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Overview of Natural Fiber-Based Packaging Materials

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ABSTRACT

One of the key elements of sustainability of humankind is the usage ratio of nature-based materials as opposed to synthetic products. This is very significant in the field of packaging materials, as people use and consume increasing amount of packaging materials every day. Packaging materials are usually produced from petroleum-based sources using non-degradable materials however, this has a negative impact on sustainability and the environment. It is important to replace them with natural-based materials, therefore cellulose is receiving more and more attention as a raw. Much research has been done for developing new nature-based packaging materials and technologies for replacement of synthetic materials. Recent articles review much research for developing methodologies, materials and composite materials for reducing environmental pollution. This paper reviews how natural-based packaging materials have spread and how it is used in many areas thanks to their favorable environmental effects. It summarizes the raw materials, additives and coatings of natural-based packaging materials, and it also addresses end-of-life options. The paper concerns also the most sensitive area of packaging is food packaging. Smart packaging is relevant for food packaging, and it seems to be one of the promising research areas for substituting artificial materials and providing additional functions.

摘要

人类可持续性的关键要素之一是基于自然的材料与合成产品的使用率. 随着人们每天使用和消费越来越多的包装材料，这在包装材料领域意义重大. 包装材料通常使用不可降解材料从石油来源生产，但这对可持续性和环境产生了负面影响. 用天然材料取代纤维素是很重要的，因此纤维素作为一种原料越来越受到关注. 在开发新的基于自然的包装材料和替代合成材料的技术方面已经进行了大量研究. 最近的文章综述了许多关于开发减少环境污染的方法、材料和复合材料的研究.本文综述了天然包装材料是如何传播的，以及由于其良好的环境影响，它是如何在许多领域使用的. 它概述了天然包装材料的原材料、添加剂和涂层，还介绍了报废选择. 论文还关注到包装最敏感的领域是食品包装. 智能包装与食品包装相关，它似乎是替代人工材料和提供额外功能的有前景的研究领域之一.

KEYWORDS

Packaging; natural based packaging; fiber-based materials; cellulose; environmental friendly; biodegradable materials

关键词

包装材料; 基于天然的包装; 纤维基材料; 纤维素; 环境友好; 可生物降解材料

Introduction

During the last century, artificial, hydrocarbon based materials developed dynamically and solved the problems of packaging, but these conventional plastic packagings are mostly non-biodegradable, and its disposal cause problems (Pulikkalparambil et al. 2023). The scale of production and use reached enormous proportions, and these products reached the untouched parts of nature from the South Pole to the middle of the ocean. That is why the use of raw materials from sustainable sources is becoming more and more important. The main reason for this is that the world's population is growing and

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through a consumer society, this means an ever-increasing use of packaging material (Oloyede and Lignou 2021). Plastic packaging materials would be suitable for reuse if properly collected, but in many countries, the collection system has not been organized well (Antonopoulos, Faraca, and Tonini 2021; Balwada, Samaiya, and Mishra 2021). Even if collection would be perfectly organized, the demand for production would have been increased because of the growing population and the demand for packaging. Government decrees and regulations already support plastic exemption, prioritizing sustainable and degradable packaging. However, fossil-based plastic packaging materials have excellent barrier and mechanical properties, and their use is favorable due to their low production costs (Reichert et al. 2020). However, everyday packaging must be sustainable, which means it shows a low environmental impact during its life cycle (Oloyede and Lignou 2021).

In the literature, numerous definition can be found for artificial and natural-based materials. In our view in this paper the artificial materials either composed hydrocarbons or during manufacturing used a chemical technology results non-degradable material, although the raw material was biodegradable.

Natural-based materials originally formed by the nature and found on the earth without any human influence, it comes from a renewable source, and the product made from it decomposes at the end of its life cycle.

In this article reviewed the natural-based packaging materials include fiber and paper-based packaging materials, however, the two are not synonymous. Paper-based packaging means a flat, sheet-like product, while fiber-based packaging includes thicker, shaped products with a 3D design.

Fiber-based packaging is well suited to reducing the environmental burden resulting from the large-scale use of plastic packaging materials. Since fiber-based packaging is completely or partially recyclable and biodegradable, it fits into the process of the circular economy, it would be advisable to give preference to them (Zaidi et al. 2022). With the rise of fiber-based packaging, the impact of marine debris and packaging on the environment can be reduced (Oloyede and Lignou 2021). Packaging industry can use the natural fibers from forestry and agricultural residues, which are renewable. Fiber-based packaging can be found in completely different areas of the market, because it can endowed with many unique properties for example, food packaging, packaging of construction materials, and cosmetics etc. Natural based packaging materials can be used perfectly for space-filling, or as a motion-absorbing material. However, the fiber-based packaging materials without additives and coatings do not have as good barrier and mechanical properties as the synthetic ones. Thus, in the field of fiber-based packaging materials, much research is directed at how to endow the packaging material with beneficial properties, in addition to retaining their biodegradable and recyclable properties.

The purpose of this review is to summarize the importance of fiber-based packaging materials. From the beginnings of the fiber-based packaging to the smart packaging materials currently on the market. In addition, placing a strong focus on the impact of these products on the environment.

History of paper-based packaging

Paper is the oldest form of flexible packaging. The Chinese used treated mulberry bark sheets to wrap their food as early as the 1st or 2nd century BC (Berger 2002; Hook and Heimlich 2017). Paper mills appeared in Europe in the 14th century (Bolanča, Mrvac, and Hajdek 2020). The technique of papermaking was constantly refined and spread throughout the world, until the 17th century it reached Europe and America via the Middle East (Berger 2002). At the same time, the production of padded cardboard boxes was started, which were used to pack fragile goods (watches, jewelry, cutlery). These boxes already had prints, which marked the beginning of advertising and carrying information to customers (Bolanča, Mrvac, and Hajdek 2020).

The paper making machine, the process for pulping wood and the lithographic printing were all invented in the 1800s. These inventions made it possible to mass produce of the paper-based packaging. At the same time, thanks to technological innovations, they were able to reduce the price

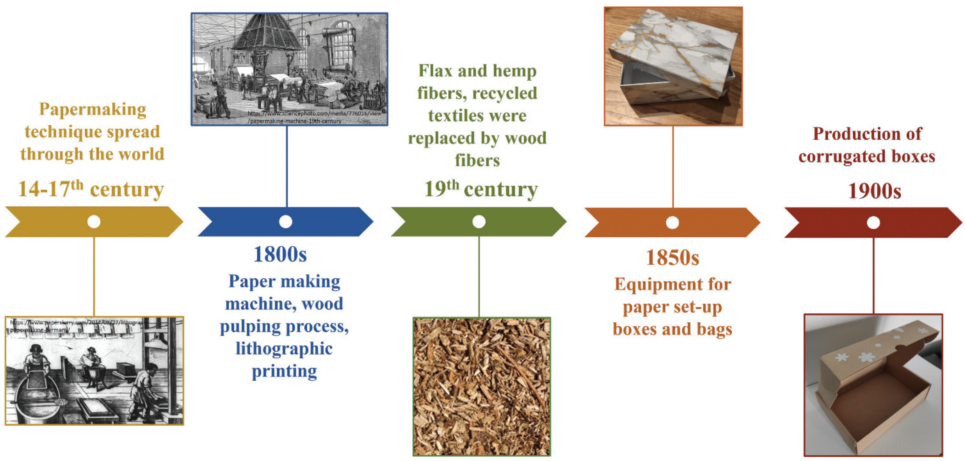

Figure 1. Timeline of paper-based packaging.

of paper. The paper packaging met the demands of mass production: enabled a high volume packaging and labeling, carried the sales information, cheap and disposable packaging (Twede 2005).

In the 19th century, a process was developed to produce the necessary source of fiber from wood pulp. The previously used flax fibers, hemp, recycled textiles, cotton, linen were thus replaced by wood fibers, which were cheap and widely available (Berger 2002; Hook and Heimlich 2017; Scott 2019). In this century paper-based materials appeared already in the case of food packaging, when they were used for packaging liquids and greasy foods (Nechita and Iana-Roman 2020).

The use of paper bags began when cotton for textile bags became more difficult to obtain due the American Civil War. The development of straight line folding, tubing and gluing processes led to the popularity of flexible packaging. In the middle of the 1800s, various equipment for the production of paper set-up boxes and bags began to spread, thereby speeding up production, since previously the boxes were assembled by hand, requiring a lot of work time. The set-up boxes and sacks had one disadvantage, it cannot shipped in a flattened form, it helped the development of the folding carton (Berger 2002; Twede 2005).

The operations and machines were constantly improved, in addition, more and more emphasis was placed on the aesthetic nature of the packaging, so the development of paper packaging also brought with it the development of printing.

The biggest breakthrough in paperboard industry was the equipment for pulping waste paper.

Parallel to the development of paper production, they also began to deal with the production of corrugated boxes in the 1900s. But before that, corrugated paper was already used for packaging purposes, glass bottles were wrapped around with it, so it functioned as a cushioning material. From 1906, increasing kind of products were packed in corrugated boxes (Twede 2005).

The production of papers with special properties required a lot of energy, so the production process cannot be said to be environmentally friendly, and with the continuous increase in energy prices, these have been transformed into expensive processes. Therefore, continuous developments followed, however the developments of the 20th century are built on petroleum-based polymers, such as waxes or oil-polymers and on lamination with plastic and aluminum foils, but these materials inhibit biodegradability and at the same time increase the environmental burden (Nechita and Iana-Roman 2020).

The historical background of the paper is briefly presented in Figure 1.

Raw materials for fiber-based packaging

Cellulose is the most abundant natural and renewable polymer in the world, so cellulose is a suitable option for replacing fossil-based materials, which have a significant environmental impact (Tshwafo 2021). Cellulose can be extracted from many sources. It can be found in wood, annual plants, furthermore in marine animals (tunicates), algae, fungi, bacteria, invertebrates and even amoeba (Brinchi et al. 2013). Another advantage of cellulose is that it is biodegradable, which means that can be decomposed into nontoxic organic salts, water, carbon dioxide and methane within 3 years during natural processes (Vercelheze et al. 2012). Considering the carbon footprint, packaging materials obtained from fiber sources are more favorable than traditional plastic or glass packaging materials. Furthermore, the advantage of fiber-based packaging materials is their lower weight, which appears as an advantage mainly during transport (Johansson et al. 2012).

Different fiber sources are available for paper production. These can be wood, agricultural waste, forest residue, municipal waste or recycled fiber. The raw materials can be divided into two main groups: primary and secondary fibers (Figure 2). Primary fibers are always virgin fibers, which can come from wood or non-wood sources, while secondary fibers are come from recovered paper or board. The properties of the fibers will greatly affect the properties of the resulting paper. While the properties of the fibers depend on the type, age and geographical location of their wood or non-wood sources (Jasmani et al. 2021).

The fibers needed for the production of paper are most often obtained from wood, but in certain parts of the world the demand for cellulose cannot be met by the local wood supply (Laftaha and Rahaman 2015; Puitel et al. 2015). The use of non-wood fibers and agricultural residues is a suitable solution for eliminating this problem. Non-wood fiber-based raw materials are already commonly used in many Asian countries, where the wood supply is limited (Johansson et al. 2012; Puitel et al. 2015). Nowadays, due to environmental concerns, increasing efforts are being made to use non-wood fibers even in regions where the amount of wood is sufficient (Abd El-Sayed et al. 2020). Also, recycled fibers are a common source in paper industry. There are types of paper which exclusively made from recycled fibers such as corrugated medium and test liner (Leh et al. 2021).

Among the agricultural fibers suitable for paper production are wheat straw, rice straw, sugarcane straw, reeds, bamboo, kenaf, oil palm or jute, hemp, and flax are popular (Hurter 2015; Soloi and Hou 2019). In recent decades wheat, bamboo and bagasse have received the most attention (Laftaha and Rahaman 2015).

Non-wood-based fibers can be divided into two main groups: common fibers and specialty fibers. Common non-wood fibers have similar properties to hardwoods, so they are suitable for replacing them. Members of this group are the cereal straws, corn stalk, reeds and sugarcane bagasse. While the specialty non-wood fibers are characterized by a long fiber length, so non-wood fibers can have the same or even better properties than softwood cellulose. Members of this group are bast fibers from

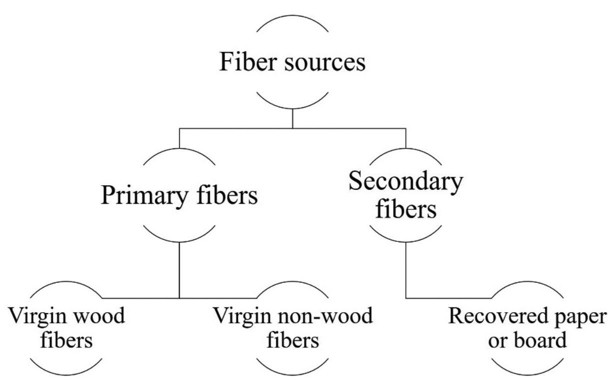

Figure 2. Raw materials of fiber-based products.

Table 1. Fiber length of non-wood fibers.

Raw materials	Fiber length (mm)	Reference
Bamboo	2.0	Ferdous et al. (2021)
Banana leaf	1.92	Ferdous et al. (2021)
Barley straw	0.91	Plazonić et al. (2020)
Canola stalks	1.17	Enayati et al. (2009)
Corn stalks	0.9	Ferdous et al. (2021)
Cotton stalks	0.9	Ferdous et al. (2021)
Jute fiber	2.02	Ferdous et al. (2021)
Kapok fiber	0.64	Leh et al. (2021)
Kaun straw	0.81	Ferdous et al. (2020)
Kenaf bast fiber	2.21	Ahmed et al. (2018)
Rice straw	0.78	Ferdous et al. (2020)
Sugarcane bagasse	1.13–1.23	Sanjuán et al. (2001)
Triticale straw	0.93	Plazonić et al. (2020)
Wheat straw	0.83–0.97	Plazonić et al. (2020), Ferdous et al. (2020)

flax, hemp, jute, kenaf, and the leaf fibers. While fibers from bamboo can belong to either group depending on the variety (Hurter 2015). According to the fiber length (Table 1), the non-wood fibers are suitable for paper making processes, since the fiber length for non-wood fibers are between 0.6–2 mm, while for hardwoods, it is around 0.7–1.1 mm, and for softwoods, it is between 2.3–3.5 mm (Byrd and Hurter 2013; De Assis et al. 2019).

Non-wood fibers are available in large quantities, thus their prices are favorable. Furthermore, non-wood fibers are characterized by a short cycle and rapid regeneration (Laftaha and Rahaman 2015). In those subtropical and tropical areas where there is a shortage of wood, bamboo forests are used for fiber and paper production (Chen et al. 2018). However, the use of non-wood fibers is not beneficial from an environmental point of view. The production of wheat straw-based pulp has a greater environmental impact than that of production of wood-based and recycled pulp, which is mainly due to the high energy and chemical requirements of wheat straw. Moreover, the environmental effects of hemp and flax-based pulp production are even worse compared to wheat straw pulp (Sun, Wang, and Shi 2017). If non-wood raw materials are used, production will decrease, because the drainage is slow which makes washing difficult, thus the paper machine speed decreases. Machines using wood fiber are up to three times faster than machines using non-wood fiber (Abd El-Sayed et al. 2020). Mixing ratios of non-wood fibers can be different. According to Abd El-Sayed et al. (2020) in the case of bagasse-based newsprint, 15–20% chemical pulp is added to achieve the desired runnability. Seleš et al. (2022) investigated papers which made combination of recycled wood pulp with 30% non-wood fibres (wheat, barley and straw). They concluded that papers printed with water-based flexographic inks showed a very good stability. In the case of straw pulp, 60–70% bleached straw pulp is mixed with 40–30% long fiber wood pulp due to good runnability and quality parameters (Laftah and Rahman 2016). However non-woody annual fibers such as rice and wheat straw, or bagasse, flax, kenaf fibers are suitable for reinforcing waste paper fibers (Abd El-Sayed et al. 2020).

However, its disadvantageous properties make it difficult to use. Compared to wood, it is characterized by its lower density, a tendency to decomposition, and contains hemicellulose. More ash and extract content are in the non-wood fibers but mostly in agricultural residues (Puitel et al. 2015).

Agricultural residues are very popular in China, so rice straw and wheat straw are often used raw materials in paper production (Hammett et al. 2001; Plazonić, Barbaric-Mikocevic, and Španić 2020). A rarer raw material, pineapple leaf fiber (PALF) was investigated by Laftaha and Rahaman, 2015). They examined its suitability for paper production and examined how the delignification time effects the papers' mechanical properties. Composite materials were investigated by Ming et al. (2021) who studied biodegradable mulch paper, which was made from pineapple leaf fiber and rice straw fiber.

The usage of non-wood fibers in the paper and pulp industry has some difficulties. First of all, the availability of the most non-wood fibers is seasonal, because the harvesting time is quite short. The mills need to store the non-wood fibers from the harvesting for the rest of the year. Secondly, most non-wood fibers have a high silica content, which causes problems during washing due to poor drainage of the pulp and the high viscosity of the black liquor. In addition, pulp made from non-wood fibers is slow to drain and therefore causes problems in the paper machine. Therefore, the paper machine must be operated at a slower speed, which means lower production, so the price of non-wood fiber paper will be higher (Abd El-Sayed et al. 2020).

Additives, coatings

Despite of fiber-based packaging materials having enormous advantages, there are conditions when the original properties cannot fulfill the requirements. Usually, the additives try to eliminate the effect of unfavorable conditions. However, this weak feature can be improved by using coatings, such as waxes, aluminum foils or polymer materials (Adibi et al. 2022; Dai et al. 2021; Hirvikorpi et al. 2010; Kunam et al. 2022; Raheem 2012). The use of polymers ensures good barrier properties for the paper (Kunam et al. 2022). However, these are often synthetic polymers, which reduces the recyclability and biodegradability of the paper (Khwaldia, Arab-Tehrany, and Desobry 2010). Furthermore, the use of a coating often results in more weight being required to perform a given function than plastic packaging, which ultimately leads to the same or even greater environmental impact (Schenker et al. 2021).

Other paper can made from secondary fibers, but it will have weaker properties because of the reduced fiber morphology and consequently lower interactions. See further details in chapter Paper recycling. This effect also negatively affects the strength properties of the paper. In order to reduce the poor barrier properties and weaker strength, additives can be added to the paper. These additives are mostly inorganic and inexpensive materials such as calcium carbonate, kaolin or synthetic polymers (Bollström et al. 2013; Nechita and Iana-Roman 2020). The petroleum-based additives will prevent the packaging's biodegradability, thus the packaging cannot be recycled. Therefore, it is necessary to use natural-based additives instead of petroleum-based materials. In the literature, we can find examples of how synthetic-based additives have been replaced natural-based additives i.e. biopolymers (Gulsoy and Erenturk 2017; Hamzeh et al. 2013; Rasa and Resalati 2014).

Among biopolymers, polysaccharides, proteins, lipids and also polyesters can be used as a coating for papers and paper products. Materials can be chosen depending on the desired result (Rastogi and Samyn 2015). Compared to petroleum-based plastics, biopolymers are biodegradable, and they can obtained from renewable sources, but they are much more expensive (Müller et al. 2014). Figure 3 shows the potential sources of biopolymers.

However, bio-based polymers have a significant disadvantage compared to synthetic polymers. Their mechanical and gas barrier properties depend on the humidity of the environment because some biopolymers have hydrophilic properties (Rastogi and Samyn 2015). Increasing the hydrophobic phase of the polymer can be achieved by adding natural extracts or essential oils. In this way, a more compact, better cross-linked structure is formed, so the water vapor permeability of biopolymer film can be reduced (Said, Howell, and Sarbon 2023). In addition, microbial contamination can exist during production and handling of biopolymers (Kunam et al. 2022). Thus, their usability in the packaging industry is limited. Additional substances can be added to the natural-based coating materials, such as plasticizers, antioxidants and antimicrobial agents, which can give the packaging materials additional beneficial properties (Khwaldia, Arab-Tehrany, and Desobry 2010).

Polysaccharides are often used as paper coatings or additives. Polysaccharides have beneficial properties like their biodegradability and non-toxicity toward living organism and good gas, aroma and grease barrier properties (Nešić et al. 2020; Vrabič-Brodnjak and Tihole 2020). The most popular of these are starch, alginate, carrageenan and chitosan (Khwaldia, Arab-Tehrany, and Desobry 2010; Munteanu and Vasile 2020). Due to the film-forming properties of polysaccharides, they have excellent gas and aroma barrier properties, but they have poor water barrier properties, due to their hydrophilic nature (Bordenave, Grelier, and Coma 2010; Khwaldia, Arab-Tehrany, and Desobry 2010).

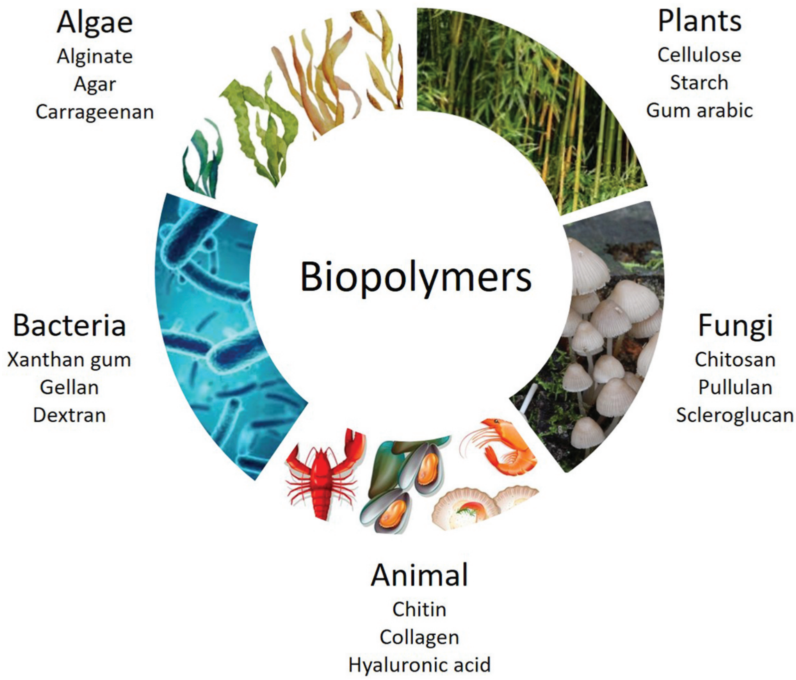

Figure 3. Natural sources of biopolymers.

Zhang and Sablani (2021) provided insight into the use of plant-based food waste or by-products in the field of biodegradable packaging. The most typical representatives of these materials are low-quality whole fruits or vegetables, fruit pomace, seeds, vegetable peels and crop biomass (Zhang and Sablani 2021). Since the traditional treatments for food waste, incineration and landfilling, cause serious economic and social, but mostly environmental problems, so more sustainable solutions must be found. For example, the valorization of food waste into value-added chemicals can be a solution so that the waste biomaterial can be used in other applications (Xiong et al. 2019). Their use as biodegradable films proved to be favorable, as they showed improved technical properties (Munir et al. 2019; Quilez-Molina et al. 2020; Rodsamran and Sothornvit 2019). With fiber-based materials, biodegradable film can be used as a coating to improve the properties of the composite formed in this way. Shankar and Rhim (2018) developed a bio-coated paper whose properties were very similar to the properties of PE-coated paper, so the three-component mixture of carbohydrates and grapefruit seed extract, which they used, could be an environmentally friendly alternative to polyethylene. Their coating is also suitable for food packaging, as the coated paper showed strong antibacterial activity against food-borne pathogenic bacteria.

Starch is an abundant, sustainable biopolymer that is used in many areas of industry due to its low cost. It is most often found in plant tubers and seeds, so it can be extracted from corn, potatoes, cassava and cereal grains. Native starch has disadvantageous properties, which limits its use in industry. Examples include its insolubility in cold water or its hygroscopic property. Thus, it can made more widely used with enzymatic chemical and physical modifications (Chi et al. 2020). Starch has long been used in the paper industry, because it is an important material for flocculation and retention control and in sheet bonding and in support of paper sizing (Maurer 2009). In the last decades were published innovative solutions for usage of starch. Their use as a film or coating is favorable, as they are edible, odorless, nontoxic, tasteless and colorless, and act as an adequate oxygen barrier. Its poor mechanical properties and sensitivity to moisture can be improved after mixing with other natural materials. By

Table 2. Mechanical properties of papers made from different raw materials.

Raw material	Tensile index (N·m/g)	Tear index (mN·m2/g)	Burst index (kPa·m2/g)	Reference
30% wheat straw + 70% recycled fiber	41.02	9.57	13.41	Plazonić et al. (2020)
30% barley straw + 70% recycled fiber	40.31	8.54	13.05	Plazonić et al. (2020)
30% triticale straw + 70% recycled fiber	41.15	10.03	13.03	Plazonić et al. (2020)
50% softwood kraft + 50% recycled	44.61	6.29	2.25	Gulsoy and Erenturk (2017);
50% softwood kraft + 50% recycled + 0.75% chationic starch	58.08	6.70	3.03	Gulsoy and Erenturk (2017);
Bagasse	42.46	4.14	2.62	Hamzeh et al. (2013)
Bamboo	25.8	12.1	1.2	Ferdous et al. (2021)
Coated rice straw paper with Longan Peel Extract (10%)	32.98	-	-	Chollakup et al. (2021)
Coated rice straw paper with Longan Peel Extract (15%)	32.67	-	-	Chollakup et al. (2021)
Coated rice straw paper with Longan Peel Extract (20%)	36.20	-	-	Chollakup et al. (2021)
Rice straw paper	32.26	-	-	Chollakup et al. (2021)
Starch coated rice straw paper	33.05	-	-	Chollakup et al. (2021)
Corn stalks	52.39	6.85	2.82	Ferdous et al. (2021)
Cotton stalks	25.2	5.6	1	Ferdous et al. (2021)
Jute fiber	28.9	18.7	2.2	Ferdous et al. (2021)
Kaun straw	42.2	5.0	2.14	Ferdous et al. (2020)
Pre-extracted bagasse	49.33	4.06	2.78	Hamzeh et al. (2013)
Recycled kraft liner	20.9	7.39	3.93	Leh et al. (2021)
Recycled kraft liner + 5% (w/w) kapok fiber	20.1	8.02	4.10	Leh et al. (2021)
Wheat straw	54.5	5.6	3.21	Ferdous et al. (2020)

mixing starch with plant extracts, polysaccharides, and proteins, new biocomposite materials can be produced (Dai, Zhang, and Cheng 2019; Ketkaew et al. 2018; Nešić et al. 2020; Volpe et al. 2018).

Table 2 shows the important mechanical properties of papers made from different raw materials and in some cases with coatings or additives.

We can find very special solutions in the field of fiber-based packaging material research. Imam et al. (2008) made thermoformed foam products consisting of processed Alaskan fish by-products, starch and fiber. The best flexural modulus value was achieved with the addition of 15% pollock frames (remaining bones). Due to the biodegradable nature of the foam product, it decomposed in 7 weeks at ambient temperature.

Cellulose nanofibers (CNF) have better properties than ordinary cellulose fibers. They have higher mechanical stability and better barrier properties, so their possibilities of use provide a wider range of solutions (Reichert et al. 2020; Tarrés et al. 2018). Since nanocellulose is extracted from cellulose after mechanical and chemical treatments, thus it is also a material from renewable source (Mishra et al. 2018). So, its application is suitable for reducing the environmental load. Films made from cellulose nanofibrils show good oxygen and grease barrier properties, thanks to their nano-sized units, their larger surface area, and the effective interactions between the nanofibrils (Tayeb, Tajvidi, and Bousfield 2020). Many articles show the usability of nanocellulose as an additive or coating to fiber-based products, where beneficial physical, mechanical and barrier properties are reported (Brodin, Gregersen, and Syverud 2014; Li et al. 2021; Lourenco et al. 2020; Tarrés et al. 2018; Yook et al. 2020). In composites, nanocellulose is suitable for replacing inorganic fillers (Reichert et al. 2020). Tayeb et al. (2020) have reported the properties of the lignin-containing cellulose nanofibrils (LCNF) and found outstanding grease barrier properties.

Paper recycling

Depending on the raw material of a packaging, we can determine whether it is an environmentally friendly packaging or not. However, the effects of the production processes also contribute greatly to the environmentally friendly characteristic. Thus, the critical point of pulp and paper production is the pollution emission of the factories and mainly the large amount of wastewater generated, the treatment of which must be emphasized (Huang 2017; Kong, Hasanbeigi, and Price 2016; Małachowska et al. 2023). But these environmental impacts can all be reduced by recycling, because with recycling we can save energy, water and the raw material (Huang 2017; Małachowska et al. 2023). Furthermore, it will lead to a reduction in the amount of urban waste, which will result in less going to landfills (Bahrami and Jafari 2019; Jamnicki, Lozo, and Barusic 2021).

From the second half of the 20th century till today, the use of recycled paper has increased. This can be attributed to the fact that consumer demands have increased, government regulations have been introduced due to environmental protection issues, and the appropriate technology has been developed for the use of recovered paper (Scott 2019).

The first important step in recycling is selective waste collection. During collection, recyclable paper may be mixed with soiled, for example, greasy paper. As a result, contaminated papers end up in the recycling cycle (Väisänen, Mentu, and Salkinoja-Salonen 1991).

There are papers with quality, which can be sent straight to the mill for processing, but there are other types of paper that need to be processed before milling (Scott 2019). An important step in the process of recycling the paper waste is the removal of printing ink and additives (Sobotkova et al. 2021). However, the fiber structure is damaged during the recycling, deinking and refining processes so the quality of the fibers constantly deteriorates (Dukarska, Buszka, and Modzelewska 2018; Tarrés et al. 2018). That means that recycled fibers are not suitable for high-grade paper (Jin et al. 2022). The quality of recycled paper will be weaker than new paper made from virgin fiber. This can be attributed to the hornification. During recycling, the drying and wetting cycles cause hornification, meaning the fiber wall loses its ability to swell. This leads to stiffening of the fibers, which reduces the ability to form bonds between the fibers (Chacon, Lavoine, and Venditti 2022; Diniz, Gil, and Castro 2004; Mo et al. 2022). The other problem is the shortening of the fibers, which is caused by mechanical erosion (Peretz et al. 2021). This is mainly shown in the lower values of the tensile strength and the weak absorption capacity which can cause problems in the end uses of paper (Bandara and Indunil 2022; Han et al. 2021). For these reasons, recycling has limits, cellulose fibers can be recycled a maximum of six or seven times (Deshwal, Panjagari, and Alam 2019; Ozola et al. 2019). Although there are some types of paper where 100% recycled fibers can be used, for example in the case of paper and board production. This can be corrugating medium and test liner, or newsprint (Bajpai 2014).

In addition, staples, and laminated covers of the paper products make the recycling difficult (Faul 2010; Vukoje and Rožić 2018). This is supported by Mahmood et al. (2021), where five different types of paper and their end-of-life options were examined. All types of paper were found to be recyclable except for coated paper. Besides coated papers there are some types of paper that are not currently recycled, including various personal care products (Scott 2019).

All materials present in the paper waste end up in the water during re-pulping. In order for this not to pollute the environment, factories must use effective wastewater treatment technologies, which in most cases are implemented through biological processes (Keprtová and Bindzar 2021).

It is difficult to describe the technological steps of recycling recovered paper in a general way, since different quality recovered papers require different operations to remove contaminants. The following operations are used to remove contaminants from the fiber fraction of recovered paper: washing, cleaning, screening, flotation. These actions can be used to remove the water-soluble inks, the fine particles, the dirt, sand, metal and the large particles and the laser and photocopy inks. There are many other operations that need to be done when paper is recycled. These include basic operations that are used whenever pulp is made, and special operations that are performed to achieve certain properties. These processes are the repulping, fractionation, refining, dispersion, dewatering, and the bleaching (Scott 2019).

The more contaminated the paper, the more expensive the process to make it suitable for paper production. It is necessary to choose an environmentally friendly way to dispose of the contaminants left after cleaning (Scott 2019). Although paper recycling is not always beneficial, since in some cases the recycling of paper cannot be realized under favorable conditions either from an economic or environmental point of view (Bajpai 2014).

Collection is an important and expensive step in the recycling process. This includes the sorting of paper by category, baling, and transporting it to a factory where paper pulp is made from it (Bajpai 2014).

For a long time, chlorine-containing chemicals were used to improve the brightness of deinked pulp, which raised environmental and toxicity issues. To avoid this, O-containing compounds began to be used for bleaching such as oxygen, ozone, hydrogen peroxide, and several other peroxygens (Saad et al. 2020). The culmination of these materials and applied technologies is the completely chlorine-free (TCF) bleaching technology. However, the most common technology in practice is the elemental chlorine-free (ECF) bleaching process (Bajpai 2012).

At the end of their life cycle, paper-based packaging materials can be recycled, organically or energetically. However, recycling and composting are significantly influenced by the processes that are carried out on paper to increase packaging performance, which most often means treatment with nonrenewable materials (Müller et al. 2014).

Paper-based food packaging

The aim of food packaging is to extend the shelf life of food during transport and storage, furthermore to protect the product from chemical, mechanical, climatic and microbiological effects so the packaging must provide a protective covering for the food. The shelf life of food is greatly influenced by the quality of the packaging system used, as well as the environmental effects that occur during its life, and also the characteristics of the packaged food itself. The main purpose of packaging is to prevent food waste and loss (Ivanković et al. 2017; Nechita and Iana-Roman 2020; Oloyede and Lignou 2021; Topuz and Uyar 2020). In addition, however, the packaging materials must also comply with the regulations on food packaging, since they cannot endanger the safety and health of consumers, i.e. the migration of harmful substances into food is regulated and cannot exceed the specified limit (Latos-Brozio and Masek 2019).

Food packaging is often made entirely of petroleum-based materials or contains petroleum-based materials as a laminate like the Tetra Pak packaging. So, it is particularly important to reveal the alternatives in this area. According to Sydow and Bienczak (2018) the following natural fibers can be promising fillers: jute, sisal, hemp, cotton, kenaf.

Paper and paperboard are good options for food packaging and widely used in the food packaging industry (Adibi et al. 2022). The hydrophilic nature and the porous structure of paper and cardboard limits their use as food packaging materials because it has weak barrier properties (Bandara and Indunil 2022; Kopacic et al. 2018). However cellulose-based packaging is already used for potato chips, pasta, cereals, nuts, bread, herbs and spices and sweets (Peelman et al. 2016). So recycled paper is most often used for dry foods, such as pasta and rice. Or in cases where the packaged goods are washed and peeled before consumption (vegetables, fruits, eggs). Recycled papers are also used for short-term storage of fast food and pizza. Only paper without various coatings is suitable for short-term storage of these fatty foods. In the case of packaging with a longer lifetime, the paper packaging material is coated with aluminum or plastic (Binderup et al. 2010).

However, paper contains sources of carbon such as cellulose and starch, which provides a suitable environment for the development of pathogenic and nonpathogenic microbes. Microorganisms or spores can get from the paper to the food, which can pose serious health risks. To regulate this, the authorities created food packaging standards, in which the microbial limit values of the paper are recorded (Zaidi et al. 2022). Paper suitable for food packaging can be made from virgin fibers, recycled fibers, or a mixture of these (Elmas and Çınar 2018).

Certain compounds can get into food from cardboard and paper packaging. The migration of these compounds is influenced by several parameters, such as contact time, temperature and the contact layer of the food packaging material. Chemicals used in pulp and paper production contribute to the contamination of recycled paper. These can be additives, dyes, adhesives or pigments (Bandara and Indunil 2022; Pivnenko, Eriksson, and Astrup 2015). According to Vapenka et al. (2016) contamination in paper packaging comes from materials used to modify functional properties, such as water- and grease resistant coatings, printing inks, and residues from recycled pulp. These substances can pose a danger to humans if they migrate to the food from the packaging (Xue et al. 2019). The presence of aromatic hydrocarbons (MOAH) and hydrocarbons saturated with mineral oil (MOSH) in food is a safety risk, meaning it can be harmful to health. The source of these substances can be recycled paper and cardboard packaging material, from which these compounds can enter the food (Buist et al. 2020; Kopacic et al. 2018). Buist et al. (2020) have investigated and evaluated technologies that can be used to reduce these safety hazards i.e. the MB12, flotation, supercritical CO_2 and thermal treatment. It was determined that each technology can reduce the potential migration of mineral oils by more than 70%, however, each technology needs to be improved, since none of them can achieve the optimal performance of all indicators.

Jamnicki et al. (2021) examined whether recycled paper is suitable for food industry purposes, as it may contain dangerous chemicals that raise food safety issues. They found that all hand sheets made of deinked cellulose are suitable for direct contact with food. In other words, this finding helps ensure that food packaging can also be handled fit into the circular economy manner.

Smart packaging

Food waste is an important issue today, as it has a significant environmental impact. Resources were used for wasted food also which was an in vain energy. Consequently, the packaging materials of this wasted food have to be disposal together with the food (Kibler et al. 2018). Innovative packaging systems can contribute to the reduction of food waste, by increasing the shelf life of food and keep the quality for longer time (Fang et al. 2017; Muratore, Barbos, and Martini 2019). For this reason, developed the smart packaging, which is based on the interaction between food and packaging. Smart packaging covers two types of technology, active and intelligent packaging solutions as Figure 4 shows (Lloyd, Mirosa, and Birch 2018; Vasile and Baican 2021).

Active packaging systems contain materials added intentionally to the packaging, so they improve food safety and quality by releasing or absorbing substances into the packaged food or the surrounding packaging environment. These substances are different natural additives derived from plants, animals or microorganisms (Irimia et al. 2021; Latos-Brozio and Masek 2019; Vasile and Baican 2021). The active packaging systems can be divided into three group according to the action mechanism. For example, the antimicrobials, and the antioxidants are the releasing systems. The second group is the absorbing system for examples CO_2 or oxygen scavengers, and moisture or aroma absorbers. The third group is the non-migrating system where the active packaging and the food must be in complete contact, as this is how it exerts its effect. For example, migration is not necessary for enzymes acting on the surface of food (Vasile and Baican 2021).

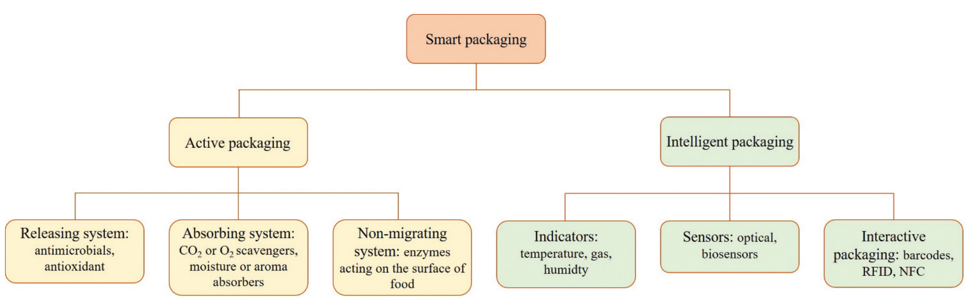

Figure 4. Types of smart packaging system.

Intelligent packaging monitors the quality of food inside the packaging in real time, evaluating its quality and ensuring safety (Xiaodong et al. 2020). Materials are used that monitor the condition of the food or the environment surrounding it (the environment inside the packaging), and the changes that occur in it are transmitted visually to the consumer provided via external product indicators (Ebrahimi et al. 2019; Lloyd, Mirosa, and Birch 2018; Vasuki, Kadirvel, and Narayana 2023). The purpose of intelligent packaging is to inform consumers, traders and manufacturers about the quality of food (Latos-Brozio and Masek 2019). Three main groups can be distinguished within intelligent packaging (Tiekstra et al. 2021). The indicators visually indicate changes in the quality of the packaged food with a change in color (Sohail, Su, and Zhu 2018). The sensors collect quantitative information about the packaged goods. They recognize and record changes in the environment or condition of the packaged food, and then provide information about it. Interactive packaging is the third group. In it, two-dimensional barcodes, radio frequency identification (RFID) and near-field communication (NFC) tags store information about the storage and distribution of packaged food (Tiekstra et al. 2021).

Intelligent packaging does not directly affect the shelf life of food, while active packaging does this is a big main difference between the two types of packaging (Ebrahimi et al. 2019; Latos-Brozio and Masek 2019).

Therefore, active packaging based on cellulose is dealt with in a lot of research which mostly deals with antimicrobial packaging, which is suitable for preventing the growth of microorganisms, thus ensuring food safety. Irimia et al. (2021) have created kraft paper with antibacterial and antioxidant properties using environmentally friendly activation processes and vegetable oils, which can thus help preserve the quality of food for a longer period. De Oliveira et al. (2021) used two different essential oils; they produced papers with active compounds isolated from the oils. Adding eugenol and linalool prevented the growth of pathogenic bacteria Ni et al. (2018) produced a flexible, starch-based coating for food packaging papers by adding ZnO nanoparticles. Then they examined the amount of ZnO nanoparticles released from the composite film, which was below the legal limit. Thus, a coating with hydrophobic and antimicrobial properties was developed for food packaging. Kostova et al. (2020) examined wrapping paper treated with dill weed essential oil. The results showed a fungicidal effect for recycled paper treated with the dill weed essential oil. This type of paper can be used for food packaging because it can improve the quality and extend the shelf life of food.

Other products from fiber-based material

In addition to the production of packaging material, cellulose-based products appear in several areas of the market. Recovered paper and recovered paper sludge can use for producing new products. These new products can be insulation panels, fertilizer/soil amender, animal bedding, egg cartons, planting pots for seedlings, and energy (Scott 2019). The final residues and sludge from paper production can be used as raw materials in other industries, e.g. in brick factories or in the cement industry (Bajpai 2014).

Many publications deal with the usability of cellulose-based materials as insulation. Benallel et al. (2021) created new thermal insulation materials using cardboard waste and plant fiber. Plant fibers are provided by agricultural by-products such as reeds, fig branches, olive leaves and alfalfa. Then these were mixed separately with different mass fractions of cardboard waste. The composites showed good insulating properties and had significant environmental and economic benefits. Ouakarrouch et al. (2022) also dealt with similar material. They used cardboard waste and vegetable fibers (reed trees, esparto fibers, fig trees and olive trees) to produce thermo-acoustical insulation panels. The results showed appropriate properties for thermal and acoustical insulation in buildings. Pasztory et al. (2017) made bark panels from black locust waste. Their thermal conductivity reached the value of 0.06 W/mK, typical of natural insulating materials. Bakatovich et al. (2022) made environmentally friendly thermal insulation panels from a mixture of reed and straw. Promising results were obtained for the panel's use in the construction industry. These publications deal with the presentation of low environmental impact materials that may be suitable for replacing synthetic insulation materials.

Conclusion

The large amount of research in packaging materials proves the efforts of scientists to find the way to reduce damage to the environment. This needs the substitution of artificial synthetic materials, which degrade biologically or chemically over a very long time into natural based materials, which can decompose easily over time or by changing the conditions. The research shows that cellulose is the main component of packaging materials, and secondly the wide range of usability of cellulose is a highlighted as a further advantage. The good recyclability of the natural based materials is also promising for minimizing carbon production during manufacturing. Fourthly, many researches discuss how the disadvantageous properties of natural-based packaging materials can be eliminate or compensate. The research that deals with natural additives and coatings to improve these properties is outstanding in this area as well.

The producers launched several products to the market made of natural based raw materials can substitute the traditional synthetic materials. The fast reaction of the packaging industry alludes a promising step to be sustainable even in the near future. However, the global results will be seen only in decades perspective.

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Author contributions

Both authors contributed to the study conception and design. Data collection and analysis and editing were performed by Zsófia Kóczán. The first draft of the manuscript was written by Zsófia Kóczán and Zoltán Pásztory and both authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. The funding acquisition was performed by Zoltán Pásztory.

Consent for publication

All authors approved the final version of the manuscript.

Ethical approval

All authors have consented to participate on the manuscript.

Highlights

- Reduce the damage of the environment with using of fiber-based packaging materials.
- Cellulose as a substitute of the fossil-based materials.
- The good recyclability of the natural based materials is promising for minimizing the carbon production during manufacturing.

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