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Comprehensive overview of sustainable food packaging material alternatives

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Abstract

The proliferation of plastic packaging materials and their accumulation as significant amounts of waste raises serious ecological concerns affecting humanity and the natural environment. New alternative packaging materials, including biodegradable and sustainable options, are being explored to address these concerns. This paper aims to provide a comprehensive overview of the literature on alternative packaging materials. This study covers biodegradable plastics, sustainable alternatives (Cellulose, Bamboo) and emerging packaging forms (edible packaging, nano-cellulose). SWOT analysis and cross-tabulation have been used to facilitate a comparative assessment of alternatives with plastic. The results show that recycling plastics or the production of bioplastics has not proven to be an effective solution. The environmental impact of sustainable and biodegradable packaging remains unclear. In addition, new materials (edible packaging materials, nano-cellulose fibres) are currently being tested that could reduce environmental impacts and waste. No alternative can fully replace plastic packaging, but new initiatives are promising.

Keywords
Alternative packaging, food packaging, plastic packaging, Cellulose, sustainable

1. Introduction

The most common packaging material today is plastic, which has become an indispensable part of our daily lives. Plastics are used in almost every sector and industry, yet the packaging industry accounts for the largest percentage of all plastics used (Shafqat et al., 2020). As most of this packaging is single-use plastic, it often ends up in landfills in large quantities. Single-use plastic packaging accounts for almost half of the world's plastic waste, and the packaging industry generates around 30% of municipal solid waste (Kumar et al., 2016). The resistance of such wastes to biodegradation has created critical ecological crises. We cannot forget that plastic packaging can play a crucial role, and there is general agreement that many types of food need some form of packaging to protect them from environmental harm, extend shelf life and reduce food waste (Firoozi Nejad et al., 2021).

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Packaging has been one of the economy's fastest-growing sectors for over a decade (Majeed et al., 2013). The most common factors that drive companies to develop new packaging are:

- the desire to refresh the product at the maturity stage of its market life cycle;
- growing environmental awareness and related external pressure to change packaging.

On the other hand, changes in product positioning, such as:

- improving packaging when the product is targeted at a different market segment;
- measures taken to respond to competition or to discriminate against competitors;
- strategic changes to the way the product is displayed on store shelves;
- scaling up production to enter new markets;
- to achieve greater consistency of the product with other products in the company;
- introducing quality changes in the product;
- introducing technical (technological) improvements to the packaging of the product (Wyrwa and Barska, 2017).

At the end of the 20th century, the concept of environmental packaging design was born. This is a way of thinking where packaging is seen as a necessary element between the product and the environment, helping to prevent their interaction. So, it protects the product from environmental stresses and, at the same time, protects the environment from the harmful effects of the product. However, this positive effect only exists when the product is in the packaging—the production of packaging material and the fact that it becomes waste after use is already environmentally damaging. Environmental packaging design aims to ensure that the packaging material performs its function with the least possible environmental impact throughout its life cycle (Tiefbrunner, 2002). The environmental regulation of packaging sets out as a general requirement for reducing environmental impacts ('reduce, reuse, recycle'). Recyclable packaging includes glass (all colours), paper, aluminium foil, takeaway containers, aluminium cans, tin and steel cans, PET, and HDPE (Marshall, 2007).

This study aims to explore the current trends in plastic packaging alternatives. The systematic literature review (the result in the appendix, Table 3) highlighted alternatives already known as food packaging materials and new options that may emerge. In the following, the alternatives presented in the literature and the new options are described in detail. In the conclusion, a SWOT analysis will be used to compare the alternatives with plastic to facilitate comparison. A cross-tabulation analysis will show how these materials have been investigated so far.

2. Alternative plastic packaging

Polyethylene terephthalate (PET) is one of the most commonly used plastics, and it is widely used as a raw material in manufacturing products such as blown bottles for soft drinks and containers for food and other consumer goods. PET bottles have replaced glass bottles as containers for storing beverages due to their light weight and ease of handling and storage. In 2007, PET beverages' annual global consumption was around 10 million tons, representing approximately 250 million bottles. This number is increasing by around 15% per year, while the percentage of recycled or taken-back bottles is very low (Frigione, 2010). Two decades ago, most (around 70%) of the packaging waste generated in the European Union (EU) was landfilled. By 2019, this has changed completely, with nearly two-thirds of packaging waste recycled. In 1998, the share of recovered material in recovered plastic packaging waste was 11% on average. Twenty years later, recycled plastic packaging material has almost quadrupled (43%) (OECD, 2022). Despite the significant progress, the road to a near-zero carbon economy is still long and winding. In recent years, the environmental impact of packaging waste, particularly plastic packaging (white pollution), has been a major concern for legislators, the media and the public (Barletta et al., 2019). Increased environmental concerns about using certain synthetic packaging and coatings and consumer demands for better quality and longer shelf-life have increased interest in research into alternative packaging materials.

2.1. Biodegradable PET and Reusable PET

Recycling waste PET polymer and producing biodegradable PET-based blends effectively reduces resource use while protecting the environment (Torres-Huerta et al., 2014). One solution to reduce packaging waste in the environment is to make the packaging biodegradable. Some plastics are biodegradable under certain conditions. Compostable plastics decompose in industrial compost, where temperature, humidity and other environmental factors promote decomposition. However, many compostable plastics do not biodegrade in nature, the marine environment, or backyard compost bins. Under the right conditions, even products made from these plastics will degrade when mixed with organic materials in an industrial

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composting facility. Some substances, such as polyhydroxyalkanoate (PHA), degrade in the sea. However, their material properties, including strength, barrier (water vapour, oxygen), and temperature resistance, are unsuitable to replace conventional plastics in consumer goods packaging when protection, shelf life and food safety are considered (Clark, 2018). In their work, Vea et al. (2021) investigated the whole life cycle of PHA and reported that the biodegradation kinetics of PHA-based plastics in the environment are very uncertain. They highlight that it is not known how surface treatment may affect biodegradation kinetics under landfill conditions. The biodegradable polymer chitosan is a biopolymer that can form semi-permeable films. In recent years, efforts have been made to develop and use chitosan films in food packaging (Torres-Huerta et al., 2014). In their research, Taufik et al. (2020) investigated whether the environmental benefits consumers perceive through recyclable and compostable bio-based plastic packaging align with how these packages are disposed of. It has been found that only compostable bio-based packaging is perceived by consumers as offering more environmental benefits than fossil-based plastic packaging, but is still being mishandled. Overall, their results suggest that compostability can be a distinguishing feature and that bio-based plastic packaging materials can be differentiated from their fossil-based counterparts (Taufik et al., 2020).

Bio-based and fossil-based refer to the manufacturing process of food packaging. Recyclability, biodegradability, and compostability refer to end-of-life options. Biodegradable plastics are completely biodegradable packaging (i.e., by living microorganisms) within 180 days. Compostable packaging is a subset of biodegradable plastics that decompose into water, biomass and gases in less than three months under composting conditions (ideally industrial conditions). Thus, a compostable product is always biodegradable, while a biodegradable product is not necessarily compostable. Many biodegradable plastics require industrial composting facilities, and if compostable/biodegradable packaging is improperly disposed of (e.g. landfill), it can lead to significant greenhouse gas emissions (Koeing-Lewis et al., 2022).

2.2. Bioplastic

Most bioplastics are first-generation materials from carbohydrate-rich crops (maise, sugar cane, Ricinus, potatoes, wheat) that could be modified for food or animal feed. Second-generation bioplastics are produced from feedstocks that are not suitable for food or feed, i.e. non-food crops ('wood cellulose', short rotation crops: poplar, willow, miscanthus) and waste materials from the processing of first biomass (food waste, wood sawdust) (Brizga et al., 2020). By definition, a bioplastic is a plastic that is bio-based and/or biodegradable. It is distinguished from biodegradable plastics, which are completely degradable through biological activity (i.e. the action of microorganisms such as bacteria, archaea, fungi and algae). Under aerobic conditions, the final products are biomass, CO_2 and water; under anaerobic conditions, the final products are biomass, CO_2, methane and water. Bio-based plastics are derived whole or in part from biomass. We can talk about oxo-degradable plastics, i.e. plastics that contain additives that accelerate their degradation under heat or UV radiation, typically in the presence of oxygen. The potential for biodegradation of such plastics to CO_2 and water is uncertain and subject to considerable debate, and residual microplastics will likely remain in the environment for longer periods. There is also degradable plastic, which is often synonymous with oxo-degradable plastic, but the term does not have a specific meaning, and there is no guiding standard. It refers to the fact that the plastic is degradable but does not give any information about the end products or how it degrades (Dilkes-Hoffman et al., 2019). Bioplastic has three subcategories and can be (1) "fossil-based and biodegradable", (2) "bio-based and biodegradable", or (3) "bio-based and non-biodegradable". The latter two categories can also be combined with the term bio-based plastics (Vea et al., 2021). The biodegradable properties of some bioplastics offer an opportunity to address this social and environmental challenge. They provide a solution for packaging uses by diverting plastics from landfills without accumulating in the environment, especially in the sea. However, such biodegradable and bio-based alternatives do not necessarily improve the overall environmental impact, especially when considering functional aspects of packaging such as end-of-life management, handling for transport and retail, and waste reduction, including increasing shelf-life (Kakadellis and Harris, 2020). According to Chen et al. (2016), biofuels and bioplastics are often seen as sustainable solutions to environmental problems such as climate change, fossil fuel depletion and acidification. However, both are criticised for being economically costly, competing with other socially useful goods such as food, and offering limited environmental benefits compared to their fossil counterparts. Their research shows PET bottles made from wood and biomass have 21% less global climate change potential and require 22% less fossil fuel than their fossil-based counterparts. In contrast, they perform worse in other categories, such as ecotoxicity and ozone depletion.

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Depending on the biomass feedstock, extraction and preprocessing are likely to be more emissions-intensive than the corresponding fossil refinery processes, as preprocessing involves significant emissions from the use of fertilisers and the significant chemical and energy inputs required to break down the retreating biomass (Chen et al., 2016).

The third generation refers to microorganisms' direct production of plastic (or monomers). However, these bioplastics are still in the development stage. Bioplastics are not only an economic challenge. The production of these polymers also poses a significant threat to the environment, especially if their production volume is increased. Biomaterials can replace petroleum-based materials directly through the substitution of petroleum-derived chemical feedstocks with feedstocks from biorefineries and indirectly through the increased use of bio-based materials to replace petroleum-based materials, such as natural fibres for packaging and insulation materials as substitutes for synthetic foams, which have been widely used so far. Regarding material properties for packaging, almost complete replacement of petrochemical plastics by bioplastics (not all biodegradable) is technically feasible. To reduce the environmental impact of bioplastics, technological improvements need, such as

- improving yields and reducing the use of agrochemicals in the production of raw materials,
- a shift to second and third-generation feedstocks,
- improving energy efficiency and the use of renewable energy in biorefineries,
- the higher conversion efficiency of biorefineries and
- further improving end-of-life management (Brizga et al., 2020).

Vural Gursel et al. (2021) present a life-cycle assessment of bio-based polyethene terephthalate (PET) bottles from cradle to grave and compare them with petrochemical PET bottles in 13 environmental impact categories. In addition to bio-based PET bottles made from Brazilian sugar cane, two alternative hypothetical bio-based product systems were considered: a European crop market mix of wheat straw and maise and a European crop market mix of wheat and sugar beet. They found that bio-based PET bottles performed worse overall than conventional petrochemical PET bottles and only performed better (around 10%) in abiotic depletion (fossil fuels). Similar performance was observed for climate change. Using European crops to produce ethanol instead of Brazilian sugar cane resulted in poorer environmental performance, as they produced lower yields than Brazilian sugar cane. When wheat straw was considered as the biomass feedstock for ethanol production, similar environmental performance to petrochemical PET bottles was observed (Vural Gursel et al., 2021). In their work, Brizga et al. (2020) report that biobased materials save on average 55 ± 34 GJ/t and 127 ± 79 GJ/ha of non-renewable energy and 3 ± 1 tCO_2e/t and 8 ± 5 tCO_2e/ha of greenhouse gas emissions compared to conventional materials. Globally, bioplastics could save 241–316 $MtCO_2e$ per year by replacing 65.8% of all conventional plastics. However, the results of the Global Warming Potential (GWP) assessment of bioplastics can be significantly affected by the chosen accounting method for biogenic carbon. They highlight that other important determinants of the climate impact of plastics are premature material degradation over their lifetime, the extent to which materials are recycled, and the proportion of fossil or biogenic carbon in the product. Kakadellis and Harris (2020), in a comprehensive summary of life cycle assessment studies of bioplastics, report that bioplastics and plastics have similar GWP impacts, with values ranging from 0.70 to 11.02 $kgCO_2$-eq/kg polymer.

The production of biodegradable packaging materials, in whole or in part, using biopolymers is not exclusive, but it is a possible process to replace plastics in food packaging partially. Because of their properties, which differ from those of plastics, their field of application is still limited. Their use reduces packaging waste by allowing such materials to be recycled into the natural cycle under appropriate conditions (composting). A precondition for this is establishing selective waste collection and creating appropriate composting sites (Beczner et al., 1997). Naturally, renewable biopolymers can be used as barrier coatings on paper packaging materials. These biopolymer coatings can retard unwanted moisture transfer in food, are good oxygen and oil barriers, are biodegradable and could potentially replace current synthetic paper and board coatings (Khwaldia et al., 2010).

2.2.1. Polylactic acid (PLA) packaging

Polylactide (PLA), a biodegradable aliphatic polyester, has been widely studied for all its applications, from food packaging to car interiors. One of the advantages of PLA is that the raw material, lactic acid, can come from renewable sources, making PLA very attractive for packaging and considered green packaging. Although the cost of PLA is relatively higher compared to petroleum-based packaging materials, it is predicted that the price will fall following the commercial

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success of the process (Ahmed and Varshney, 2011). PLA is a thermoplastic polymer dehydrated and polymerised from fermented products of corn starch. It is widely used in packaging but is expensive and has strict degradation requirements (Chen et al., 2022). Recently, the price per kilogram of bioplastics has fallen significantly. For example, the price of PLA, which was $6,000/ton in the 1990s, fell to $1984.14/ton by 2010.

Furthermore, the rise in oil price has brought the price of bio-based plastics in line with the price of oil-based thermoplastics. In terms of energy, producing biopolymer-based plastics requires less energy than their conventional counterparts. For example, 1 kg of PLA requires only 27.2 MJ of fossil fuel-based energy. In contrast, polypropylene and high-density polyethene require 85.9 and 73.7 MJ/kg, respectively. Thus, it can be concluded that biofuels successfully address concerns about cost, energy consumption, sustainability, and recycling processes compared to their synthetic counterparts (Abdul Khalil et al., 2016). Annual production of PLA is estimated at 140,000 tons, and PLA and its composites are expected to have the potential to replace petroleum-based products.

PLA has desirable properties such as good transparency and processability, glossy appearance, and rigidity. PLA shows better thermal processability than other biopolymers; therefore, different processing techniques, such as cast film, blown film, fibre spinning, and injection moulding, can produce PLA films. There are numerous examples of PLA-coated/laminated paper being used commercially for food products, such as stand-up pouches for dry fruit, trays moulded from Cellulose, and paper cups for cold liquids (Tyagi et al., 2021; Holler et al., 2023). This is also confirmed in a study by Raghuvanshi et al. (2023). They found that PLA-based nanocomposites are 100% compostable and environmentally friendly, with very low impact on the environment and human health. PLA-based nanocomposites also extend the shelf-life of packaged fruit and prove to be much more efficient than PET-based composites. Therefore, it is concluded that polylactic acid could be an excellent alternative to petrochemical-based packaging materials for use as a filler and is recommended as a safe and environmentally friendly solution. Moreover, Ingrao et al. (2015) showed that PLA has a marginally better environmental performance than plastic. Their GWP results are 4.826 $kgCO_2eq$ for PLA compared to 5.11 $kgCO_2eq$ for plastic. However, the CO_2 emissions from granulate production are slightly higher for PLA (2.65 $kgCO_2eq$) than for plastic (2.59 $kgCO_2eq$). Two main reasons have been highlighted: the cultivation of feedstock (maise) and transport. Firoozi Nejad et al. (2021) showed that PLA has a 49% lower carbon footprint than PET or polyethene.

3. Sustainable packaging – natural materials

Several organisations have tried to create 'sustainable packaging' sets, such as the Sustainable Packaging Alliance (SPA) in Australia and the Sustainable Packaging Coalition (SPC) in the US. Some companies have tried to reduce the "waste footprint" of packaging (Lewis et al., 2007), as packaging accounts for 20–40% of the product's waste footprint (Ingrao et al., 2015). In one case, a carbon tax was introduced to reduce the waste footprint of food packaging. Carbon emissions from food shopping are estimated to account for around 30% of total household greenhouse gas emissions in developed economies, with supermarkets accounting for a large share of food spending. As a result, there is a growing recognition that effective sustainability policy requires direct consumer involvement and that divergent consumer choices within stores can lead to significant reductions in the carbon footprint of food packaging (Panzone et al., 2021). Four principles of sustainable packaging have been formulated: the packaging system provides real value (efficient); the packaging system is designed to be used; the packaging materials are continuously cyclical, and material degradation is minimised; the packaging elements used in the system, including materials, coatings, inks, pigments and other additives, do not pose a risk to people or ecosystems (clean) (Lewis et al., 2007). The amount of packaging required for a product can be reduced by making the product lighter. This requires companies to measure the ratio between the amount of packaging material used and the product delivered. The reduction in the amount of materials used in packaging elements results from design or material innovation. For example, in 2006, Unilever introduced a three times more concentrated detergent than conventional detergents (Dharmadhikari, 2012).

3.1. Cellulose packaging

Cellulose fibres have been known as traditional food packaging materials for centuries, but high-performance plastic-based solutions have gradually replaced them. Typically, cheaper and lightweight plastics have enabled the development of new packaging types and packaging conversion processes, contributing to the efficient preservation and distribution of fresh and processed foods, thereby reducing food wastage. Commercial plastic packaging materials, such as polypropylene (PP), polyethene (PE) or polyethene terephthalate (PET), can be easily converted and effectively recycled in their pure form.

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Combined in multilayer structures, they can have very high barrier properties, but they are much more difficult to handle in recycling processes. Without effective management systems, plastic packaging often increases the amount of waste. Plastic materials do not degrade easily in nature because they were originally designed to last. In countries where sustainable waste management systems are not widely available, waste accumulates in landfills, rivers and oceans, becoming a major environmental concern (Schenker et al., 2021). In response to concerns about the sustainability of plastic packaging and the impact of plastic pollution on our environment, large companies have started to replace plastic packaging with fibre-based solutions. Most cellulose fibre materials have favourable end-of-life properties, given that they are generally recyclable with well-established recycling infrastructure in most countries. Consumers understand the importance of recycling and apply it by sorting and recycling these materials (e.g. 85% of packaging paper and cardboard is recycled in Europe). In addition, some cellulose fibre materials have long been known to biodegrade in soil (Béguin and Aubert, 1994) and marine environments (Hofsten and Edberg, 1972). Cellulose fibre materials are widely available from certified sources and can be accessed responsibly without deforestation or ecosystem degradation. Finally, for the above reasons, many cellulose fibre materials are positively valued by consumers, which enables sustainability communication and makes these materials valuable to stakeholders in the supply chain, such as brand owners, retailers or consumers. However, cellulosic materials are not considered superior to plastics in terms of functionality and often require more weight for the same function, which can lead to similar or even greater environmental impacts than plastic packaging (Schenker et al., 2021). Cellulose fibre packaging materials have been used in the food industry for centuries and are largely made from wood or wood fibre (Johansson et al., 2012).

Cellulose fibre packaging materials, such as paper, cardboard and moulded Cellulose, are part of the broader cellulose-based packaging (which includes regenerated cellulose films, cellulose derivatives and composite materials where the fibres are embedded in a polymer matrix). Fibre-based packaging materials can be divided into flexible (paper) and rigid (paper board, moulded cellulose, corrugated board) categories, with further designations largely related to their application and historical use. The focus is on innovative materials that have the potential to replace hard-to-recycle fossil-based plastics in terms of packaging functionality while preserving the intrinsic reproducibility of traditional cellulose fibre materials.

Plastics can be shaped into various three-dimensional objects without size or shape restrictions. On the contrary, fibre-based packaging materials are often supplied as a sheet or roll of material that can only be converted into a three-dimensional object by glueing and/or folding. Fiber containers and bags are also difficult to close tightly. There is a marked difference between all fossil-based plastics and all cellulose fibre-based materials: plastics have a total load of 3-5 kg $CO_2eq_{/kg}$, while Cellulose fibre-based materials have a total load of less than 1.5 kg CO_2eq/kg. This does not necessarily mean that all fibre-based packaging offers better environmental performance than plastic-based alternatives, as the amount of fibre needed for a given protection may be more than the amount needed. Cellulose fibre-based materials are fairly widely recyclable, but their environmental performance would not change significantly if incinerated with energy recovery. Similarly, no results have been shown for organic recycling (composting or bioremediation), as packaging materials are not widely accepted in organic recycling schemes today (Schenker et al., 2021).

In the past, paper and other fibre-based materials have been largely recognised as a major source of industrial pollution and the destruction of forests of high conservation value. Over the past 40 years, the wood and paper industry has completely changed its image by tightening pollution controls in most countries developing transparent and responsible forest procurement systems. Scandinavian and Central European countries are known for forestry practices that maintain full forest cover and promote biodiversity while ensuring high yields (Rossi et al., 2018). Therefore, the eco-design of Cellulose fibre-based packaging should focus on identifying solutions that minimise weight gain compared to plastic-based packaging (Schenker et al., 2021).

However, it must be recognised that there is a possibility that a widespread and poorly designed switch to cellulose fibre materials could have negative environmental consequences. This could be due to increased deforestation in countries with weak environmental legislation, increasing land competition. Although the land-use impacts of fibre-based cellulosic materials have not been calculated, it is clear that they will be much greater than those of their fossil-based plastic counterparts, which use almost no land outside of the oil wellfield and factory infrastructure used for refining. However, increased land use does not necessarily have to harm the environment, especially given that well-managed forests preserve biodiversity from natural ecosystems (Rossi et al., 2018).

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To avoid significant biodiversity impacts from increased land use of fibre-based wood cellulose, a strong, responsible forest products sourcing strategy should be implemented within companies that seek to increase the proportion of fibre-based wood cellulose packaging. In addition, indirect pressure on the soil can be reduced or avoided altogether if a broader sustainability strategy complements the cellulose fibre packaging strategy. Reducing food loss and waste or increasing the proportion of plant proteins in a company's portfolio can significantly reduce a food company's land use impacts while contributing to additional climate and other environmental benefits. Combining a fibre-based cellulose packaging strategy with a broader sustainability strategy will ensure that no carbon leakage occurs and that the packaging strategy delivers sustainability benefits beyond climate change and narrow packaging value chains (Schenker et al., 2021).

4. Additional types of packaging

4.1. Bamboo packaging

In China, an environmentally friendly pot manufacturing technology was developed using bamboo fibre as the raw material for pots, with only 3 wt% tapioca starch added as an adhesive/filler. This technology outperforms traditional pulp moulding, which is polluting, energy-intensive, and has significant environmental benefits. Bamboo resources are abundant globally; bamboo cultivation covers over 36 million hectares worldwide (Chen et al., 2022). Bamboo grows to a usable size in 3–5 years and is managed sustainably with proper pruning for better growth. A high-quality natural raw material that can be used for tableware and packaging. Using green bamboo pulp fibre to make disposable, environmentally friendly tableware has significant advantages regarding resource availability, material properties and environmental protection. The resulting products have huge market potential and significant social, environmental and economic value (Singh et al., 2023).

4.2. Nanocellulosic fiber

Various methods to improve the properties of biopolymer-based films have been proposed for their successful practical application. One of the most commonly used methods is the addition of nanomaterials, in particular, cellulose nanofibers. Due to its nano size, it interacts with the material at the atomic, molecular or macromolecular level, thus influencing the functional behaviour of biopolymer films. Cellulose nanofibers derived from natural resources are recognised as the most abundant and renewable polymeric material and a key source of sustainable materials on an industrial scale. Because of their attractive properties such as biocompatibility, biodegradability and chemical stability, cellulosic materials have been used as raw materials in the production of paper, pharmaceuticals and textiles for more than 150 years (Cherian et al., 2022; Mary et al., 2022).

In recent years, nano cellulosic materials have attracted researchers' interest in maximising packaging materials' mechanical and barrier properties. Using cellulose nanofibers in packaging minimises the cost of packaged products as they are widely available and inexpensive. Cellulose nanofibers are also good for the environment thanks to their recyclability and reusability. The effective design of cellulose nanofibers for sustainable packaging involves their qualitative and quantitative operation throughout the product life cycle. In addition, the design of nano-cellulose materials provides a better experience for the end-user and enables efficient manufacturing systems. Cellulose fibres are traditionally used in packaging categories such as dry foods, frozen or liquid foods, beverages and fresh foods.

The most commonly used cellulose-based food packaging is cellophane, also known as regenerated cellulose film. Several cellulose derivatives, such as carboxymethyl cellulose, methylcellulose, ethyl cellulose, hydroxypropyl cellulose, hydroxyethyl cellulose and cellulose acetate, are used to produce cellulose-based films. Cellulose acetate and cellulose triacetate are also widely used as rigid packaging film, as are other derivatives, due to their low gas and moisture barrier properties. Cellulose nanofibers are derived from natural resources (wood or plants) and are, therefore, almost inexhaustible, renewable and globally abundant. Moreover, cellulose nanofibers do not interfere with the human food chain and do not need petrochemical ingredients for their production. Therefore, nano-cellulose fibres are used in many applications. The packaging sector could be one of the areas where cellulose nanofibers can be used for sustainable and environmentally friendly packaging (Abdul Khalil et al., 2016; Gervasoni et al., 2023). Using starch-based bio-packaging with nano-cellulose fillers as an alternative to synthetic plastics (Mahardika et al., 2023), (Perera et al., 2023).

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4.3. Edible packaging

Nowadays, edible films have become a major area of research in food packaging, as they play a role in reducing the problem of plastic pollution (Adhikary et al., 2023). Researchers have recently focused on edible food packaging made from starch. Edible packaging is considered a sustainable and biodegradable alternative for active food packaging and optimises food quality compared to traditional packaging. The benefits of edible packaging are recognised in terms of the packaging's ability to maintain food quality, extend shelf life, reduce waste and contribute to the economy of packaging materials. The development and application of edible films is one of the most promising areas in food science, as they are versatile, can be made from a wide range of materials and can carry various active ingredients such as antioxidants and/or antimicrobial agents (Rangaraj et al., 2021; Petkoska et al., 2021). Starch has been a potential candidate for this venture, where starch from both conventional and non-traditional sources is used to produce starch-based edible food packaging (Tyagi et al., 2021). A polysaccharide-based edible film has recently been used in the meat industry to prevent moisture loss and improve texture (Petkoska et al., 2021). Overall, innovation in edible packaging has the potential to become an everyday part of consumers' lives. However, edible packaging is unlikely to solve the problem of plastic waste pollution, but it can make a significant contribution (Rangaraj et al., 2021).

5. Conclusions

The alternative packaging materials in use, as detailed in the previous chapters, are analysed using a SWOT analysis (Table 1). This chart shows alternative packaging materials' strengths, weaknesses, opportunities and threats. This makes it easier to compare them with plastic packaging.

Table 1. Results of the SWOT analysis
Source: own editing

	Strengths	Weaknesses	Opportunities	Threats
Biodegredable PET	decomposition, reducing resource use	not suitable for replacing plastic	semi-permeable film in food packaging	improper consumer treatment
Bioplastic	made from plant biomass, oxygen and oil barrier, biodegradable	uncertain decomposition into Carbon dioxide and water	can be used as a closing statement, technically can replace plastic	not necessarily improve the environmental impact, ecomnomically costly, competing food
PLA	renewable raw material, good transparency	high cost	price decreases, requires less energy, potential substitude, better thermal processability	the changeover does not necessarily mean less environmental impact
Cellulose	widely available, less environmental impact, recyclability, biodegradable	not easily shaped, more material needed, non-functional in many cases	consumers recycle, enable sustainable communication	badly planned switchover would have environmental consequences

The following conclusions can be drawn from the table. Biodegradable PET's strengths lie in its reduction of resource use and degradation in industrial composters. Its weakness is that it is not a suitable alternative to traditional plastic regarding protection, shelf life, and food safety. However, it has the potential to form semi-permeable films and can also be used in food packaging. Meanwhile, there is a risk that consumers will handle it incorrectly, i.e. not dispose of it properly. **Bioplastic**'s strengths lie in that first-generation bioplastics are made from carbohydrate-rich crops, while the second generation is made from non-food crops or waste from biomass processing. They have good oxygen and oil barrier properties and are biodegradable. Its weakness is that its biodegradability to carbon dioxide and water is uncertain. It has a wide range of potentials, such as its biodegradable property offering the possibility to address social and environmental challenges; it could provide a solution for packaging applications; the production of biodegradable packaging materials using biopolymers is a possible process; it can be used as a barrier coating on paper packaging materials and a complete replacement of petrochemical plastics is technically feasible. Their risks are that they do not necessarily improve the overall environmental impact; they are economically costly; they compete with food using the same raw materials; they offer limited environmental

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benefits, and their scope is limited. The advantage of **PLA** is that its raw material can come from renewable sources, and its material is characterised by good transparency and processability. Its weakness is that it can be produced at a higher cost than plastic. Potential benefits include lower cost over time, less energy required to produce it, making it a potential substitute for plastic, and improved thermal processability. The threats do not necessarily improve environmental performance in the whole life cycle. The advantages of **Cellulose include its reduced environmental impact, beneficial end-of-life properties, recyclability,** biodegradability, and wide availability. It has the weakness that the lower environmental load is only valid for the same mass; in many cases, it is not functional; it does not have the property of being easily malleable or even difficult to close tightly. Opportunities include being recycled and positively valued by consumers, which enables sustainability communication and, therefore, becomes valuable to the parties in the supply chain. There is a risk that its environmental performance would not change significantly if it were burned for energy recovery, and a large-scale, poorly planned switch to wood cellulose could have negative environmental consequences.

This suggests that none of these options is a perfect alternative to plastic, but there are some promising alternatives. The advantage of **Bamboo** is that it is a rich source, takes 3–5 years to grow and is a high-quality natural material. It has the potential to outperform Cellulose. It has environmental benefits; it can be used to make disposable and environmentally friendly containers and has huge market potential. The use of **nano cellulosic fibre minimises costs and is environmentally friendly. I**ts design provides a better experience for the end user and enables efficient manufacturing systems. **Edible packaging** is a sustainable and biodegradable alternative that maintains food quality, extends shelf life and reduces waste. Innovation has the potential to become part of consumers' everyday lives, but there is still much resistance. These materials are mainly still experimental, but all have potential.

To complement this, we have produced a cross-table (Table 2) listing the raw materials tested from certain perspectives, showing what else might need to be tested before they can be used:

Table 2. Cross-table of the different packaging materials studied

Factors studied	Biodegradable PET packaging	Bioplastic packaging	PLA	Cellulose packaging	Bamboo packaging	Nanocellulosic fiber	Edible packaging
Reducing the use of resources	X		X		X	X	
Mechanical protection of food		X	X		X	X	
Increasing food shelf-life			X				X
Food safety							X
Dealing with social and environmental challenges	X	X		X		X	X
Reducing packaging waste	X	X		X	X	X	X
Energy-efficient			X				
Positive end-of-life properties				X	X	X	
Degradable in soil and marine environments				X	X	X	
Life-cycle assessment	X	X	X	X			

Source: own editing

The criteria shown in the table have been compiled based on the studies processed in the literature analysis. Then, we checked which packaging materials had already been tested against these criteria. In most aspects, information was available for Nanocellulosic fibre. Increasing the shelf life of the food and mechanical protection were the aspects that came up in most cases. The least frequently mentioned aspects were soil and water degradability and positive end-of-life properties. However, these aspects could reduce the amount of waste that accumulates. In several cases, a material has been reported to reduce packaging waste and the amount of material used, but surprisingly, food packaging reduces food loss rather than waste. On this basis, it can be said that there is a lot of research potential in this field, and there are still unexplored

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components in the use of different materials. So far, only four of the packaging materials presented have been subjected to a life cycle analysis. No new alternatives have been investigated. Future research should include a comprehensive assessment of potential sustainable alternative packaging materials regarding their environmental impact over the whole life cycle.

Overall, long-established food packaging materials have gradually been replaced by plastic. The negative consequences of this widespread use of plastic packaging have changed how alternatives are used to replace it. There have been several attempts, such as reusing or biodegradability of plastics production of bioplastics. However, they have not proved to be a sufficient or good alternative. Sustainable and biodegradable packaging materials are also gaining space, but their positive impact on the environment is not fully understood, and their usability is limited. However, there are also promising new materials in the experimental phase, such as edible packaging or nanocellulosic fibres. Their use helps to reduce the environmental impact and the volume of waste. Each packaging material presented has advantages and disadvantages, and several possibilities exist. However, at the moment, none of them can properly replace plastic.

Appendix

Table 3. Results of the systematic literature analysis

Article	Packaging type	Methods
Abdul Khalil et al., 2016	Cellulosic nanofiber	Review
Adhikary et al., 2023	Polysaccharide-based packaging	Review
Ahmed and Varsney, 2011	Polylactide (PLA)	Review
Beczner et al., 1997	Biopolymer	Overview study
Béguin and Aubert, 1994	Cellulose	Overview study
Brizga et al., 2020	Bioplastic	Potential environmental consequences of substitution
Chen et al., 2016	100% bio-based polyethene terephthalate (PET) bottles, fully fossil-based and partially bio-based PET bottles	Comparative environmental Life Cycle Analysis (LCA)
Chen et al., 2022	Bamboo fibre, polylactic acid (PLA)	Investigated by exploring how the properties of their microstructures affect their mechanical properties
Cherian et al., 2022	Nano-cellulose based coatings	Discusses aspects, challenges and future perspectives of nanocellulose-based coatings
Clark, 2018	Biobased and Renewable Plastics	Review
Dilkes-Hoffman et al., 2019	Bioplastics	Online survey of Australian consumers
Gervasoni et al., 2023	Active food packaging based on cellulose nanocomposites	Review
Hofsten and Edberg, 1972	Cellulose fibers	The rate of degradation in aquatic environments
Holler et al., 2023	Polylactic acid (PLA), bio-polyethylene (Green-PE)	The effect on the oxidative stability of sunflower oil was investigated
Ingrao et al., 2015	Polylactic acid (PLA)	Discusses application of Carbon Footprint (CF)
Johansson et al., 2012	Renewable fibres, bio-based materials	Review
Kakadellis and Harris, 2020	Biodegradable plastic	A systematic review based on life-cycle assessments (LCAs)
Khwaldia et al., 2010	Biopolymer coatings	Existing and potential applications are discussed
Koeing-Lewis et al., 2022	Compostable bio-based food packaging, fossil-based plastic	Analysis of implicit attitudes
Mahardika et al., 2023	Nano-cellulose	Mini review
Mary et al., 2022	Starch-based material	Overview
Perera et al., 2023	Nano-cellulose and metal oxide-based composite	Review
Petkoska et al., 2021	Edible packaging	Review
Raghuvanshi et al., 2023	Bionanocomposite films for intelligent food packaging	Review
Rangaraj et al., 2021	Edible active packaging films	Review
Schenker et al., 2021	Cellulosic fiber-based materials	Describes the climate change impacts of using Cellulose
Singh et al., 2023	Nano-cellulose	Extract nano-cellulose from bamboo fibre by chemical treatment and mechanical grinding.
Taufik et al., 2020	Bio-based plastics	Lab-in-the-field study
Torres-Huerta et al., 2014	PET/PLA, PET/chitosan blends	Synthesis, miscibility, and degradation in real soil environment
Tyagi et al., 2021	Barrier coatings	Review
Vea et al., 2021	Polyhydroxyalkanoate (PHA)-based plastics	Life cycle assessment (LCA) to assess environmental performance
Vural Gursel et al., 2021	Bio-based polyethylene terephthalate	Life cycle assessment
Wyrwa and Barska, 2017	Active packaging	Discuss of application

Source: own editing

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