Food Wastes as Packaging Materials

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Packaging materials have to allow controlled respiration, maintain polymer structure against mechanical damage, prevent microbiological and chemical spoilage of food, and act as a selective gas and water vapor barrier. The most widely used materials in the food packaging industry are glass, plastics, metals, and paper. As mechanical properties of materials are important for food protection, mostly flexible and rigid synthetic packaging materials are preferred.

Keywords: biopolymers ; biocomposites ; edible films and coatings ; active packaging ; intelligent packaging ; food waste

1. Introduction

Food waste and food by-product generation is a significant problem that causes undesirable environmental, economic, and social effects. There is a great awareness of the severity of the problem; thus, the EU and many other countries promote action plans to decrease food wastes, such as the Farm to Fork Strategy, Circular Economy Action Plan, and EU Waste Legislation. Reduction of food waste could be an important solution to decrease production costs and lead to more efficient food systems. Furthermore, more environmentally sustainable food systems can be created, and food security and nutrition can be improved through waste reduction [1].

Valorization of food waste from industrial food processing provides many economic, social, and environmental benefits, such as the production of value-added products in different application fields such as organic fertilizers, animal feed, biofuels, and electricity [2][3]. In the last decade, many studies have been conducted for the valorization of food wastes to produce food ingredients, functional foods, nutraceuticals, pharmaceuticals, and cosmeceuticals as they contain many health promoting bioactive compounds such as polyphenols, proteins, lipids, vitamins, and dietary fiber that may improve nutritional, functional, and technological properties of the food products [4][5][6][7]. As a next eco-conscious step of waste valorization, recent studies have demonstrated that the advances in food packaging technology may be an efficient solution to reduce the amount of food waste and by-products through the utilization of waste- and by-product-derived natural materials in the food packaging industry For instance, by integrating antioxidant compounds obtained from food waste into packaging material, food products become safer and more resistant against spoilage processes.

2. Food Packaging Materials

The global demand for packaging was approximately USD 974 billion in 2018. It is expected that the value of smart packaging will reach USD 26.7 billion by 2024 followed by intelligent and active packaging systems [8]. Basically, shelf-life extension of food products is the first aim of food packaging. As mechanical properties of materials are important for food protection, mostly flexible and rigid synthetic packaging materials are preferred [9].

Despite their technological benefits, packaging materials are great sources of waste generated in the world. In 2018, approximately 77.7 million tons of packaging waste was generated. A rise of 6.7 million tons was observed in the amount of generated packaging materials in the ten years from 2008 to 2018, corresponding to an increase of 9.4%. In the EU, the highest packaging waste was generated from paper and cardboard by 40.9% (31.8 million tons), followed by plastics and glass by 19.0% (14.8 million tons) and 18.7% (14.5 million tons), respectively [10].

Approximately 60% of the plastic production was related to the food packaging industry [11]. Regulatory recycling actions have been applied for packaging plastics to reduce the environmental effect of petrochemical plastics [12]. Due to the awareness of consumers on food safety, health, and nutritional value of food products, the substitution of synthetic polymers by biopolymers and the development of sustainable food packaging systems will ensure reduction of environmental impacts and waste generation. Accordingly, in recent years the development of biodegradable polymers obtained from plant materials, which may replace petrochemical plastics, has increased.

Biodegradable packaging using biopolymer materials offers some advantages, such as being inexpensive, non-toxic, and transparent as compared to plastics. Furthermore, they are resistant to mechanical damage, and they have water vapor permeability that is useful for packaging of fresh fruit and vegetables. Biodegradable packaging has water absorption capacity and low friction coefficient, and it also acts as a barrier to odors, aromas, fats, and oils [13]. In recent years, it has become a promising trend to add natural additives, extracts, and food processing waste products, including phenolic acids, tannins, proanthocyanidins, or flavonoids, in order to improve food packaging performance.

Through the use of recycled materials and renewable resources as raw materials, reuse, recycling, and biodegradation of packaging materials, the sustainability of food packaging can be achieved. Many packaging innovations have been developed using novel bio-based materials with improved performances in order to increase the packaged product quality, extending the shelf-life and decreasing food waste [14]. Among different packaging applications, the integration of antioxidant acting compounds and/or spoilage indicators in packaging systems are reported to have great potential to reduce food wastes [15].

Significant attention has been given in recent years to find alternative polymer materials as added-value novel packaging materials through fruit and vegetable waste valorization. Accordingly, the application of fruit and vegetable wastes and by-products as food packaging materials seems to have two-sided effects. This would both reduce the amount of food packaging waste and the amount of fruit and vegetable-based waste and by-products.

3. Fruit and Vegetable Industry Wastes and By-Products

According to the report of FAO [11], 1.3 billion tons of food waste and food loss has been generated annually. This huge amount of waste and loss may occur at different stages of food processing, such as pre-harvest, harvest, on farm post-harvest, transport, storage and distribution, processing and packaging, retail, and public household consumption [16]. The cost of food waste and loss was estimated at USD 936 billion globally [17]. The agri-food industry generates a significant amount of waste and by-products, contributing to 40–50% of the total discard from different parts of plant sources such as peels, pulps, skins, pomaces, shells, roots, stems, stones, leaves, and seeds [18].

In recent years, production of fruit and vegetables has been increasing in order to meet consumer demand. Approximately 0.9 billion tons of fruits and more than 1 billion tons of vegetables were produced in 2017 [19]. Among different fruit and vegetable types, the highest amount of waste is produced from mango (60%), followed by citrus fruits (50%), passion fruit (45%), peas (40%), pineapple (33%), and pomegranate (40%). Furthermore, banana, apple, grape, potato, and tomato are other important waste sources [20][21].

The peels, pomace, and seeds of fruit and vegetables are important sources of bioactive compounds such as proteins, dietary fibers, colorants, and phytochemicals. These phytochemical compounds show a variety of beneficial health effects, including antioxidant, antimicrobial, anti-inflammatory, anti-diabetic, anti-carcinogenic, and cardioprotective effects [7][20][22][23][24].

The peel of banana, mango, avocado, citrus, and apple and pomace of grape are important sources of dietary fiber that varies between 51 and 70% [25][26][27]. On the other hand, tomato and carrot pomaces contain high amounts of fiber corresponding to 50% and 64%, respectively [20].

Peel and seeds of fruit and vegetables contain high levels of phenolic compounds, including phenolic acids, flavonoids, and tannins. Most of the by-products contain higher amounts of phenolics compared to their flesh part. For example, mango peel was found to have higher total phenolic content (92.6 mg gallic acid equivalents (GAE)/g) than its flesh (27.8 mg GAE/g), both at ripe and unripe stages [28]. For example, avocado peel contains higher phenolic content than its seed and pulp [29].

4. Food Packaging Innovation

Food packaging obtained from fruit and vegetable wastes and by-products is of great interest due to their unique characteristics. When these wastes and by-products are applied to food packaging systems, they provide many advantages such as increased antioxidant activity, antimicrobial activity, improved mechanical properties, and improved quality of protected food products. There are several studies on the incorporation of these wastes in biopolymers, biocomposites, active packaging systems, intelligent packaging systems, and edible films and coatings to test their applicability for improved packaging characteristics. Some examples of applications of fruit and vegetable wastes and by-products in different food packaging systems are given in**Table 1**.

Table 1. Application of fruit and vegetable wastes and by-products in food packaging systems.

Waste/By-Product	Packaging System	Applied Food Product	Packaging Properties	Reference
Pomegranate peel (PPE)	Active packaging—PPE at different concentrations (0, 25, 50, 75 mg/mL of film forming solution) added to zein films	Kalari cheese	inhibition of all target pathogens, ↑ antioxidant and antimicrobial activity, delay of oxidation, improved film flexibility, ↑ tensile strength	[30]
Pomegranate peel extract (PPE)	Chitosan (1% *w*/*v*) and alginate (2% *w*/*v*) edible coatings + PPE (1% *w*/*v*)	Guava	improved postharvest guava quality, delayed senescence, ↓ respiration rate, retarded oxidation, ↑ phenolic content and ascorbic acid levels	[31]
Tomato by-product extract (TBE)	TBE added to films containing poly(vinyl alcohol) (3% wt/v) and chitosan (1% wt/v)	-	improved antibacterial activity toward *S. aureus* and *P. aeruginosa*, ↑ resistance of films, ↑ antioxidant activity	[32]
Red grape seeds, white grape seeds, tomato waste extracts	stabilizers added to polypropylene (PP) films	-	red grape seed: ↑ PP stabilization and ↓ oxidation, greater than tomato extracts	[33]
Mango peel and seed kernel	Edible film-containing mango peel flour (1.09%) and glycerol (0.33%), and extract of mango seed (0.078 g/L)	Peach	↑ permeability, antioxidant activity, hydrophobicity, and surface properties, 39% less O_2 consumption, 64% less ethylene production and 29% less CO_2 production	[34]
Potato peel	Bioactive film—potato peel at different ratios of potato cull (0, 0.5, 1, and 1.3 g peel/g cull)	-	improved elongation and dose dependently, ↑ antioxidant activity, ↑ tensile strength, ↓ film solubility, ↓ moisture and water activity	[35]
Banana peel extract (BPE)	Chitosan composite film—BPE at concentrations 4%, 8%, and 12%	Apple	best results with 4% BPE, ↑ thickness, ↓ moisture content, ↓ water vapor permeability, improved mechanical properties, and postharvest apple quality	[36]
Blueberry leaf extract (BLE)	Chitosan coating + BLE (4%, 8%, 12%)	Blueberry	↓ decay of the fruit, ↓ weight loss, inhibition of target pathogens, ↑ total phenolic content	[37]
Grapefruit seed extract (GSE)	Carrageenan-based antimicrobial film + GSE at 0.6, 3.3, 6.6, 10, and 13.3 g/mL	-	↑ water vapor permeability, ↓ tensile strength, ↑ elongation, inhibition of tested pathogens, improved UV barrier property	[38]
Apple peel polyphenols (APP)	Chitosan film + APP at 0.25, 0.50, 0.75, and 1.0%	-	↑ thickness, density, swelling degree, solubility and opacity, improved water barrier property, ↑ antioxidant property, inhibition of tested pathogens	[39]
Grape seed extract (GSE)	Pea starch (3% *w*/*w*) and glycerol (1.8%) + 1% GSE	-	↑ thickness, oxygen permeability, ↓ tensile strength, ↑ antibacterial effect by phenolic acids	[40]
Green tea extract (GTE)Pectin from citrus fruits	Pectin and polyethylene glycol + 0.5 g/100 mL GTE	Pork patties	↓ lipid peroxidation, ↑ radical scavenging activity, ↑ antibacterial effect	[41]
Red cabbage	PVA/chitosan hydrogel + 25% (*v*/*v*) anthocyanin extract from red cabbage	Milk	pH-sensitive color change for spoilage detection	[42]
Lycium ruthenicum Murr (LR)	Starch and glycerol + 0, 1, 2, and 4 wt % anthocyanins from LR	Pork	↑ thickness, ↓ moisture content, ↑ scavenging activity, pH-sensitive color change for spoilage detection	[43]
Red cabbage	PVA/starch solution + 23% (*v*/*v*) anthocyanin extract from red cabbage and boric acid and 0.5, 2, 5, 10, and 20% propolis extract	-	↑ tensile strength, ↑ moisture retention, ↑ antibacterial effect, pH-sensitive color change for spoilage detection	[44]

Due to reasons including the current global consumption of plastics and the regaining of biopolymers to utilize them in the fabrication of biodegradable materials, there has been increasing interest to utilize alternative raw materials from agricultural and food processing wastes in food packaging applications [45]. Biopolymers, called renewable polymers, can be classified into four categories: (I) biomass-based polymers, particularly from agro-resources, including polysaccharides (starches, lignocellulosic products, pectins, gums), lipids and protein (casein, whey, collagen/gelatin, zein, soy, and gluten), (II) polymers obtained by microbial conversion (poly(hydroxyl alkanoates) (PHAs)), (III) polymers chemically synthesized using monomers obtained from agro-resources (poly(lactic acid) (PLA)), and (IV) polymers obtained by chemical synthesis from fossil resources (aliphatic co-polyesters, aromatic co-polyesters) [46]. Among others, in this review we focused on the use of fruit and vegetable by-products including starches, cellulose derivatives, and pectin.

Starch has been considered as one of the most promising polymeric hydrocarbons and is composed of a mixture of two types of glucose polymers: 20–25% amylose, and 75–80% amylopectin. Starch can be used as a filler, coating, or film due to its easy availability, abundance, biodegradability, lower cost, and good mechanical properties, providing a mixture with conventional polymers and ease of processing by the equipment used in conventional polymer processing, including extrusion and injection molding [47]. In addition to these, starch presents thermoplastic behavior. On the other hand, it is not possible to use thermoplastic starch widely because of its moisture sensitivity and poor mechanical properties.

It is biodegradable, recyclable, renewable, biocompatible, and comparatively highly endurable [48]; therefore, it can be used in coatings, laminates, films, additives in construction products, nanocomposites, and pharmaceuticals [49]. The structure of cellulose is related to the isolation process, quantity of inter- and intramolecular hydrogen bonds, and degree of polymerization and crystallinity [50]. Therefore, it is transformed into cellophane film, exhibiting better mechanical properties. Furthermore, cellophane is coated to enhance its humidity barrier structures to be used for bakery products, processed meat, cheese, and candy.

Pectin, widely present in agricultural waste materials, can be altered by demethylation in the presence of calcium ions to form edible films [51]. Due to the fact that the moisture resistance of pectin films is quite low, it is limited to being utilized in food packaging. Thus, various attempts have been implemented on blending pectin and other biodegradable materials such as chitosan/pectin laminated films [52] and pectin/poly (vinyl alcohol) blends [53].

Due to concerns about environmental issues, changes in the climate pattern, as well as global warming, the production of biopolymer-based green composites and reinforcement with natural fibers have gained great attention. Thereby, the use of eco-friendly bio-based materials, including the valorization of agricultural wastes, has been currently the subject of various investigations [54][55]. Furthermore, countries such as France, Costa Rica, and Brazil have decided to withdraw the non-biodegradable plastics in the composition of disposable materials until 2020, 2021, and 2028, respectively [56].

Composite materials reinforced with synthetic fibers such as aramid, glass, and carbon fibers have a number of desirable properties including high strength, good wear resistance, reliability, and high fatigue life. Natural fibers are classified into three main categories: vegetable, animal, and mineral fibers. Fibers from vegetables or plants are then categorized as leaf fibers such as banana and pineapple; bast-based fibers like kenaf, jute, flax; and fibers from seed, including cotton, rice husk, and coir. [57] explored the kinetics of thermal decomposition of different agricultural waste fibers including banana pseudostem, pineapple leaf, and sugarcane bagasse fibers.

For instance, edible films and coatings could decrease the loss of aroma or otherwise prevent the migration of disturbing flavors of the outer atmosphere into the food [58][59]. On the other hand, the whey protein isolate had no noticeable effect on the color and texture of the food [60]. Another application of edible films is to improve the appearance or visual quality of food with high gloss coatings, especially on fruits and vegetables [58][61]. While whey protein isolates, shellac, dextrin, and zein are suitable materials for a gloss coating, zein and dextrin are more sensitive to humidity and becoming de-adhered and cracked.

After heating, plasticizers are added to the protein solution, increasing the intermolecular space between the proteins and resulting in higher flexibility of the film as well as a higher gas permeability [62]. The application as a food packaging takes place during the dehydration step by dipping or spraying; then it is termed as a coating, or alternatively the prepared solution is dried as solid sheets prior to packaging, which is termed as a film [63][64]. After that, the temperature is further increased, followed by the addition of a plasticizer, which increases the flexibility and water permeability of the coating, until the solution is finally dried for film formation [65][66]. Nevertheless, such lipid-based coatings are often combined with protein solutions due to the high inflexibility of lipids used alone as coatings or films [67].

While the use of edible films and coatings based on food wastes has been more focused, the development of a combination of edible and active packaging has also been promoted. An increased consumer demand regarding food safety also clarifies the high priority on developing active packaging for slowing down the processes of food spoilage, which may cause food poisoning [68]. While the whey protein coating significantly reduced the oxidation and served as an effective oxygen barrier, the antioxidants showed no further effect on food oxidation. As already mentioned, the second most interesting point in active packaging is the development of antimicrobial coatings.

These advantages as well as the principle of intelligent packaging must not be confused with the technique of active packaging, although both can be summarized with the term smart packaging [69]. While active packaging has a specific function on the foodstuff and protects it against influencing factors, e.g., oxidative processes, intelligent packaging measures such changes and gives this information to the consumer without influencing the food [69][70]. The focus of intelligent packaging is on the detection of gas molecules (H2, O2, NO2, and CO2) and the pH level, all factors which cannot be seen directly by the consumer and especially not if the packaging is still closed [71][70]. Hence, in several studies the combined advantages of using anthocyanins as radical scavenger and spoilage indicator in food packaging was analyzed [43][72][73].

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