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Review

Agro-Food Waste Valorization for Sustainable Bio-Based Packaging

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Abstract: In recent years, the increase in the generation of agro-food processing waste, coupled with uncontrolled disposal and inefficient recovery methods, has raised concerns among society, industries, and the research community. This issue is compounded by the accumulation of conventional synthetic packaging. Owing to their significant environmental and economic impacts, the development of sustainable, biocompatible, and biodegradable materials has become an urgent target. In this context, research efforts have been directed toward developing new packaging materials based on renewable sources, such as agro-food waste, contributing to the circular economy concept. However, despite significant advances, novel agro-food-waste-based packaging solutions still largely remain at a laboratory scale. This situation highlights the urgent need for further understanding and thorough investigation into how to upscale these products, thereby promoting engagement, investment, and awareness across various fields. This review aims to discuss the current advances in food packaging development using agro-food waste. It covers the main agro-food wastes and by-products currently recovered for sustainable packaging systems through various approaches, such as the extraction of valuable compounds or waste treatments for incorporation into packaging materials, techniques for their valorization, and recent applications of agro-food waste materials in films and coatings. It also addresses the toxicological and safety approaches, challenges, and future perspectives. After an extensive review, we conclude that current research faces challenges in transitioning novel findings to commercial scale, primarily due to safety factors, high production costs, performance deficits, legislative ambiguities, lack of consumer awareness, and inadequate governmental regulations. Consequently, significant investments in research and development appear to be mandatory in the coming years, aiming for optimized, safe, and cost-effective solutions.

Keywords: waste valorization; natural active compounds; renewable polymers; sustainable materials; bio-based films and coatings; agro-food industry

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1. Introduction

Globally, 1.3 billion tons of food is wasted each year, representing one-third of the total food produced for human consumption [1–4]. Food loss and waste represent huge socioeconomic costs, besides being a moral issue since 12% of the global population is affected by hunger. Food waste and loss are present at every stage across the food supply chain, which covers farm, postharvest, processing, distribution, retail, and consumers. Researchers around the world make a food loss estimate of 24% in production stages and more than 24% in postharvest, which is alarming [5]. As a relevant percentage of food suitable for consumption is lost or wasted along the agro-food processing chain, the food industry may have a relevant contribution to this problem. Furthermore, global food waste/loss, which includes food processing waste, represents a 4.4 Giga tons equivalent of carbon dioxide per year, which is about 8% of the total greenhouse gas emissions generated by human activity [6].

Much of this food waste/loss is used as animal feed. However, this residue has substantial potential in the development of bioplastics as an alternative to synthetic polymers derived from petroleum, thus meeting the growing demand for biopolymers [1]. Although conventional packaging derived from petrochemicals represents convenience and has exceptional barrier and mechanical properties, it leads to huge sustainability issues that impact the environment, unbalance ecosystems, and bring accumulative risks to human health. Reaching these exceptional resistance properties can make the degradation of synthetic polymers more difficult, which affects their life cycle. In general, most synthetic packaging and coating materials are discarded after only a single use and end up in the environment or landfills. Foodservice and packaging industries contribute to more than one-third of total plastic usage, and global plastic accumulation is estimated to increase by up to one-third of the current volume by 2030. In addition, some synthetic materials can release harmful compounds and partially decompose into microplastics, leading to health, safety, and toxicological risks for humans, other animals, and ecosystems, such as marine environments [7]. Synthetic plastic materials have created a huge waste management problem, and the application of new packaging technologies must consider their industrial feasibility and competitiveness, especially in terms of resistance and barrier properties, convenience, safety, and costs [6]. Thus, great efforts have been made in accelerating the development and design of sustainable alternatives for conventional packaging [7]. Table 1 summarizes the main differences when comparing conventional and bio-based packaging.

Table 1. Differentiation between conventional and bio-based packaging systems.

Characteristics	Conventional Packaging	Bio-Based Packaging	References
Source	Fossil/petrochemical, such as polyethylene and polypropylene	Natural and non-fossil materials, such as agro-food waste and biopolymers from plant or animal sources (pectin, starch, chitin, etc.)	[8,9]
Mechanical and barrier properties	Outstanding and very good market acceptance	Poor/inferior performance. However, they can be blended and/or reinforced with other materials to overcome these limitations	[7–9]
Environmental effects	High and long-term environmental impacts	Minimal environmental impact and low carbon footprint	[10]
Availability	Exhausted resources	Readily available and renewable	[7–10]
Circular economy approach	Non-sustainable, limitations for recycling, and non-biodegradable	Sustainable, biocompatible, and biodegradable materials	[9]
Applicability in food industry	Widely applicable	Limited application (most are still in a laboratory scale)	[10]
Discard perspectives	Usually discarded after only a single use and end up in the environment or landfills, which leads to globally increased synthetic plastic accumulation. Additionally, these kinds of materials can release harmful compounds and partially decompose into microplastics, leading to health, safety, and toxicological risks for humans, other animals, and ecosystems	Environmentally friendly, nontoxic, and most are completely biodegradable in the natural environment. However, migration and safety aspects need to be addressed when developing this kind of packaging	[7]

Given the unprecedented impact caused by synthetic materials over the years, the use of food waste as a bio-based raw material to produce biopolymers has proven to be a viable alternative. These new materials represent a sustainable, biocompatible, biodegradable, and nontoxic option for future plastics, leading to a progressive substitution of synthetic plastic materials [1]. Moreover, food waste valorization not only helps reduce the quantity of waste generated each year but also minimizes environmental contamination. Uncontrolled decomposition and disposal of agro-industrial waste contribute to the contamination of water, land, and air [3]. Among agro-waste, fruits, vegetables, peels, cakes, bagasse, pomaces, grains, and seeds stand out. Their potential as raw materials for obtaining natural polymers has been reported [2].

Around the world, large amounts of agro-industrial waste are generated, but only a small portion of it is valued. These residues contain a variety of nutritious substances, bioactive compounds, and materials with good film-forming abilities, among others of great relevance. The synthesis of bio-products using agro-industrial waste as a raw material aligns with the much-needed circular economy (Figure 1), thus posing an urgent challenge for researchers and industries [11]. Agro-industries, such as the cassava starch industry, produce large amounts of processing waste, which also means a waste of money, resources, labor, materials, water, and energy. These agro-industrial waste materials represent alternative sources of natural polymers and potential to be directly applied in biodegradable food packaging without any substantial procedures, which may lead to a significant reduction in time, cost, and effort [12]. Annually, 20 million tons of corn husk, a by-product of corn production, is wasted. However, corn husk is a potential alternative for nanocellulose production, as its cellulose content varies from 30 to 50%, besides being a renewable and biodegradable raw material for packaging development [13]. Banana peels have also been studied to create sustainable food packaging [14]. Brewer's spent grain is a significant by-product of beer production, generating about 20 kg per 100 L of beer produced. The European Union produces approximately 3.4 Mt of brewer's spent grain each year, which mainly ends up as animal feedstock or in landfill. However, it constitutes a rich source of fibers (cellulose, arabinoxylan, and lignin), proteins, and phenolic compounds, leading this agro-waste to be a potential alternative to produce biomaterials for food packaging in the circular economy [15].

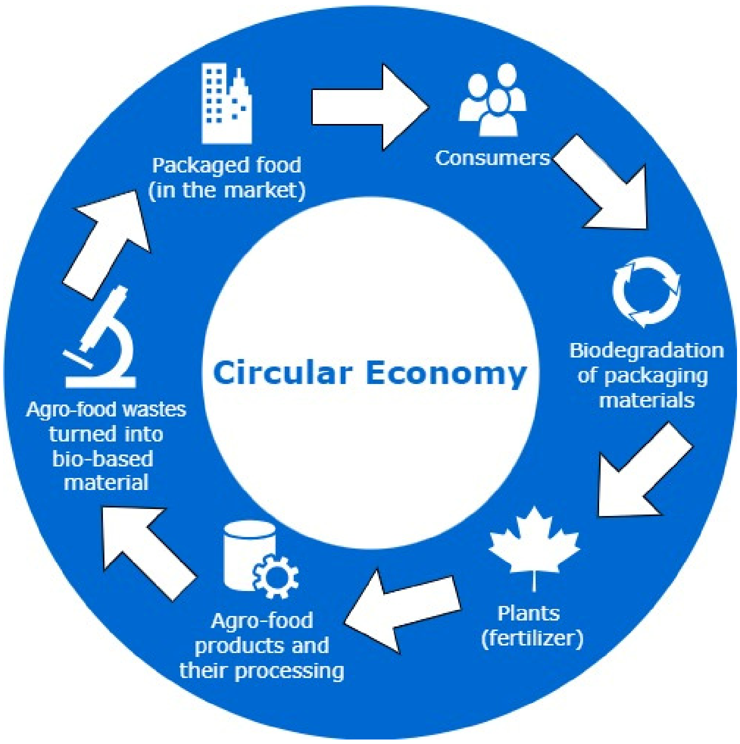

Figure 1. Circular economy for application of plant by-products/wastes in the food chain through biodegradable and sustainable packaging.

Particularly, agro-industrial residues from fruits and vegetables, which are considered biomass-rich in a variety of functional bioactive ingredients, such as carotenoids, phenolic compounds, dietary fibers, fatty acids, pigments, etc., are still underexplored, despite providing a wide availability of compounds capable of adding value and bringing innovative solutions to the food industry, such as active packaging technologies [16]. Besides phytochemicals, fruit and vegetable wastes are important sources of natural polymers, such as pectin, which constitutes about 30% of orange peel weight, for example. This renewable and abundant resource can be applied to produce active bioplastics and bio-composites, meeting the increasing demand for green solutions to petroleum-derived plastic packaging [17].

Additionally, nanotechnology approaches, such as nanocarriers, nano-processes, and a variety of nano-systems, have been included in most research in recent years. Innovative nano-encapsulation techniques protect target compounds from environmental stresses, improve long-term storage and bioavailability of natural bioactives, expand surface-area action, and contribute to overcoming the drawbacks of bio-based polymeric matrices intended to be applied as food packaging [16,18].

The recent European regulation underlines the necessity to limit plastic use, leading some researchers to propose biodegradable packaging materials produced from agro-food waste [19]. Agro-wastes from different sources, such as grape pomace, fruit and vegetable peels, sugarcane bagasse, and rice husks, have been highlighted as potential raw materials for sustainable and biodegradable polymer production due to their renewable characteristic, circular economy, and environmentally friendly approach. Production of about 90 million tons of oil equivalent (MTOE) has been generated from agricultural waste, which includes a variety of supply chains. Moreover, only a small portion of agro-waste is recovered for uses such as animal feed and manure. Furthermore, the Food and Agriculture Organization (FAO) has recognized that 20–30% of fruits and vegetables are wasted during the postharvest process [20].

Another point to consider is the low rate of recycling: less than 9% of synthetic plastic materials are produced each year (400 million tons). Drawbacks such as a lack of suitable designs, and the absence of easy, scalable, and eco-friendly methods in current recycling techniques, contribute to this low rate. Additionally, problems related to synthetic plastic accumulation, landfilling, and the accelerated growth of the global population have oriented researchers toward the production of biodegradable polymers. Two approaches have been identified to achieve this: biodegradable polymers from bio-based sources, such as agricultural waste and renewable materials, and bio-based polymers synthesized by modifying non-biodegradable polymers. However, the latter presents some limitations and has been contested due to the use of synthetic stabilizers and photo-initiators in the synthesis process, which inhibits biodegradation and UV oxidation. Given the factors mentioned above, the production of bio-based polymers from renewable sources has become crucial in the coming years, especially those based on agricultural waste, which aligns with the need for circular models and sustainability approaches [20].

Considering the above discussion, this review aims to provide a general approach to current advances in bio-based packaging that incorporate agro-food waste partially or entirely into the system. Despite significant advances in recent years, the development of most novel packages based on agro-food waste remains at a laboratory scale. Therefore, this topic should be addressed continuously and extensively, aiming for a deeper understanding and thorough investigation of what has been done and what needs to be done in this scenario to bring these materials to a commercial scale. Furthermore, an analysis of how nanotechnology has been incorporated in this context is also discussed along with the above-mentioned topics.

2. Typical Agro-Food Waste Recovered for Development of/Obtaining Valuable Materials/Compounds Intended to Be Applied in Sustainable Food Packaging

Food waste generation spans all stages of the food supply chain, from postharvest, post-production, handling, and storage, to manufacturing and processing, wholesale, and retail and, ultimately, consumption stages. Europe, annually, contributes to food waste generation with about 90 million tons, 38% of which comes from food manufacturing sectors [4]. Commodity-wise, roots, tubers, and oilseeds show the highest loss rate (25%), followed by fruits and vegetables (21%). Meat and animal products reach a loss of 12%, while cereals and pulses are only up to 8% [21].

A range of significant by-products/wastes can be found in various industries. Fruits and vegetables show up as sources of polysaccharides, antioxidants, flavonoids, phenols, carotenoids, lipids, and phytochemicals. Through animal waste, meat, seafood, and derivatives, it is possible to obtain proteins, enzymes, chitin, collagen, and gelatin, as well as being relevant nitrogen sources. Dairy products are highly indicated as carbon and nitrogen sources, while waste oil offers fatty acid, methyl esters, and glycerol. Lastly, cereal and grain industries generate a fibrous waste rich in lignin and cellulose [4].

Researchers worldwide have been dedicated to developing low-impact technologies capable of recovering such wastes and transforming them into valuable products [1]. Agro-food wastes have been studied as primary or secondary feedstock for obtaining biopolymers, through extraction or fermentation (with or without pre-treatment), and natural bioactive compounds [3]. Polysaccharides, such as starch and cellulose, are abundant in plant-based agricultural wastes, making them crucial precursors for the production of renewable natural materials. These materials are applied primarily in food packaging, tissue engineering, and bioplastic formation. Moreover, seafood debris is also a good source of natural polymers, such as chitin, which is a starting polysaccharide in chitosan biopolymer production [1]. As depicted in Figure 2, there is a broad range of biopolymers produced from different waste streams.

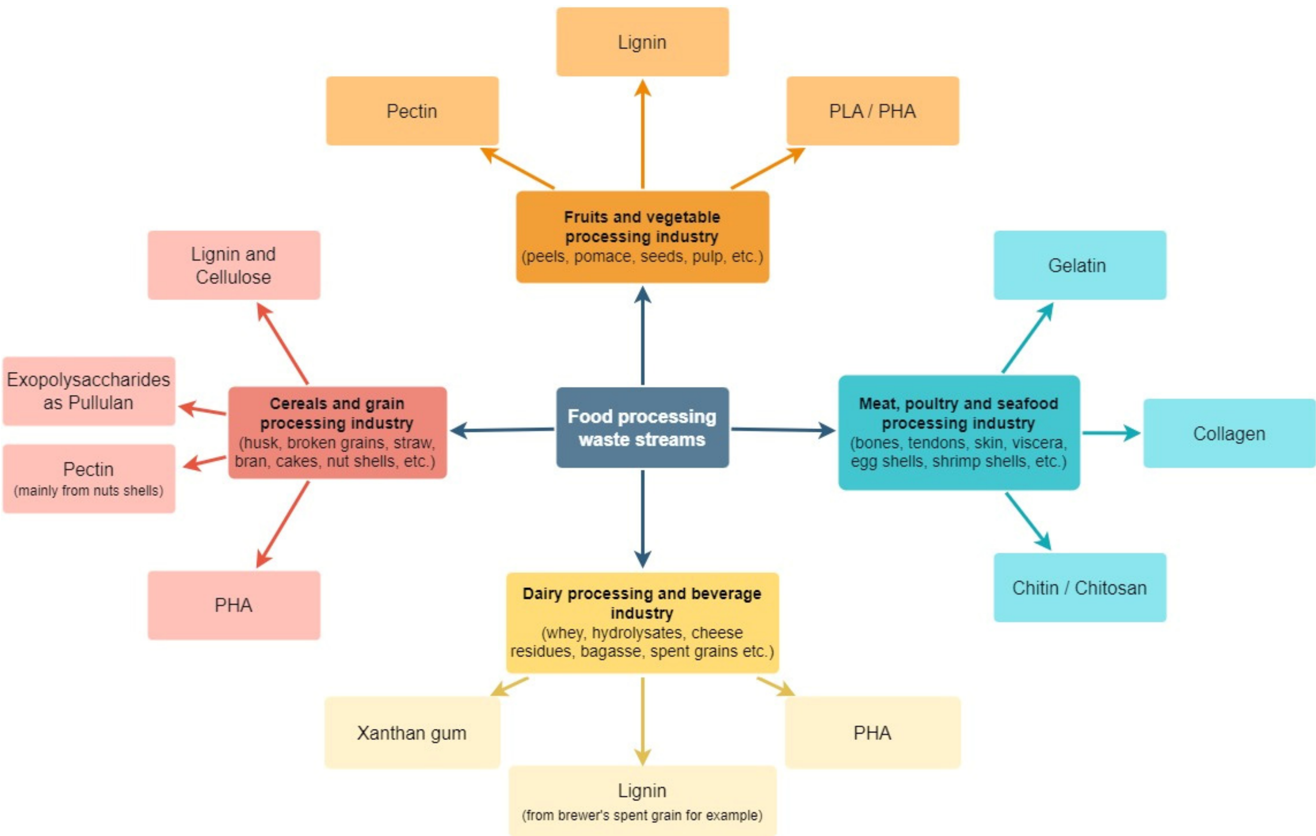

Figure 2. Biopolymers produced from different waste streams.

Agro-industrial food waste also contains a significant quantity of lipids, and this oily waste is a viable resource for the synthesis of biopolymers, acting as a carbon substrate. For instance, polyurethanes may be produced from lipids present in the food waste and then used in coating materials, foams, adhesives, etc. Dairy waste is an essential resource from which a variety of value-added products may be derived, such as whey and bioactive peptides. Protein-based biopolymers may also be produced from food waste generated during the processing of plant-based raw materials (sunflower, grains, soybean, cereal, and maize) and animal-based (collagen and gelatin). These protein-based biopolymers' properties, such as biodegradability, biocompatibility, strong mechanical strength, thermal resistance, and water resistance, make them potentially attractive for films/coatings in food packaging [1].

Therefore, agro-food wastes represent a potential research trend, and in recent years they have been applied as starting materials to produce bio-based plastics, as well as antioxidant and antimicrobial compounds, plasticizers, proteins, and other relevant substances, mainly focusing on sustainable packaging materials. Besides the environmental and sustainability aspect, agro-food waste is inexpensive and readily available [20]. Moreover, food waste as a raw material for bio-based packaging must undergo a pre-treatment process to improve or modify its physicochemical and biological properties, alongside a successful recovery process to convert it into value-added substances [4].

Despite their potential application in food packaging systems and importance for circular economy and environment, agro-food wastes and by-products present huge challenges that need further and detailed evaluation, such as the heterogeneity of each food waste and each food waste batch, hygiene and safety conditions, and cost-efficiency approaches. Furthermore, for industrial applications, the material must meet the protection and containment functions of food packaging, so normalization and scale-up of the production process for these waste materials still need to be deeply addressed [22,23].

Therefore, the following sections will provide a detailed description of the main agro-food wastes and by-products, including cereal-, plant-, and animal-based ones, and how they have been recovered for packaging applications as films/coatings/composite materials (see Table 2 for a detailed description), which covers bioactive compounds, polysaccharides, biopolymers, proteins, etc. Alongside this, the techniques, benefits, and challenges of waste valorization in terms of sustainable packaging, and how nanotechnology has emerged in this scenario, will also be discussed.

Table 2. Recent research on agro-food waste valorization and different approaches for its application in films and coatings.

Agro-Food Waste	Recovering Application in a Packaging Approach	Achieved Worthwhile Impacts	References
Onion, artichoke, and thistle by-products	Extracting active compounds for application in alginate-based edible packaging. Additionally, the residue after extraction was proposed as a bulk material for secondary packaging (cardboard production).	Tensile strength significantly increased by 5–21% and elongation at break by 5–12% compared to the blank film based on only alginate. In addition, preliminary studies based on visual analysis suggested higher durability and prolonged shelf-life of meat and vegetable samples treated with active packaging.	[19]
Carrot processing waste	Biodegradable bio-composites made up of carrot minimal processing waste, by optimizing its combination with hydroxypropyl methylcellulose and high-pressure micro-fluidized cellulose fibers.	The optimized formulation (containing 33 wt.% of carrot processing waste) led to biodegradable bio-composites with suitable properties for food packaging industrial applications (about 30 MPa of tensile strength, 3% elongation at break, and 2 GPa of Young's modulus). The protocol to produce this bio-composite material was successfully scaled up through a continuous casting process, with a production rate of 1.56 m^2 per hour.	[24]

Table 2. *Cont.*

Agro-Food Waste	Recovering Application in a Packaging Approach	Achieved Worthwhile Impacts	References
Mango peels	Development of active films containing mango peel extract incorporated into a fish gelatin matrix.	Significant reduction in solubility from 40 to about 20% and increasing from 7.65 to 15.78 MPa in tensile strength, compared to control films. The incorporation of mango peel extract significantly increased the total phenolic content and antioxidant activity of the produced films.	[25]
Beetroot bagasse	Active zein films incorporated with betalain extract (ultrafiltered and non-ultrafiltered) from beetroot bagasse, with potential application as active food packaging.	Films containing ultrafiltered betalain extract showed a more uniform and smoother surface, more hydrophobicity, and higher antioxidant activity than films with the non-ultrafiltered extract. However, in general, greater antioxidant activity was reached by increasing the concentration of betalains.	[26]
Citrus peel (grapefruit and lemon) wastes	Active edible films based entirely on citrus peel wastes (grapefruit peel methanolic extracts and encapsulated lemon peel extracts as sources of active compounds, and a grapefruit peel pectin matrix).	Pectin extracted from citrus peel showed better thermal stability and superior physico-chemical properties than commercial citrus pectin. The bioactive components and the optimal film formulation exhibited strong radical scavenging and antimicrobial activities against foodborne pathogens. Films containing encapsulated extract presented better tensile strength, thermal, water vapor/UV barrier properties, and soil biodegradability than films based on commercial citrus pectin. Additionally, the active films were able to inhibit the growth of *E. coli* O157:H7.	[27]
Seaweed waste	Bio-composites based on a blend of poly lactic acid (PLA) and seaweed processing waste (enriched filter cake).	Slight increase in the tensile modulus at low seaweed waste content. Additionally, according to thermal properties, the rigid amorphous phase content was enhanced in the bio-composites, suggesting the application of these wastes as fillers for biomaterials.	[28]
Lemon and fennel industrial wastes	Lemon and fennel wastes were recovered as secondary raw polysaccharide sources, with the extracted polysaccharides being exploited as natural plasticizers of sodium alginate-based films.	Significant decrease of the glass transition temperature of the polymer, an enlightened increase of elongation at break, and faster degradation kinetics of films incorporated with lemon and fennel polysaccharides.	[29]
Asparagus waste	Application of asparagus waste extract as a functional component to improve the anti-fungal activity of polysaccharide-based coatings (hydroxyethyl cellulose and sodium alginate).	The edible coatings composed by a blend of 1.0% w/v hydroxyethyl cellulose and 0.5% w/v sodium alginate were incorporated with asparagus waste extract and showed a continuous, smooth, and porous structure. Additionally, they presented favorable anti-fungal activity against *Penicillium italicum*, a significant delay in color change, reduction in weight loss, and maintenance of total phenolic and flavonoid contents.	[30]
Tomato and lemon by-products	Recovery of antioxidant compounds from lemon and tomato by-products for use as natural additives in active food packaging based on polymeric matrices (low-density polyethylene (LDPE), poly-lactic acid (PLA), and G-polymer (GP)).	The water barrier properties of PLA and GP films were significantly improved by the addition of lemon and tomato extracts. Active PLA and GP films released high amounts of polyphenolic compounds.	[31]

Table 2. *Cont.*

Agro-Food Waste	Recovering Application in a Packaging Approach	Achieved Worthwhile Impacts	References
Purple sweet potatoes and peels of dragon fruits	Development of κ-carrageenan-based pH-sensing films incorporated with anthocyanins or/and betacyanins extracted from purple sweet potatoes and peels of dragon fruits.	Betacyanins significantly improved the film's thermal stability. Both anthocyanins and betacyanins substantially improved the oxidation resistance, water vapor permeability, ammonia sensitivity, and UV-shielding performance of the films. Additionally, the films showed good color stability and feasibility as freshness indicators of pork.	[32]
Winery solid by-product (Vinasse)	Fish gelatin and/or PVA (polyvinyl alcohol) colorimetric films based on a winery solid by-product for monitoring shrimp freshness. Anthocyanins were extracted from this waste and added to the film matrices.	The incorporation of wine extract enhanced the films' flexibility. The PVA-wine extract film showed the best color stability. Furthermore, the color of all indicator films showed significant changes, suggesting their potential as intelligent packaging systems.	[33]
Grapefruit seeds	Chitosan-based colloid edible coating incorporated with grapefruit seed extract for the preservation of cherry tomato by delayed microorganism growth.	Effective inhibition and delay in growth of *Salmonella* and total mesophilic aerobes, significant *Salmonella* inactivation on cherry tomatoes, reduced CO_2 generation, retarded titratable acidity decrease during storage at 10 and 25 °C, and reduced weight loss at 25 °C. The active coating did not affect lycopene concentration, color, and sensory properties.	[34]
Wheat bran	Maize starch-based films containing wheat bran fibers as filler for the film's structure.	The tensile strength increased with the increase in wheat bran fiber content from 0 to 10% *w*/*w* (around 5.07 MPa).	[35]
Psyllium seed husk and husk flour	Edible bio-composite films based on psyllium seed, and directly prepared from psyllium seed husk and husk flour.	Psyllium husk (PH) and psyllium husk flour (PHF) acted as reinforcements in the polymeric matrix. The plasticized PH and PHF films were shown to be deformable with increased toughness due to the reinforcing effect.	[36]
Grape skin (a by-product of wine)	Development, via an extraction-free process, of pH-sensitive k-carrageenan-based intelligent films, adding anthocyanin-rich grape skin powder as the indicator.	Prepared films are shown to be highly pH-sensitive. The film turned from purple to green when total volatile basic nitrogen (TVB-N) was 14.63 mg/100 g, suggesting its potential as a pork freshness indicator.	[37]
Chickpea hull	Carboxymethyl cellulose-based active films enriched with polysaccharides from chickpea hull (CHPS).	Significant increase in tensile strength, improved thermal stability, increase in antioxidant activity (DPPH and ABTS), significant inhibitory effect against *E. coli* and *S. aureus*, and a higher CHPS concentration and inhibitory activity.	[38]
Ripe banana peel	Chitosan films are incorporated with the banana peel extract as the antioxidant and cross-linking agent. The composite coatings provided an improvement in the quality maintenance of apples.	Reduction in moisture contents, water solubility, water vapor permeability, and hydrophilicity, excellent antioxidant activity in different food simulants, and a lower respiratory rate and weight loss of apples than the fruits coated using the control solution.	[39]
Mango kernel	Mango kernel starch-based coatings were able to improve the shelf-life and contributed to a significant reduction in the oxidation rate for roasted coated almonds.	The oxidation rate was significantly low in all coated samples. The coated nuts (with sorbitol as a plasticizer) did not show any sign of deterioration during 100 days of storage at 40 °C compared to uncoated nuts, which showed rancidity just after 50 days. In sensory analysis, all coated nuts had higher scores for color, flavor, and texture than uncoated nuts.	[40]

Table 2. *Cont.*

Agro-Food Waste	Recovering Application in a Packaging Approach	Achieved Worthwhile Impacts	References
Blueberry residue	Development of intelligent films, by thermocompression, based on cassava starch and blueberry residue as pH change indicators.	Significant color change in a pH range from 2 to 12, visually perceptible, and essential for the intelligent approach in food packaging.	[41]
Coconut processing waste	Biodegradable nano-composite film based on PVA (polyvinyl alcohol) polymeric matrix and linseed/lemon oil (as active agents) and reinforced with cellulose nanofiber from coconut industry waste (coconut shells).	Significant increase in the strength (from 2.56 ± 1.18 to 6.72 ± 0.27 N/mm^2) and elongation (from 36.21 ± 7.43 to $102.44 \pm 17.59\%$) for the bio-nano-composites compared with the control (neat PVA film). Excellent biodegradability ($87.34 \pm 0.91\%$ degradation on the 45th day). Essential oils improved antioxidant properties and antimicrobial activity against foodborne pathogens.	[42]
Potato peels	Eco-friendly biodegradable PVA-based film incorporated with cellulose nanoparticles from potato peel and fennel seed oil.	Significant increase in tensile strength and reaching up to 140% in elongation. Relevant reduction in the oxygen transfer rate of the films, compared to previous literature. Enhanced antibacterial property and significantly high free radical scavenging activity.	[43]
Salicornia ramosissima waste	Research about two isolation processes to produce cellulose nanofibers from *Salicornia ramosissima* waste, with potential applicability as a reinforcing agent of polymeric composites.	Enzyme treatment was able to successfully isolate cellulose nanofibers from *Salicornia* waste, encouraging their applicability as reinforcing agents of polymeric composites.	[44]
Whole potato peel	Development of films for food packaging, based on potato peel powder reinforced with bacterial cellulose. Further addition of curcumin as the active agent.	Successful development of active films using whole potato peel incorporated with bacterial cellulose and curcumin. The incorporation of bacterial cellulose increased the mechanical properties and reduced oxygen permeability and water vapor permeability. Curcumin effectively helped to inhibit the lipid oxidation of fresh pork during 7 days of storage.	[45]

3. Agro-Food Waste Conversion Techniques Performed to Obtain Feasible Materials and Compounds Aiming at Sustainable Food Packaging Applications

Waste conversion processes aim for a partial or total liberation of target components, and increased accessibility of components such as proteins, lipids, and polysaccharides for subsequent applications. Examples include blending or cross-linking extracted biopolymers to obtain bio-based plastics for packaging, and extraction with subsequent encapsulation of bioactive compounds. Technologies used to convert food waste into feasible raw materials or to obtain relevant compounds from it include mechanical and thermal processes (e.g., ultrasound, microwaves, milling, and heating methods), chemical treatments (e.g., acid-alkali pre-treatments), biological conversion (e.g., fungal pre-treatment method), and enzymatic hydrolysis, which is the primary mechanism to breakdown polymers into their corresponding monomers and/or intermediates, converting polymeric structures into fermentable products [4]. The latter, mainly related to polyhydroxyalkanoates (PHA) production, are the fundamentals of industrial biotechnology and, thus, beyond the scope of this review.

Physical methods are usually applied as the first step to change the particle size, reduce moisture content, or separate materials for subsequent stages. Chemical pre-treatments involving acids are often used for lignocellulosic waste to increase the accessibility of these low-cost materials. Pre-treatments involving alkalis are applied to hydrolyze ester bonds between vegetal polysaccharides and lignin for solubilizing lignin. Cellulose-based bioplastics can be obtained from food waste with high cellulose content, such as peanut husks and citrus peels via physical/chemical modification [4]. Cesare Rovera et al. [46] developed a protocol based on alkali and stirring methods for extraction of high-purity cellulose and cellulose nanocrystals from different lignocellulosic agro-food wastes, such as garlic stalk, corncob, and giant cane cut-up, and from this protocol it was also possible to extract lignin fractions. Furthermore, the conversion of macro-sized cellulose to cellulose nanocrystals was carried out by acid hydrolysis. A final yield of ∼40–50% cellulose nanocrystals was obtained for all three wastes, and the authors proposed further applications in the development of new materials for food packaging. For chitin-based biopolymers, they can be produced, via physical/chemical treatments, from crustacean-processing wastes (e.g., shrimp shells). Furthermore, the biological fungal pre-treatment aids in delignification, which leads to better productivity. Importantly, a combination of different pre-treatment processes aids in improving the performance or the final yield [4].

A variety of vegetable/fruit wastes, such as peels, skin, fruit fractions, pomace, and fruit seeds, have been studied in recent years through valorization techniques. Among them, pectin is the main natural polymer recovered from fruit peels and its conventional extraction method includes high thermal and acidic (sulfuric, hydrochloric, and nitric acids) treatments, similar to other natural polymer extraction methods [47]. Sani et al. [48] extracted pectin from apple peels through an acidic treatment and applied it in the development of composite films based on potato starch/apple peel pectin/ZrO_2 nanoparticles/microencapsulated *Zataria multiflora* essential oil to be used in quail meat packaging. The same method, with a few modifications, was used by Khalil et al. [27] to extract pectin from citrus peel waste (grapefruit and lemon peel) and develop active edible films based entirely on citrus peel wastes. In addition to pectin, phenolic compounds were also extracted from the dried waste powders using different solvents, such as acetone, distilled water, ethanol, and methanol, and further encapsulated by applying maltodextrin.

Because of the environmental problems related to acidic/alkaline-extraction methods and significant energy input from high thermal treatment, novel and "green" technologies have been developed and optimized. Ultrasound-assisted extraction provides a lower energy requirement, reduced extraction duration, less solvent utilization, and enhanced yield compared to traditional techniques [47]. Shivamathi et al. [49] worked on the optimization of ultrasound-assisted extraction of pectin from custard apple peel. The extracted pectin was compared to commercially standard pectin of citrus, as well as showing improvements in gelling properties.

Non-conventional technologies also include pulse/moderate electric-field-mediated extraction that improves product quality and quantity using less energy and time. Microwave-assisted extraction, which constitutes a rapid, low-solvent, and improved yield/quality process, and enzyme-assisted extraction, which is an acid-free, low-temperature, and low-energy process, are also novel techniques for natural polymer extraction. However, the latter presents relevant challenges, such as the high cost of pure enzymes and the secondary metabolites (flavonoids and phenolic compounds) of fruit wastes may affect and limit enzyme activity. Combined strategies have also been considered to optimize these techniques and obtain bio-based materials feasible for up-scaled packaging [47]. Food waste has also been applied through the nano-reinforcement technique, acting as nano-fillers to increase the strength, barrier properties, and feasibility of bio-based materials [50].

Depending on the raw material, bio-polymeric materials can be produced through the direct application of agro-food waste (using minimum process steps), the extraction from that waste, a combination of techniques, or synthetized by microorganisms using the biomass as a nutrient source, which are the fundamentals of industrial biotechnology. Regarding the development of sustainable food packaging systems based on valorization of agro-food wastes, the main techniques applied are the recovery and extraction of value-added compounds and their incorporation into sustainable packaging systems, as well as the production of biomaterials. A variety of pre-treatments and extraction processes have been applied to separate valuable compounds, such as antioxidants and nutraceuticals, from food waste matrices, as well as additional isolation and purification steps to ensure purity and remove residues. Considering the production of biomaterials, different routes can be taken [51].

The direct use of agro-food by-products to obtain bio-based materials and biopolymers has been highlighted because of advantages such as the use of whole waste and the decreasing of process steps, waste, and the cost of production, compared to pure biopolymers extracted from agro-food sources [45]. Therefore, some of the waste generated along the agro-food industrial chain can be applied directly as a bio-based material to produce bioplastics without any specific pre-treatments or high-tech processing techniques. Xie et al. [45] produced active films using whole potato peel waste, combined with additive agents (bacterial cellulose and curcumin). The potato peel waste powder was prepared through simple steps (cleaning, drying, and grinding) and it worked as the base material for direct production of films. Their films showed improved mechanical properties and a relevant reduction in oxygen and water vapor permeability.

Another example is the co-product from the potato starch industry, known as potato protein concentrate, which can be molded by a compression process to obtain a bio-based plastic. This technique is often used to manufacture thermoset and thermoplastic polymeric composites. Another common technique used in conventional plastics' processing is injection molding, which could also be applied to some agro-food wastes, such as the by-products (press cake and meal) generated from the rapeseed oil industry [51]. Furthermore, naturally presenting polysaccharides, such as starch, cellulose, and pectin, can be extracted from the biomass for packaging applications. However, because of challenging limitations, alternatives such as blending, nanoparticle additives, cross-linking, and different modifications have been applied to these biopolymers to produce feasible materials. For example, banana peel extract has been applied as a cross-linking agent in composite coatings. The incorporation of banana peel extract resulted in a greater strengthening of the binding between phenolic compounds present in the extract and chitosan molecules. This was possible through a strong interaction between the phenolics in banana peel extract and the -NH_2 group of chitosan molecules. Overall, the incorporation of 4% of extract was capable of making the structure of the films denser and more uniform [39].

Overall, common pre-treatment techniques for agro-food waste valorization cover mechanical, thermal, biological, and chemical treatments, extraction of target compounds, as well as encapsulation of bioactive compounds, and they aim to reduce the waste size, extract target, and smaller compounds, improve their bioavailability, and eliminate inert or undesired materials. Combined processes help to achieve the intended properties of the final bio-based packaging materials or to more efficiently obtain the relevant target compounds from waste [51].

4. Potential Uses of Typical Agro-Food Waste/Residues for the Development of Sustainable Bio-Based Packaging

The conversion of agro-food waste into value-added products is gaining attention from scientific and industrial fields due to the urgent demand for renewable, cheap, and sustainable materials [52]. For example, seafood-processing waste (such as shrimp and crab shells) is a valuable source of chitosan, a crucial biopolymer for many industrial applications, including the production of films and coatings. Plant-derived polymers, such as cellulose, are another potential resource from agro-industrial waste to produce bioplastics for packaging applications [11].

Sustainable food packaging materials have been extensively studied, particularly in recent years, due to the increasing need to explore alternative routes for their development. Agro-food processing by-products have proven to be a viable resource for this. Plant-based by-products account for a significant portion of food waste generation, and they can be derived from various parts of plant systems, such as the husk, pomace, peel, skin, seed, and hull [53]. Figure 3 shows some important components of these plant wastes that have been exploited to develop biodegradable/sustainable coatings and films.

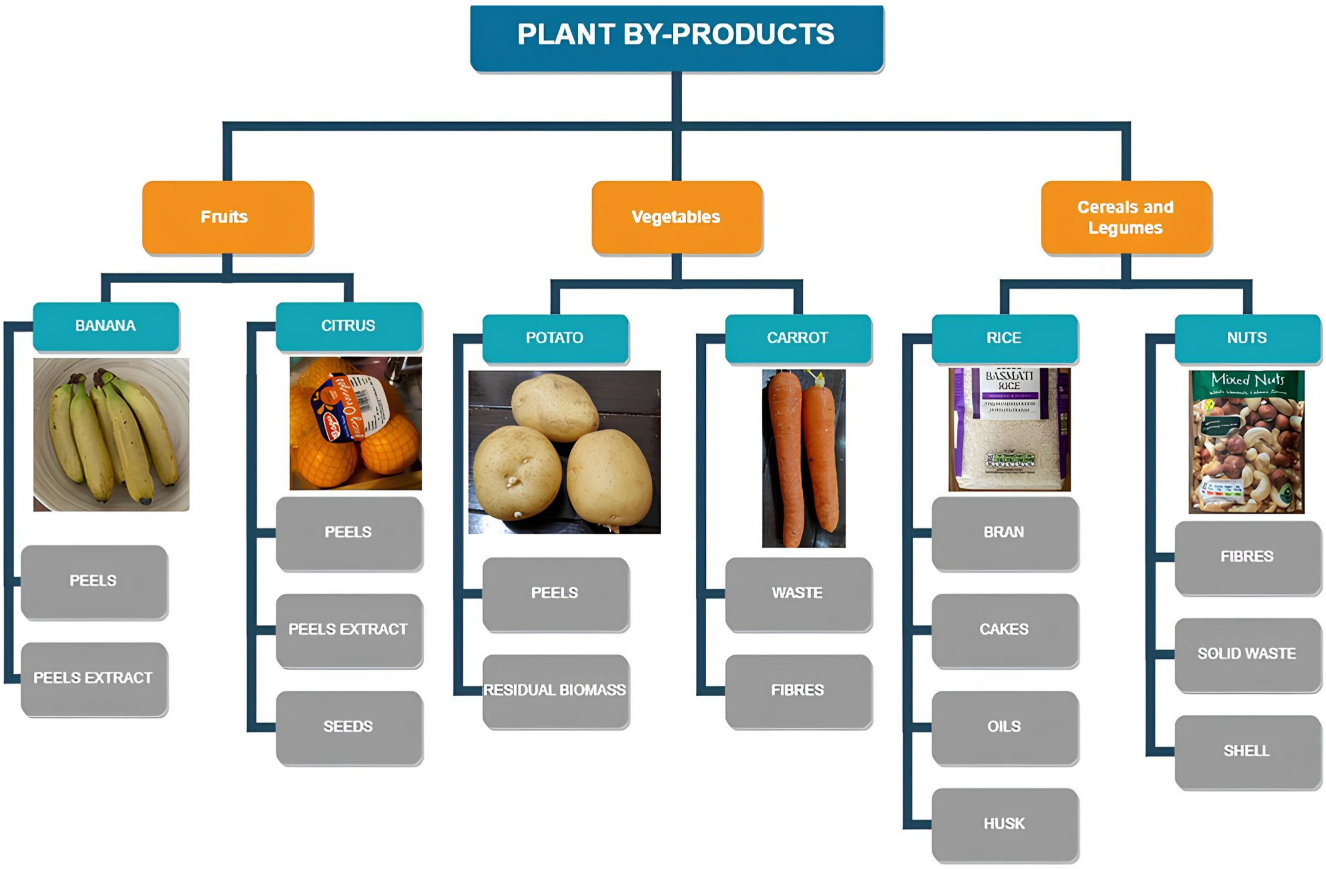

Figure 3. Components of plant-based by-products with potential application in sustainable packaging.

In the fruit and vegetable agro-industrial sectors, the generated waste represents about 42% and includes peels, seeds, skins, stems, leaves, roots, pomace, and leftovers from processing industries, which are also potential sources of a wide variety of bioactives [1,21,27]. For instance, about 40% of the total weight of a fresh banana is made up of the peel. Among tropical fruits, mango is the second-highest produce after banana, and the major by-products from mango-processing industries are mango peel and seed, which represent 35–60% of the total weight of mango fruit and can be considered a potential resource of antioxidant agents for biodegradable and edible packaging. In addition, the mango seed makes up 45–85% of the kernel, which is an inexpensive and renewable source of starch [53]. Pomegranate-processing industries generate a considerable amount of waste, such as peels, which make up about 50% of the total pomegranate weight. This undervalued waste is a potential source of bioactive compounds such as phenolic acids, flavonoids, lignans, stilbenes, and hydrolysable tannins, which have showed feasibility for being incorporated in packaging materials providing active properties [54].

Citrus fruits, one of the most popular crops globally, provide peel wastes, which are excellent sources of vitamins, polyphenols, and D-limonene. As shown in Figure 4, citrus peels have been valorized in many ways intended for packaging applications [21,27]. In addition to the antioxidant characteristics of the active compounds, they also display important health-promoting attributes, such as anti-inflammatory, cardio-protective, anti-carcinogenic, and lipid reduction effects. However, their exposure to light, heat, moisture, and acids can lead to oxidation and degradation, causing undesirable organoleptic changes. This instability can also make their application difficult in food packaging systems. To overcome this challenge and preserve the sensitive active compounds, encapsulating technologies have been applied, in addition to promoting stabilization and improving their bioavailability. Moreover, polysaccharides, such as pectin, can also be obtained from citrus fruit waste. Polymeric matrices based on citrus peel pectin play an important role in the production of active contact materials, such as edible films, composites, and coatings, adding value and promoting a sustainable approach for bio-based packaging materials [27].

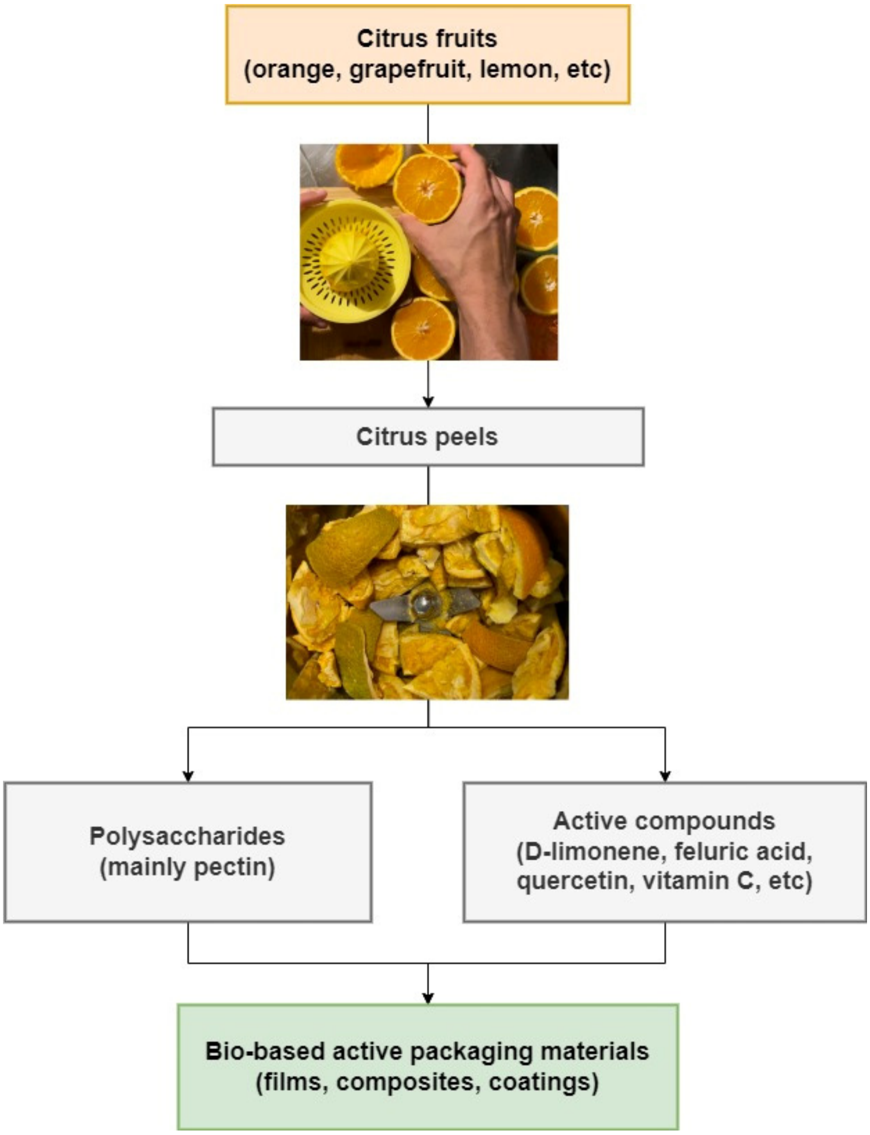

Figure 4. Scheme for valorization of citrus peels intended for packaging applications.

Given the relevance of these bioactive compounds obtained from different agro-food waste sources, nano-delivery systems have been designed for the encapsulation and protection of target active compounds and their release control, especially for applications in food packaging materials. In addition, nano-encapsulated systems have helped to improve the bioavailability of health-promoting active compounds. These nano-systems can include nanoparticles, nano-emulsions, nanocarriers, and nano-composites [54].

Based on the concept of a circular economy, increasing efforts have been made to achieve the goal of a zero-waste economy and to find sustainable processing methods to produce renewable polymeric materials instead of conventional ones, as well as obtain natural active compounds, such as essential oils and phenolic components, to be applied in functional sustainable packaging [19]. In line with this, the next sections will describe the most recent advances in the development of bio-based packaging according to the waste source applied.

4.1. Plant-Based Wastes (Roots, Tubers, Oilseeds, Fruits, and Vegetables) for Packaging Applications

Agricultural waste, particularly plant-based waste, is among the primary residues studied in recent years. Fruit pulp, pomace, oils and extracts, bagasse, seeds, and peels are examples of the variety of agro-waste resources from which various bio-based products can be derived [20]. New bio-based polymeric matrices, for example, have been developed from agro-food waste and by-products. Madera-Santana et al. [28] developed bio-composites based on a blend of polylactic acid (PLA) and seaweed waste. They found that the industrial production of agar generates a large amount of seaweed waste during the filtration stage, called filter cake, which constitutes about 70% of the raw material used. The composition of this seaweed waste mainly includes residual seaweeds enriched with cellulose, hemicellulose, and agar residues, as well as small quantities of floridean starch and diatomite earth (used as filtration aid). This makes the filter cake a valuable material for use in bio-composites.

Otoni et al. [24] optimized and scaled up the production of cellulose-reinforced biodegradable composite films made from carrot-processing waste, which is generally discarded or used as animal feed, thus being undervalued. In this study, researchers optimized the film formulation whose composition presented 1/3 of carrot-processing waste, and the produced bio-composites were shown to be feasible for industry since the manufacturing protocol was successfully scaled up through a continuous casting procedure. Di Donato et al. [29] recovered lemon and fennel wastes and used them as secondary raw polysaccharide sources. These were then extracted through green processes and applied as natural eco-friendly plasticizers in sodium alginate-based films, aiming to improve the performance of these fragile and brittle films. Brittle properties are one of biggest challenges for development of bio-based materials, and natural compounds able to improve the tensile strength, elongation at break, and plasticity of those materials should be further investigated. Another big challenge is the moisture resistance and hydrophilicity of bio-based packaging. Zhang et al. [39] developed chitosan films/coatings added with banana peel extract, which worked as antioxidant and cross-linking agents, as mentioned previously. In addition to providing excellent antioxidant activity, the extract from this waste helped to reduce moisture contents by ≅24%, water solubility by ≅25%, and water vapor permeability by ≅37%, which led to a reduced hydrophilicity. Nawab et al. [40] worked on mango kernel starch coatings, which improved the shelf-life and significantly reduced the rate of oxidation in the coated roasted almonds.

Plant-based by-products emerged as an excellent source of bioactives with antioxidant and antimicrobial activities, which have been incorporated into different polymeric matrices for active and intelligent packaging systems [53]. Melo et al. [55] produced antioxidant films using mango kernels, which are rich in polyphenols such as mangiferin and gallic acid. Kurek et al. [56] exploited blueberry and blackberry pomace as sources of polyphenols (kaempferol and quercetin) to be applied in a novel antioxidant and pH indicator film based on chitosan. Mariño-Cortegoso et al. [31] recovered antioxidant compounds from lemon and tomato by-products for application as natural additives in active food packaging constituted by polymeric matrices, such as low-density polyethylene (LDPE), PLA, and G-polymer (GP). Kamer et al. [33] extracted anthocyanins from winery solid by-products for incorporation in fish gelatin/PVA colorimetric films, aiming to monitor shrimp freshness. Other researchers worked on blueberry residue, which contains significant pH-sensitive compounds, such as anthocyanin, as a pH change indicator in cassava starch intelligent films, obtaining significant color change in a pH range from 2 to 12 [41].

Liu et al. [30] incorporated asparagus waste extract into a hydroxyethyl cellulose and sodium alginate edible coating. This natural additive functioned as a component to improve the coating's anti-fungal activity, thereby maintaining the postharvest quality parameters of strawberries and extending their shelf-life. Rodríguez-Félix et al. [26] developed active zein films incorporated with betalain extract from beetroot bagasse, identifying the potential of this extract to stimulate the active characteristic of the packaging. Won et al. [34] incorporated grapefruit seed extract into chitosan-based coatings, and this active agent inhibited and delayed growth of *Salmonella* and total mesophilic aerobes, as well as significant *Salmonella* inactivation on coated cherry tomatoes. They highlighted that climacteric fruits such as cherry tomatoes are typically ripened and senesce during the postharvest process, in addition to being highly susceptible to foodborne pathogens. Therefore, finding solutions that can control the growth of microorganisms, maintain quality, and delay ripening/weight loss is a critical target for this industry.

Gao et al. [32] developed κ-carrageenan-based pH-sensing films for application as a freshness indicator for pork. To achieve this, they incorporated anthocyanins and/or betacyanins extracted from purple sweet potatoes and dragon fruit peels into the films. Dash et al. [57] worked on edible biodegradable films made of sweet potato starch and lemon waste pectin matrix incorporated with TiO_2 nanoparticles, which exhibited UV prevention capacity. Yu et al. [18] studied the production of nanocellulose from various biomass wastes (forest, agricultural, algae waste, and industrial by-products) and their potential applications in high-value products. Among them, green nanomaterials with excellent performance in the composite material formulation can be widely applied in the food packaging field. The authors also highlighted other relevant applications for nanocellulose, such as papermaking, adhesives, reinforcing agents, thermoplastics, and biomedical composites.

Recent research has focused mainly on maximizing or completely recovering/reusing agro-food wastes. Khalil et al. [27] developed active, edible food packaging based entirely on citrus peel waste. The film formulations included grapefruit peel extracts and encapsulated lemon peel extracts as sources of active compounds, and the basis for the film/coating was a grapefruit peel pectin matrix. The bioactive additives demonstrated strong antioxidant properties and remarkable antimicrobial activities against four strains of *E. coli* O157:H7, and contributed to enhancing the tensile strength, thermal, water vapor/UV barrier properties, and soil biodegradability of the produced films. Y. Liu et al. [58] recovered potato starch from potato peel waste and modified it into cationic starch to use as the polymeric matrix for composite films/coatings loaded with curcumin. The authors concluded that this composite material showed potential as bioactive packaging and as an alternative to minimize agricultural waste disposal. Charles et al. [59] developed biodegradable edible films based on potato peel starch with potential use in packing perishable and cooled foods. Jiang et al. [60] developed a novel multifunctional film using peel waste of white-fleshed pitaya (*Hylocereus* spp.) through a combination of the pitaya peel pectin working as a biopolymer and the pitaya peel betacyanins as the active components. The developed material showed promising potential as a color-tool packaging for monitoring the freshness of shrimps. Furthermore, Torres et al. [61] worked on the integral valorization of potato waste (flesh, peels, skin, and processing wastewaters) through the biorefinery concept, to recover starch and bioactive compounds for non-food and food applications, such as edible coatings.

In view of the nanotechnology approach, research efforts have been dedicated to producing nano-systems from various agro-food waste resources able to enhance mainly mechanical and barrier properties, as, in general, biodegradable polymer-based materials exhibit deficient mechanical and barrier properties compared to synthetic petroleum-based materials. Therefore, nano-fillers from natural and renewable sources such as agro-food waste have been used in composites to overcome the limitations of these biodegradable polymeric matrices [42,62]. For instance, R. Arun et al. [42] developed biodegradable nano-composite films for food packaging, whose formulation included cellulose nanofibers from coconut industry waste (coconut shells). These nanofibers worked as reinforcement agents and helped to reach a significant increase in the strength and elongation of the developed composites. Ramesh and Radhakrishnan [43] achieved improvements in the oxygen barrier properties, tensile strength, and elongation properties of the PVA-based films by incorporation with cellulose nanoparticles from potato peel and fennel seed oil. Minimizing the gas transfer rate, such as oxygen and carbon dioxide, is considered another significant goal during development of bio-based films and coatings, especially to control the respiration rate in fruits and vegetables.

Due to a greater surface-to-volume ratio, nano-composites provide a denser and more compact structure, leading to less free volume compared to non-nanoscale composites. Furthermore, nanosized compounds are significantly more reactive than their macro- or micro-scale counterparts. As such, a smaller number of nanomaterials is required to achieve certain effects on a coating or film than would be for larger-sized components. Through nanoscience and nanotechnology, it is possible to produce nanoscale (1–100 nm) materials with superior properties, such as improvements in mechanical, thermal, and barrier functionalities [62]. Currently, research studies are focusing on developing nanocarriers/nanomaterials that can enhance foods' shelf-life without causing adverse effects on living organisms or environmental systems [63].

However, despite significant advances over the past few years, a major challenge remains: to devise a feasible process that delivers performance and properties on a commercial scale, comparable to existing materials. Then, huge efforts and investments need to be made through research areas and industrial sectors to find effective solutions for recovery of these wastes into valuable and sustainable materials for society [20].

4.2. Cereal and Legume Residues (Rice, Maize, Wheat, Barley, and Soybean) for Packaging Applications

Cereal by-products, rich nutritional sources, are still underexploited and mainly applied as feed, bio-refinery substrates, or even wasted. Thus, new solutions have been targeted by cereal-processing industries to minimize their waste volume and obtain valuable materials, which includes sustainable packaging applications [35,36,64].

Cereal by-products are mainly generated from the milling industry. At earlier stages of processing, before milling, all cereal seeds that do not fit the standard grading are discarded and addressed to a by-product called "grain screenings". Following the cereal milling step, the main by-product is the cereal bran composed of coat seeds and an aleurone layer. Furthermore, depending on the mill used, size fractions' separation, and grinding process, different by-products can be obtained from the cereal-processing industry [36,64].

Rice bran is one of the most relevant by-products generated after polishing brown rice, and contains significant amounts of dietary fibers, essential fatty acids, polyphenols, and antioxidants. In addition, their oils and cakes, such as rice bran oil, constitute cereal by-products rich in unsaturated fatty acids and phytochemicals with significant antioxidant activity, which could be applied in active food packaging systems. Dry and wet milling are the two main methods to process maize, and both produce relevant by-products for the production of bio-based materials. Dry milling generates residual cereal by-products known as maize cake and maize bran fraction. The latter represents a potential source of polymers (heteroxylans and cellulose) and phenolic acids (ferulic and diferulic acid), a potential alternative as active agents or for natural polyesters' production. In addition, maize fibers and proteins are produced as residual content in the wet milling technique, and those compounds can also be applied in bio-based packaging systems in many different ways, such as reinforcement agents or protein-based films [64].

Fu et al. [35] produced maize starch-based films containing wheat bran fibers as fillers. Tóth and Halász [36] worked on edible bio-composite films based on psyllium seed husk and husk flour as reinforcements in a polymeric matrix, which led to development of deformable films with increased toughness. Chi et al. [37] studied an extraction-free process to create a pH-sensitive, k-carrageenan-based intelligent film, with grape skin powder as an indicator agent.

Another important resource for bio-based systems are the by-products resulting from the barley-processing industry, being the fine flour and course meal milling by-products from pearled barley and spent grain from brewing. A variety of cereal resources, such as oat husk residues, have been studied for the production of cellulose nano-systems to be used as reinforcing agents in bio-composites for packaging applications. Regarding cereal brans, such as wheat bran, they could provide a source of phenolic compounds for active packaging systems. Moreover, lignocellulosic by-products, straw, and bran have shown great results as starting materials for the co-production of enzymes and bioplastic production, with possible application in compression molding techniques intended to obtain bio-based packaging systems [64].

The nuts industry also provides a relevant number of by-products, for example, almond hulls. Hulls can be a source of fibers, lignin, protein, tannins, and phenolic compounds, and polysaccharides such as pectin [65]. Akhtar et al. [38] developed carboxymethyl cellulose-based films enriched with polysaccharides from chickpea hull, which delivered an increase in tensile strength and antioxidant properties, improvements in thermal stability, and a significant inhibitory effect against *E. coli* and *S. aureus*.

Legume by-products can also be an outstanding resource to obtain bio-based materials. Soybean waste has been studied as an abundant protein source that can be processed through widespread techniques, such as compression molding, injection molding, extrusion, 3D printing, and electrostatic spinning, to obtain protein bioplastics for packaging [66].

4.3. Animal-Based Wastes (Meat and Dairy Products) for Packaging Applications

In Europe alone, more than 20 million metric tons of animal waste are generated per year. Most of this waste has traditionally been used as fertilizer or animal feed. However, animal-based waste constitutes a valuable source of proteins and other relevant compounds [21]. By-products of meat industry processing include blood, skin, horns, bones, and viscera. These waste products are rich in proteins and can be used to provide additional antimicrobial and antioxidant properties through hydrolyzed peptides to a wide range of materials, with the aim of extending foods' shelf-life. For instance, collagen and gelatin are two crucial components that can be obtained from meat-based waste. Furthermore, another main animal-based waste with great potential for production of biomaterials is seafood waste, which involves shells (from shrimp, crabs, etc.), skin, fish bones, viscera, and other by-products. These by-products can provide valuable products, such as oils, omega-3, fatty acids, and polymers such as chitin, and all these compounds are valuable resources for active and sustainable food packaging systems [67].

A relevant role is also played by the dairy industrial sector when regarding food waste generation. In addition, since they are rich in organic content and then easily spoiled, this waste creates a significant issue from environmental and human health perspectives. In view of this, extensive research efforts have been carried out aiming to develop novel and feasible processes for dairy waste valorization [1], including routes for production of bio-based materials that could be applied for novel packaging systems. One of the most significant wastes in dairy industries is whey, which is a by-product of cheese production. Whey content includes carbohydrates, bioactive peptides, prebiotics, lactose, fats, proteins, minerals, vitamins, and many other high-value compounds [21,67]. This composition makes whey a valuable candidate for development of bio-based systems. For instance, whey has been successfully applied to develop milk protein-based active edible packaging systems as edible films/coatings in food products [68]. Abedi et al. [69] developed an edible coating based on whey protein concentrate and rosemary essential oil to extend the shelf-life of fresh spinach. The developed material was able to decrease the total microbial and coliform growth. Andrade et al. [70] produced an active whey-protein-based coating incorporated with seaweed extract, which was able to inhibit lipid oxidation in chicken breasts for a 25-day storage period [21,71].

5. Toxicological, Safety, and Migration Aspects Related to Development of Novel Sustainable Packaging Based on Agro-Food Waste Valorization Approaches

There has been a significant increase in interest in recycling, reusing, and recovering food by-products and waste due to the circular economy approach and environmental concerns related to waste mismanagement. Achieving these goals involves the valorization of waste/by-products across a wide range of applications and fields. However, reintegrating these materials into the food chain requires thorough and careful evaluation of processes to ensure their suitability, feasibility, and above all, consumer safety and health. Presently, EU food safety regulations mandate that modified or new materials based on valorized residues comply with established requirements as non-hazardous products for human consumption, which also applies to those aimed at animal feed. While many studies focus on extracting nutrients and bioactive compounds from food by-products and waste, few of them deeply evaluate safety aspects, which limits their application at the industrial level. Assurance of quality and safety, including toxicological and migration aspects, is a crucial step for this type of research [67].

Food contact packaging materials address risks related to safety and health aspects, and these should be carefully examined and thoroughly monitored to prevent toxic, carcinogenic, and harmful compounds in food. Migration is influenced by a variety of factors, such as the type of contact, duration, temperature, nature of packaging material, nature of migrant substances, and concentration of these migrants in the packaging. Therefore, the application of antioxidants, pigments, and bio-based polymers should consider this concern, and deeply evaluate all migration routes and factors related to the novel packaging materials [72].

Most safety assessments performed by researchers in the food industry cover physicochemical and quality studies, such as solubility, mechanical and barrier properties, color, and texture, microbiological tests concerning foodborne pathogens, such as *Salmonella*, *Listeria*, and *E. coli*, and evaluations of contaminants, including pesticides, metals, toxins, and the migration of hazardous organic/inorganic compounds. In addition, cytotoxicity and mutagenic activity must be taken into consideration [67].

Another concern in this field is the potential toxicity when compounds are nanosized. Some researchers question whether certain safe compounds could become toxic at the nanoscale, leading to doubts about whether these nanomaterials should be specifically regulated. The lack of sufficient scientific data gives rise to relevant concerns about the toxicity, behavior, and bioaccumulation of these new materials/compounds. Therefore, further research should be conducted to deeply assess the risk and exposure associated with the application of nanoscale materials. This will not only support their efficacy but also ensure their safety [54]. Despite the significant progress of nanomaterials in the last few years, their toxicity, accumulation, and safety aspects remain uncertain. Nanoparticle food applications are increasing at a rate faster than they should be, without the necessary knowledge and proper regulations and standardization. In addition to public engagement and participation, safe and useful food products, including food packaging systems, will only be achieved through a better understanding of the characteristics surrounding these nanomaterials (mainly nature, size, and composition), exposure levels to them, and individual sensitivity. Cellular toxicity can be reached according to the composition and shape of each nanomaterial, through a variety of mechanisms [73]. Therefore, a deep investigation of components' migration from food contact packaging into food products must be carried out upon the development of novel food packaging materials to ensure food safety and integrity, as well as consumer health and environmental assurance [74].

6. The Challenge of Developing Bio-Based Materials for Packaging

Successful research outcomes have demonstrated the potential for the application of agro-food waste by-products and wastes for the packaging industry. However, the development of bio-based materials from these resources is still facing challenges related to, for example, functionality, food application, performance properties, and costs for up-scaling the process to an industrial approach [23,64], adding to the complexity and multicomponent systems of this novel developed packaging [7].

Treatment processes for agro-waste valorization contribute to increasing these costs and influence economic and commercial feasibility [66]. Furthermore, most agro-food wastes and by-products are very susceptible to deterioration and spoilage because of the high moisture content, and the presence of fermentable sugars and proteins, leading to a limited shelf-life and increased environmental contamination, in addition to the heterogeneity/seasonality related to agro-food wastes/by-products [15]. Therefore, potential solutions, aiming to develop commercial sustainable packaging systems, are based on thorough research and development to optimize industrial processes, exploring cost-effective production technologies, and financial support for bio-based packaging initiatives. Table 3 shows the main challenges that remain in agro-food waste valorization for bio-based packaging, as well as potential solutions and future prospects.

Table 3. Challenges, potential solutions, and future prospects in agro-food waste valorization for bio-based packaging.

Challenges	Detailed Explanation	Potential Solutions	Future Prospects	References
High production costs	The chemical complexity, fermentation or extraction conditions, and treatment processes for product recovery contribute to high production costs.	Research and development to optimize processes, exploring cost-effective production technologies, and financial support for bio-based packaging initiatives.	Development and implementation of more efficient production technologies, availability of financial incentives and subsidies for bio-based packaging, and establishment of economically viable business models.	[23]
Lower performance characteristics compared to conventional materials	Bio-based materials for food packaging currently show inferior barrier and mechanical properties when compared to conventional materials.	Innovation in material science to improve the quality of bio-based materials, and modification of existing materials to enhance performance.	Advanced bio-based materials that match or exceed the performance of conventional materials, and market acceptance of improved bio-based packaging.	[7]
Availability and seasonality of agro-food waste/by-products	The availability of agro-food wastes and by-products varies based on factors such as crop seasonality, geographic location, and waste management practices.	Strategic planning and coordination across the supply chain, developing innovative storage solutions, and broadening the range of feedstocks for bio-based packaging.	Diversification of feedstock sources, technological advancements in waste/by-product storage and preservation, and improved coordination in agro-food waste supply chains.	[15]
Legislative ambiguity	Current laws and regulations concerning bio-based materials and waste valorization can be unclear or inadequate, creating uncertainty and potential barriers to development.	Active policy advocacy to clarify and improve regulations, collaborative engagement with regulators and policymakers, and development of industry standards for bio-based packaging.	Establishment of clear, comprehensive, and supportive regulations for the use and production of bio-based packaging, widespread adoption of industry standards, and increased collaboration between industry, regulators, and policymakers.	[15]

Table 3. *Cont.*

Challenges	Detailed Explanation	Potential Solutions	Future Prospects	References
Lack of consumer awareness and acceptance	Many consumers may not be aware of the benefits of bio-based packaging or may have concerns about its safety and effectiveness.	Launching educational campaigns to raise consumer awareness, demonstrating the safety and performance of bio-based packaging through rigorous testing and certification.	Increased consumer acceptance and demand for bio-based packaging, and greater public understanding of waste valorization and the benefits of bio-based materials.	[75]
Limited infrastructure for collection and processing of agro-food waste	Many regions may lack the necessary infrastructure to collect and process agro-food waste on a large scale, posing logistical challenges.	Investment in infrastructure development, promoting decentralized waste collection and processing, and fostering partnerships between government, industry, and waste management entities.	Establishment of robust and efficient infrastructure for agro-food waste collection and processing, and development of localized and sustainable waste management practices.	[76]
Technological constraints in waste treatment and conversion	Existing technologies may not be sufficiently effective or efficient in treating and converting agro-food waste into usable materials for packaging.	Advancements in waste treatment and conversion technologies, promoting research and innovation in this area.	Breakthroughs in waste treatment and conversion technologies, making the process of producing bio-based packaging more efficient and viable.	[77]

Compared to conventional packaging, bio-based materials still present limitations related to barrier (gas/moisture) and mechanical properties. Therefore, potential innovations have been proposed to overcome their inferior performance, such as blending, multilayer configuration, nano-composites, and modifications in current materials or technologies [7]. Another significant barrier to the development of bio-based packaging is legislation ambiguity and unclear standards for this kind of material, which contributes to delays in the process of development and adoption of agro-food waste-derived packaging materials [15].

Consumer acceptance and awareness should also be deeply evaluated in relation to how consumers react to the reuse of biological nutrients and the insertion of waste-to-value products in the food area. This could accelerate the introduction of agro-food waste in future packaging materials, leading to more cost-effective and industrial-scale production of bio-based materials. In general, consumers' points of view are affected by demographic variables, gender and age effects, sustainable orientation, safety perceptions, etc. Research has shown that information and discussion on this subject can lead to a positive attitude toward waste-to-value products, so transparent and proper communication, such as educational campaigns, may help consumers to become familiarized with these new technologies [75].

This sustainable-oriented transformation will also require more investment and optimization of physical infrastructure systems for the collection and processing of agro-food waste, and human infrastructure, covering the front-line workers until reaching governance, industry, and institutions [76]. Moreover, the current methods of processing and converting agro-food wastes and by-products into feasible packaging materials are still at a laboratory scale, so there is an urgent appeal for advancements in waste treatment and conversion technologies [77].

7. Conclusions

Agro-food waste valorization has emerged as a compelling strategy to address the mounting global waste crisis. By transforming waste from diverse sectors, such as agriculture, the dairy industry, fisheries, and the citrus sector, a wealth of valuable materials can be produced. These range from bioactive compounds, nanocellulose, and even biopolymers for packaging applications, thereby contributing to a more sustainable, circular economy. Additionally, this approach carries profound implications for environmental conservation, human health, and potential economic benefits. However, this innovative pathway is not without challenges. Paramount among these are potential safety concerns, particularly when these waste-derived products are destined for reintroduction into the food chain. Rigorous safety assessments that encompass toxicological and migration aspects are, therefore, crucial to ensure consumer safety and acceptance. Moreover, the development of biodegradable and bio-based polymers for packaging from agro-food waste, despite its substantial promise, confronts significant obstacles. High production costs and performance deficits compared to conventional materials constitute primary barriers. Therefore, significant investments in research and development are imperative, focusing on cost reductions, process optimization, and enhancements in the functional properties of bio-based materials. Legislative ambiguities and the lack of clarity also represent formidable challenges, highlighting the urgent need for clear, comprehensive, and supportive regulations. The broad-scale adoption of innovative waste recovery technologies and the circular economy model will significantly shape the trajectory of this field. Equally important are initiatives aimed at enhancing consumer awareness and encouraging governmental regulations that foster large-scale commercial production. Looking ahead, advancements in agro-food waste valorization are poised to be transformative. These advances will not only further progress toward a sustainable future but will also expand the applications of waste valorization. Through continued research, innovative technology, and supportive policies, the future of agro-food waste valorization is indeed bright.

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