsc.2021.100557

Storz, H., & Vorlop, K.-D. (2013). Bio-based plastics: Status, challenges and trends. *Landbauforschung - Applied Agricultural and Forestry Research*, *63*, 321–332. https://doi.org/10.3220/LBF_2013_321-332

Sugiarto, S., Pong, R. R., Tan, Y. C., Leow, Y., Sathasivam, T., Zhu, Q., Loh, X. J., & Kai, D. (2022). Advances in sustainable polymeric materials from lignocellulosic biomass. *Materials Today Chemistry*, *26*, 101022. https://doi.org/10.1016/j.mtchem.2022.101022

Tassinari, G., Bassani, A., Spigno, G., Soregaroli, C., & Drabik, D. (2023). Do biodegradable food packaging films from agro-food waste pay off? A cost-benefit analysis in the context of Europe. *Science of The Total Environment*, *856*, 159101. https://doi.org/10.1016/j.scitotenv.2022.159101

Teixeira-Costa, B. E., & Andrade, C. T. (2021). Natural Polymers Used in Edible Food Packaging—History, Function and Application Trends as a Sustainable Alternative to Synthetic Plastic. *Polysaccharides*, *3*(1), 32–58. https://doi.org/10.3390/polysaccharides3010002

Testa, F., Di Iorio, V., Cerri, J., & Pretner, G. (2021). Five shades of plastic in food: Which potentially circular packaging solutions are Italian consumers more sensitive to. *Resources, Conservation and Recycling*, *173*, 105726. https://doi.org/10.1016/j.resconrec.2021.105726

The History Of Packaging: From Ancient Times To The Future. (n.d.). Retrieved February 22, 2023, from https://packagingguruji.com/the-history-of-packaging/

The Paris Agreement. (n.d.). Retrieved March 13, 2023, from https://unfccc.int/process-and-meetings/the-paris-agreement

Thompson, R. C., Moore, C. J., vom Saal, F. S., & Swan, S. H. (2009). Plastics, the environment and human health: Current consensus and future trends. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 2153–2166. https://doi.org/10.1098/rstb.2009.0053

Tripathi, N., Misra, M., & Mohanty, A. K. (2021). Durable Polylactic Acid (PLA)-Based Sustainable Engineered Blends and Biocomposites: Recent Developments, Challenges, and Opportunities. *ACS Engineering Au*, *1*(1), 7–38. https://doi.org/10.1021/acsengineeringau.1c00011

Umaraw, P., & Verma, A. K. (2017). Comprehensive review on application of edible film on meat and meat products: An eco-friendly approach. *Critical Reviews in Food Science and Nutrition*, *57*(6), 1270–1279. https://doi.org/10.1080/10408398.2014.986563

V, A. K., Hasan, M., Mangaraj, S., M, P., Verma, D. K., & Srivastav, P. P. (2022). Trends in Edible Packaging Films and its Prospective Future in Food: A Review. *Applied Food Research*, *2*(1), 100118. https://doi.org/10.1016/j.afres.2022.100118

Varghese, S. A., Siengchin, S., & Parameswaranpillai, J. (2020). Essential oils as antimicrobial agents in biopolymer-based food packaging—A comprehensive review. *Food Bioscience*, *38*, 100785. https://doi.org/10.1016/j.fbio.2020.100785

Venkateshaiah, A., Havlíček, K., Timmins, R. L., Röhrl, M., Wacławek, S., Nguyen, N. H. A., Černík, M., Padil, V. V. T., & Agarwal, S. (2021). Alkenyl succinic anhydride modified tree-gum kondagogu: A bio-based material with potential for food packaging. *Carbohydrate Polymers*, *266*, 118126. https://doi.org/10.1016/j.carbpol.2021.118126

Vilela, C., Kurek, M., Hayouka, Z., Röcker, B., Yildirim, S., Antunes, M. D. C., Nilsen-Nygaard, J., Pettersen, M. K., & Freire, C. S. R. (2018). A concise guide to active agents for active food packaging. *Trends in Food Science & Technology*, *80*, 212–222. https://doi.org/10.1016/j.tifs.2018.08.006

Wang, H., Qian, J., & Ding, F. (2018). Emerging Chitosan-Based Films for Food Packaging Applications. *Journal of Agricultural and Food Chemistry*, *66*(2), 395–413. https://doi.org/10.1021/acs.jafc.7b04528

Wang, J., Euring, M., Ostendorf, K., & Zhang, K. (2022). Biobased materials for food packaging. *Journal of Bioresources and Bioproducts*, *7*(1), 1–13. https://doi.org/10.1016/j.jobab.2021.11.004

Waste Framework Directive. (n.d.). Retrieved March 12, 2023, from https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

Wu, F., Misra, M., & Mohanty, A. K. (2021). Challenges and new opportunities on barrier performance of biodegradable polymers for sustainable packaging. *Progress in Polymer Science*, *117*, 101395. https://doi.org/10.1016/j.progpolymsci.2021.101395

Yildirim, S., Röcker, B., Pettersen, M. K., Nilsen-Nygaard, J., Ayhan, Z., Rutkaite, R., Radusin, T., Suminska, P., Marcos, B., & Coma, V. (2018). Active Packaging Applications for Food: Active packaging applications for food…. *Comprehensive Reviews in Food Science and Food Safety*, *17*(1), 165–199. https://doi.org/10.1111/1541-4337.12322

Yuvaraj, D., Iyyappan, J., Gnanasekaran, R., Ishwarya, G., Harshini, R. P., Dhithya, V., Chandran, M., Kanishka, V., & Gomathi, K. (2021). Advances in bio food packaging – An overview. *Heliyon*, *7*(9), e07998. https://doi.org/10.1016/j.heliyon.2021.e07998

Zubair, M., Pradhan, R. A., Arshad, M., & Ullah, A. (2021). Recent Advances in Lipid Derived Bio-Based Materials for Food Packaging Applications. *Macromolecular Materials and Engineering*, *306*(7), 2000799. https://doi.org/10.1002/mame.202000799

Zubkiewicz, A., Szymczyk, A., Sablong, R. J., Soccio, M., Guidotti, G., Siracusa, V., & Lotti, N. (2022). Bio-based aliphatic/aromatic poly(trimethylene furanoate/sebacate) random copolymers: Correlation between mechanical, gas barrier performances and compostability and copolymer composition. *Polymer Degradation and Stability*, *195*, 109800. https://doi.org/10.1016/j.polymdegradstab.2021.109800

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