

# Research on Food Packaging and Storage

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Packaging represents a vital element of the food industry, as it must support the processing, handling, transport and distribution operations of the contained food. Traditionally, packaging materials were designed to protect and maintain the quality of food products during storage regarding external agents, such as microorganisms, water vapor, oxygen, light, etc. [1,2]. Furthermore, packaging helps to prevent the loss of desirable compounds (e.g., volatiles responsible for a product's aroma). The packaging materials used globally by the food industry include paper, metal, glass, and plastic. The latter is frequently employed in the form of mono- or multi-materials in diverse combinations [3]. Packaging and coatings have experienced impressive progress in recent decades, driven by the rising demand for safe and high-quality food [2], in addition to the need for adaptation for the circular economy.

The concept of circular economy has become ubiquitous in recent years, and is gaining increasing attention worldwide. However, an extensive portion of the packaging industry is based on a linear model in which the packaging is designed, produced, consumed, and finally disposed of. As a result, a massive amount of post-consumer waste is generated, which is a current global concern. In this sense, many research studies aim to outline the transition from a linear to a circular system through packaging design [4]. For the circularity of packaging materials, scientific and technological studies highlight: (i) improvements in packaging supply chain efficiency; (ii) reductions in the environmental impact of packaging; (iii) improvements in packaging process development; and (iv) the implications of packaging's regulatory compliance [5].

As highlighted, the main research focus of this area is to explore the environmental aspects of packaging. Reducing, reusing, and recycling represent three fundamental options within this context. The principle of reduction aims to minimize the use of raw materials, energy input and waste production, while reuse refers to the repeated use of products or components for their intended purpose. Reusing packaging is an innovation opportunity to revolutionize the way we think about packaging and is one of the possibilities to reduce the consumption of materials. Reuse can deliver significant benefits to users and businesses. Reusable and returnable packaging, reusable shipping items, returnable shipping packaging, and other similar terms are used to describe packaging that can be used for many trips over an extended period of time [6]. Recycling is primarily used to save energy, resources and emissions, reducing environmental impact. However, only some types of materials can be recycled and/or reused repeatedly for an unlimited number of times (e.g., metal and glass), and others have limited recyclability due to the loss of performance (e.g., thermoplastics, paper and cardboard) [7]. An emerging research area is related to replacing plastic packaging with paper packaging, as paper is recyclable and made from renewable sources. However, it is worth mentioning that this change in material type can lead to a reduction in the products' shelf life, since paper, even with a coating, presents lower barrier properties than plastics. Therefore, the management and processing of materials with limited recyclability have become significant issues for the scientific and industrial community, for which strategies for an economic waste cycle are being developed [8].



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Another key aspect within the packaging sustainability context is life cycle assessment (LCA). The environmental impact of the massive expansion of food systems, including packaging, will inevitably increase. Therefore, efforts will be required to reduce the harmful effects of the food production and packaging chain, including the use of LCA methodologies to ascertain the impacts of diverse products [9]. There is an elevated worldwide movement to reduce food loss since, besides the problem of hunger, it also affects environmental preservation. According to LCA studies, the impact of food loss itself is higher than the impact of final packaging disposal [10]. While food production represents about 50% of energy consumption, packaging accounts for approximately 10% [11]. Furthermore, if the emissions of greenhouse gases from the food chain are considered, agricultural production represents about 40% of CO<sub>2-eq</sub> emissions, while packaging corresponds to approximately 5% of CO<sub>2-eq</sub> emissions [12]. Therefore, the loss of food due to poor packaging design produces an exceedingly severe environmental impact compared to the packaging itself. In the industrial sphere, LCA can support decision making, especially for companies willing to minimize their environmental impacts along the production chain or even to replace their packaging with recyclable materials or renewable sources [13].

Polymers from renewable sources stand out as important renewable and biodegradable options, complying with the demand for sustainable packaging [14]. Although not biodegradable, conventional polymers from renewable sources (e.g., sugarcane), such as PE and PET, are available on the market. They can be recycled, representing a significant advantage. Numerous biological sources additionally demonstrate impressive potential for possible packaging materials. However, they still need to be widely investigated to enable an adequate relationship between performance and production cost. As examples, polysaccharides and proteins are extensively employed in the formation of films and coatings [14]. However, one of the critical challenges in packaging development based on these raw materials remains their severe sensitivity to water vapor and their poor mechanical properties [15]. To overcome the shortcomings of biopolymer-based films, various strategies, such as blending with other polymers, the incorporation of nanofillers, and bioactive compounds (e.g., essential oils, plant extracts, and/or pure active ingredients), have been proposed [16].

The incorporation of functional compounds in polymeric matrices can result in “smart/intelligent” active films and coatings which can extend the shelf life of food products. Recent active and intelligent packaging technologies allow the interaction of the packaging material with the food product. The benefits of smart packaging include: detecting defects; monitoring quality and tracking packaged food products to control storage conditions from the production stage to the consumption stage; and using various sensors and indicators such as time–temperature indicators and gas and humidity sensors [17]. Meanwhile, active packaging helps to extend the shelf life of products by using adsorption/absorption and diffusion systems for various materials, such as oxygen and ethylene scavengers, carbon dioxide absorbers/emitters, flavor release/adsorption systems, antioxidants and antimicrobials [18].

Another extremely relevant application in packaging technology that has gained prominence in recent years is modified atmosphere packaging (MAP). Fresh and minimally processed foods sustain physiological and metabolic processes after harvest, and are therefore susceptible to quality deterioration and reduced shelf life. Successful MAP design is achieved by the mathematical integration of the dynamic physiological characteristics of the product and packaging material properties, along with optimal equilibrium atmospheric conditions for the product in question [19]. The specific mixture of gases in the package in each application will depend on the type of product, packaging materials, and storage temperature [20]. In addition, the application of a vacuum in order to reduce the O<sub>2</sub> content in the packaging is an alternative method widely used. This technology is conceived by the evacuation of interstitial air that results in compression as a consequence of the vacuum [3]. Predominantly, it is widely applied to products susceptible to oxidation and processed packaged foods.

To avoid post-process contamination, several products are processed inside their packaging, and thus the packing must withstand the processing conditions. Hence, it is meaningful to understand the interactions between packaging, food, and processing. Some packaged food-processing technologies are already widely consolidated in the industry, such as pasteurization and sterilization. However, in recent years, studies have focused on innovative methods of processing packaged foods, such as high-pressure processing, microwave-assisted sterilization, irradiation, plasma, ultrasound, UV light treatments, and pulsed light, among others [21]. As these technologies utilize distinct mechanisms of action, the packaging requirements for each one of them are different and must be investigated regarding their integrity related to different processing methods, as well as their efficiency during the food's shelf life.

There are at least three situations in which a shelf life determination may be necessary: (i) to determine the shelf life of existing products; (ii) to examine the effect of specific or combination factors, such as storage temperature, packaging materials, processing parameters or food additives on the shelf life of the product; and (iii) to determine the shelf life of prototypes or newly developed products. The shelf life can be determined from the product or consumer side. On the product side, the product deterioration is investigated as a function of time and may involve the growth of undesirable microorganisms, a decrease in desired components (e.g., vitamins), or an increase in unwanted components (e.g., dark pigments or moisture). On the other hand, the consumer's side involves asking consumers to accept or reject food that has been stored for various periods of time [3].

In addition to all aspects of packaging technology and food stability, the safety of food contact materials (FCMs) must be taken into consideration for the successful application of the developed packaging. FCMs are intended for the protection and preservation of food. However, their contact with food may sometimes cause the migration of different substances previously present in the packaging, becoming vehicles for their contamination [22]. These substances include low-molecular-weight polymers, residual solvents, plasticizers, antioxidants, and monomers, among others. Therefore, the migration of these substances needs to be controlled, as they can be toxic to humans and the environment. Assessing the compliance of a package in contact with food in accordance with current legislation is extremely important, as the package must guarantee the safety, quality and compliance of the product contained therein, thus avoiding being a source of contamination, whether physical, chemical or biological [3].

Overall, contemporary developments in food packaging and safety should focus on sustainable materials towards the circular economy, with adequate properties to protect the products. Simultaneously, packaging must be safe for contact with food and economically viable. All of these requirements should not overlook the aspects equally valued by the consumer, such as convenience, functionality, and personalization. The union of these aspects may guide current and future research, with outstanding results for the benefit of the environment and society.

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