Sustainable materials in the flexible packaging industry – an overview

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Abstract: The article presents the latest solutions for sustainable flexible packaging materials, covering articles published in 2017–2022. Discussed, among others bio-based, biodegradable, and recycled polymers, and paper, which are slowly being adopted by the industry and are expected to replace traditional packaging materials from non-renewable sources in the coming years.

Keywords: sustainable materials, flexible packaging, bio-based polymers, biodegradable polymers, recycling, circular economy.

Zrównoważone materiały w branży opakowań elastycznych – przegląd literaturowy

Streszczenie: W artykule przybliżono najnowsze rozwiązania dotyczące zrównoważonych elastycznych materiałów opakowaniowych, obejmujące artykuły opublikowane w latach 2017–2022. Omówiono m.in. biopolimery, polimery biodegradowalne, a także pochodzące z recyklingu oraz papier, które są powoli adoptowane przez przemysł i oczekuje się, że w kolejnych latach zastąpią tradycyjne materiały opakowaniowe ze źródeł nieodnawialnych.

Słowa kluczowe: zrównoważone materiały, opakowania elastyczne, biopolimery, polimery biodegradowalne, recykling, gospodarka o obiegu zamkniętym.

Since the discovery of plastic materials in the early decades of the 20th century, petrochemical industries started to create associations including companies such as ExxonMobil, BASF, Chevron Phillips, Dow Chemicals and DuPont. These companies continue to have a major part in the global production of raw resin materials until today. These associations were urged from their desire to use waste materials derived from crude oil and natural gas production. The most plentiful of these by-products was ethylene gas. This was processed by a British company called Imperial Chemical Industries (ICI) which successfully made the first plastic originating from this raw material, beating their competitors. ICI was formed back in 1926, they had their first commercial success with Perspex in 1932 and later with Melinex PET film [1]. Currently, the most common packaging material is plastic. According to studies, if plastic materials were substituted with other materials, the weight of the packaging could almost quadrable, while the volume could increase to more than double [2, 3].

Over the course of years, plastics assisted human life and played a key role in the economic development of numerous countries [4]. Polymeric films can be descripted as thin uninterrupted materials characteristically up to 200 μm thickness. Plastic materials above this thickness can be descripted as sheets. Various resins are used for the manufacture of polymer films. These resins have their own unique physical properties which are used to satisfy the needs of various applications. These properties can provide barrier, stiffness, and heat-sealing ability [5]. Apart from the different resins used to manufacture a polymeric film, the final film itself can also be clear, metalized, translucent, matt, coloured and its surface can be smooth, rough, or feel like paper. Polymeric films are manufactured from raffia grade resins using multiple production methods including film extrusion, coextrusion, cast film extrusion, blown film extrusion and calendaring [6].

Nevertheless, plastic films normally converted in the flexible packaging industry currently include polypropylene, polyethylene, polyvinyl chloride, polyamide, and polyethylene terephthalate which are sourced from non-renewable resources and more specifically from fossil fuels [5,7]. On the other hand, bio-based materials are created using a set of biopolymer materials that can be made by a diversity of raw materials, for instance, biomass (including agricultural plants, marine animals, and microorganisms) or synthesized by a chemical process using natural raw materials (such as cellulose,

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starch etc.) [8]. Biomass can be used to create innovative bio-based materials for food packaging applications, reducing the need of fossil-based plastics [9]. The amplified environmental awareness has inspired the evolution for the creation of multiple bio-based polymers, which are originated from renewable sources, as replacements to petroleum-based polymers. Hence, this led to the production of innovative "bioplastics" for commercial applications. At this point, it is crucial to mention that not all biodegradable plastics are bio-based, and not all bio-based plastics are biodegradable. For instance, Bio-PET, (Polyethylene terephthalate) can be produced from biomass as well, although this is not biodegradable. Moreover, some fossil produced materials are biodegradable, for example, the ones from polycaprolactone [10]. Despite numerous attempts to encourage the application of biodegradable polymers in packaging, only a limited number of bio-based and biodegradable polymers can meet the requirement for packaging applications, particularly the ones of food packaging. This is attributed to efforts to obtain desired oxygen transmission and water vapor barrier performance like traditional fossil-based plastics. Biopolymers created from protein and starch usually display an increased oxygen barrier, but significantly low moisture barrier attributed to their natural hydrophilicity and sometimes weak mechanical properties as well [11, 10]. Transition to a circular economy is the key to endorse sustainable packaging materials. Relying on principles including resource efficiency and reduced carbon footprint can help in the reduction of packaging material waste [12].

SUSTAINABLE SOLUTIONS

To cope with the drawbacks of ordinary plastics, many research efforts were focused on environmentally friendly materials including bio-based and bio-degradable plastics. The human-induced consequences from the disposal of non-biodegradable plastics to the environment are gathering increasing awareness. Furthermore, the reduction of fossil feedstocks will inevitably result in a remarkable demand and supply deficit in traditional fossil-based packaging materials. These two issues have fuelled research into finding sustainable replacements to traditional polymers [13]. The term "sustainable development" refers to a development paradigm that considers the environment which "responds to the needs of the present without compromising the ability of future generations to meet their own needs" [14]. Considerable attention has been gained for sustainable solutions, due to these materials that can be decomposed into core ingredients by microorganisms and enzymes, along with the fact that they can be made from renewable resources [15]. Biodegradable plastic materials with almost identical functions to their conventional counterparts have been developed with considerable effort. Currently, environmentally friendly plastic-based packaging has proven to be acceptable for commercial use [16]. The ability to estimate and anticipate the shelf life of a product depends on knowing its barrier properties. Two of the most essential barrier aspects, particularly for food packaging, are oxygen permeability and water vapor transmission. Traditional polymers can be replaced with biopolymers provided that certain required aspects for a given application are comparable between them [17,18]. Main sustainable solutions for flexible packing can be summarised as below. Given the current context, it would be advantageous to provide a comprehensive explanation regarding the distinctions among the terms "degradable," "biodegradable," and "compostable."

The term degradable refers to a material that can break down into smaller fragments over time due to natural processes such as exposure to sunlight (UV radiation), heat, moisture, or mechanical stress. However, the breakdown process of degradable materials may not necessarily involve microorganisms, and the resulting fragments may persist in the environment for an extended period.

Biodegradable materials are capable of being broken down into simpler substances by the action of microorganisms (such as bacteria, fungi, or enzymes) present in the environment. These microorganisms consume the material as a source of energy, resulting in the conversion of the material into natural elements, such as carbon dioxide, water, and biomass. Biodegradable materials can decompose faster than non-biodegradable ones, but the specific time varies depending on factors like temperature, humidity, oxygen levels, and the nature of the material itself.

Compostable materials are a subset of biodegradable materials but with additional specifications. A material is considered compostable if it not only breaks down into simpler substances through the action of microorganisms but also transforms into compost—a nutrient-rich soil amendment that can support plant growth. Composting is a controlled process that requires specific conditions, including the right mix of organic matter, temperature, moisture, and oxygen. Compostable materials typically degrade within a defined time, leaving behind no visible or toxic residue.

It is important to note that the terms "biodegradable" and "compostable" are often used interchangeably, but compostable materials specifically meet stricter standards for degradation and leave behind beneficial end-products. In addition, the rate of degradation and the specific environmental conditions required for decomposition may vary between different materials, so it is necessary to consider specific certifications and standards to ensure accurate claims regarding product degradability or compostability [19–21].

Bio-based polymers

Bio-based polymers frequently resemble fossil-based plastics in structure. Since these polymers share and have the same qualities as their petrol-based predecessors, they are easily interchangeable [22]. Bioplastics are usually composed of sugar cane, corn, or starch, and may comprise little petroleum or oil [23]. Bio-based materials can be characterised as renewable. Traditional polymers, on the other hand, are created from diminished fossil fuels, contributing to the reduction of the planet's resources [24]. The largest field of application for bio-based plastics is packaging, including both flexible and rigid packaging [25]. Bio-based films for flexible packaging include Bio-PE (Polyethylene), Bio-PP (Polypropylene) and Bio-PET (polyethene terephthalate) [24, 25]. The resulting bioplastics are chemically equal to their fossil counterparts [23]. Unlike regular PE, which is made from fossil fuels, bio-based PE is made from renewable resources like plants, with sugar cane used most [24]. The majority of bio-based PE is produced in Brazil (Braskem), in a manufacturing site that has a 200-kilo tonne annual capacity. Bio-PE has properties identical to petrochemical PE but is produced from ethylene from bioethanol instead of crude oil [26]. The bio-based content can start from 30% of the final produced film [27].

Polypropylene is the most important organic building block for poly-olefin production, it usually contains approximately 30% biobased content [28]. Bio-based polypropylene finds application in films used in the packaging industry. Bioethanol for bio-PP manufacturing is produced from sugar fermentation, bio-syngas, and cooking oil [29]. Borealis and Neste teamed together to start using renewable propane in Borealis PP plant, which will enable the company to initiate providing bio-based propylene and subsequently bio-PP. Moreover, LyondellBasell and Neste recently announced the production of bio-PP at a commercial scale. Finally, Mitsui Chemicals commercially produced biomass polypropylene derived from bio-based hydrocarbons using Neste technology [28, 30–32].

Another polymer used in flexible packaging is PET, which is made by polymerisation of ethylene glycol and terephthalic acid. The bio-PET currently available on the market is produced through the polymerisation of ethylene glycol obtained from biological resources, mostly from sugarcane [1]. Nonetheless, this bio-PET is an environmentally friendly choice in terms of CO_2 emissions and depletion of energy sources [26]. Bio-PET is the most apparent choice as a replacement to fossil PET, mainly because both the properties and the technology to produce, process, and manufacture bio-PET films is already known and well established. However, bio-PET development is still a long way from becoming a workable alternative to fossil-based PET, as there are still significant obstacles in producing biobased terephthalic acid efficiently [24].

However, land cultivation to produce biobased films requires 2.5 times the amount of fresh water compared to conventional films [33]. Another threat associated with bio-based plastic manufacture is the potential conflict with land utilized for food production. Nevertheless, presently this is not an important concern as bioplastic production only occupies a negligible part of global agricultural land. The benefits outweigh the drawbacks since important research is being conducted to expand the availability of bio-based plastics [34].

Biodegradable polymers

Physicochemical or biological deterioration occurs in all polymers. Oxo-degradable and hydro-degradable plastics, respectively, are engineered to decompose through oxidation and hydrolysis processes. They are typically non-biodegradable and need modifications to achieve biodegradation [22, 35]. Biodegradable packaging films are made from plastic with additives inserted during the manufacturing process. These additives are usually enzymes that help the plastic to degrade. It can be decomposed by living organisms, including bacteria or fungi under aerobic or anaerobic conditions, without harming the environment. The biodegradation rates of biopolymer materials have been reported to last between couple of days or months for most raw materials [36]. Common feature of all biodegradable plastics is requirement of a catalyst like UV light, heat, or humidity which will initiate the breakdown reaction [37,38]. Microorganisms (bacteria or fungi) can break down biodegradable plastic materials into water, naturally occurring gases like carbon dioxide (CO_2) and methane (CH_4), or biomass. Factors such as temperature, presence of microorganisms, oxygen and water are all important to facilitate biodegradability [27]. A particularly popular option to replace conversional plastic is poly lactic acid (PLA). PLA provides excellent clarity and stiffness comparable to traditional OPP. It is also biodegradable thermoplastic made from sugarcanes and corn, which are both completely renewable resources. Compared to various synthetic polymers, it can offer similar mechanical properties like high stiffness and strength [39–41].

Another new method commercially applicable is the usage of a special additive, which is added to a masterbatch of plastic resin. Packaging created from this specific resin will degrade in anaerobic conditions. Once the packaging will be disposed to a landfill, the enzymes present there will digest the film which enables the degradation of the film, while at the same time generating landfill gas. This LFG (landfill gas) can be captured by specialised systems and used as a clean and renewable energy source. Hence, these plastics can create methane in a reasonable time [42]. Biodegradable materials can be degraded by soil microbes into natural components like water, carbon dioxide, and methane [43]. To certify biodegradability, a variety of specified tests are available. Standardized tests examine time required for the biodegradation process. For the materials to be classified as biodegradable, it must pass go through a testing process such as ASTM D5511-02. It is a test method to determine the anaerobic biodegradability of plastics. In this method, conditions simulate these found in landfills [22]. Biodegradable additives can be added to any flexible packaging film including PE, PET and PP also including their variations such as metalized film [44].

Post-industrial and post-consumer recycled materials

Another sustainable way to create films for flexible packaging is through recycled resin. This resin could originate from a variety of sources and processes. PIR (post-industrial recycled) is a blend of plastic waste recovered from industrial and manufacturing processes. The post-industrial material is created during the manufacturing process. Since these wastes are generated within the industry, the composition, contamination and homogeneity of these materials are well controlled [45].

Post-consumer materials can be referred as "materials generated by households or by commercial, industrial, and institutional facilities in their role as end-users of the product that can no longer be used for its intended purpose. This includes the returns of materials from the distribution chain" [46]. Due to their geographically spread generation and the large spectrum of polymers used, the collection of post-consumer plastics is a challenging process. Packaging materials which are commonly used include PP, PET, and LDPE. These are usually collected for recycling due to their widespread use [45].

According to a recent report, the majority of recyclable collected film is either LDPE (low density polyethylene) or LLDPE (linear low density polyethylene). Collecting only food grade films is quite difficult due to logistical issues. To efficiently collect and recycle materials recyclers are trying to acquire vast quantities of mixed waste and these are possible to contain several types of PE films. Therefore, the final recycled product is possible to contain HDPE and LDPE from post-consumer films as well as films from non-food applications such as stretch film. This will result in having a contaminated recycled resin product which is not suitable for food packaging films [47].

PCR (post-consumer recycled) packaging films which content mixed plastic waste usually are not straightforwardly recyclable at the end of their life. Some petrochemical businesses employ a pyrolysis process to turn this waste into resin that may be utilized to make new products. Packaging and labelling solutions containing PCR (chemically or mechanically recycled) material are also included [48]. Post-consumer films are well-suited for chemical recycling. Pyrolysis facilities that could create raw materials would allow shipping as liquids, which are much denser than flexible packaging films [49]. This synthetic oil can then be converted into a food-grade polypropylene film, afterwards printed, and formed again as a product wrapper. This kind of raw material was used by Nestlé Australia in KitKat products [50].

There is also the term pre-consumer recycled, these are materials or by-products originated from production processes which become waste [51]. Therefore, these recycled materials are accelerating the transition to a circular economy in plastics.

Paper as an alternative approach

Paper, a versatile material, is widely utilized not only for writing and printing but also for packaging various solid goods that do not necessitate stringent barrier specifications, as mentioned by Shen et al. [52]. Among consumers, paper has gained considerable recognition as a more ecologically sound alternative to plastic. It is notably superior to plastic in terms of its biodegradability and recyclability, as asserted by Moreira [53]. Consequently, paper-based composite laminates, incorporating polymers and metal foils like aluminium, have gained popularity due to their ability to prolong the shelf life of packaged items. Furthermore, paper-based flexible packaging materials are often combined with plastic, aluminium, or coated with resin. However, this renders the paper non-recyclable [27, 53]. Conversely, the recycling process for paper is straightforward as it can be re-pulped, offering certain environmental advantages when employed as a flexible packaging substrate. When the packaged product does not require stringent barrier properties, some brands may be encouraged to replace plastic packaging with paper [53].

An example of a company that has chosen this path is Nestlé, which has decided to globally package their Smarties confectionery brand using recyclable paper packaging. This shift will eliminate approximately 250 million plastic packs sold worldwide each year [54]. The choice between sustainable flexible packaging options, whether based on paper or plastic, primarily depends on the specific application at hand. Achieving a sustainable flexible packaging sector entails a greater emphasis on developing a circular economy, reducing the number of substrates per package, improving recycling processes, and adopting flexible packing solutions that are more conducive to recycling [53].

CONCLUSIONS

The search for suitable packaging made of renewable raw materials, which at the same time protects the product, is becoming more and more attractive, especially in the food industry. Nowadays, all stakeholders are concerned with maintaining the quality and freshness of the product throughout its life cycle, which is essential for marketing and consumption purposes, while reducing the amount of plastic waste. At the same time, attempts are being made to improve food quality on a global scale by reducing plastic waste to combat environmental damage.

Packaging cannot be intangible and will continue to be present as it is essential for the preservation, storage and transport of products. A significant increase in the share in the packaging market in recent years draws the attention of the printing industry to the development prospects of this sector. Many factors, such as the need for a unique consumer experience, the widespread use of e-commerce, the trend towards sustainable development and environmental protection, as well as the evolution of digital technology, make the reformulation of packaging from a simple product container to the carrier of a whole unique experience [55].

Currently, the demand for replacing plastics derived from fossil fuels with biodegradable plastics for packaging materials is constantly growing. The development of biodegradable packaging is influenced by several variables, including policy, legislative changes, as well as global demand for food and energy resources [43]. According to recent findings, even if consumers recognize the importance of sustainable packaging materials, they are not prepared to spend more and receive a product in sustainable packaging [47]. Therefore, consumers have not yet developed sustainable purchasing behaviour [56]. This can be attributed to emerging consumer resistance to overrated environmental claims [57]. Despite conflicting arrangements for paying premiums for sustainable products, the need to ensure environmentally friendly packaging materials for future generations is unquestionable.

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