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ACTIVE BIODEGRADABLE FILMS FROM FRUIT WASTE: A REVIEW OF ADVANCES AND APPLICATIONS

FILMES BIODEGRADÁVEIS ATIVOS A PARTIR DE RESÍDUOS DE FRUTAS: UMA REVISÃO SOBRE AVANÇOS E APLICAÇÕES

PELÍCULAS BIODEGRADABLES ACTIVAS A PARTIR DE RESIDUOS DE FRUTAS: UNA REVISIÓN DE AVANCES Y APLICACIONES

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ABSTRACT
Due to the harmful effects of excessive plastic packaging on the environment, there is a growing demand for sustainable alternatives in the food industry. This article provides a comprehensive review of the progress made in the development of biodegradable and active films produced from fruit waste, with a specific focus on the integration of antioxidant and antimicrobial compounds. The research was conducted through the ScienceDirect platform and MDPI in December 2024, leading to the identification of nine relevant studies. The results suggest that agricultural byproducts, including peels, pulps, and seeds, are valuable sources of bioactive compounds capable of providing functionality to packaging, resulting in increased shelf life and reduced use of synthetic additives. The casting technique was widely used in the studies, demonstrating its efficiency in integrating natural additives. Despite significant advances, few studies have tested the direct application of the films to food, highlighting a gap in the practical validation of these technologies. Nevertheless, the findings reinforce the potential of these materials as a viable and environmentally friendly alternative to conventional plastic packaging.

Keywords: Biodegradable Packaging. Fruit Waste. Bioactive Compounds. Sustainability.

RESUMO
Devido aos efeitos prejudiciais das embalagens plásticas excessivas no meio ambiente, há uma demanda crescente por alternativas sustentáveis na indústria de alimentos. Este artigo fornece uma revisão abrangente do progresso feito no desenvolvimento de filmes biodegradáveis e ativos produzidos com resíduos de frutas, com um foco específico na integração de compostos antioxidantes e antimicrobianos. A pesquisa foi realizada por meio da plataforma ScienceDirect e MDPI em dezembro de 2024, levando à identificação de nove

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estudos relevantes. Os resultados sugerem que os subprodutos agrícolas, incluindo cascas, polpas e sementes, são fontes valiosas de compostos bioativos capazes de proporcionar funcionalidade às embalagens, resultando no aumento da vida de prateleira e na diminuição do uso de aditivos sintéticos. A técnica de casting foi amplamente empregada nos estudos, mostrando sua eficiência na integração de aditivos naturais. Apesar dos avanços significativos, poucos estudos realizaram testes de aplicação direta dos filmes em alimentos, o que evidencia uma lacuna na validação prática dessas tecnologias. Ainda assim, os achados reforçam o potencial desses materiais como alternativa viável e ecológica às embalagens plásticas convencionais.

Palavras-chave: Embalagens Biodegradáveis. Resíduos de Frutas. Compostos Bioativos. Sustentabilidade.

RESUMEN

Debido a los efectos nocivos del exceso de envases de plástico en el medio ambiente, existe una creciente demanda de alternativas sostenibles en la industria alimentaria. Este artículo ofrece una revisión exhaustiva de los avances en el desarrollo de películas biodegradables y activas producidas a partir de residuos de fruta, con especial atención a la integración de compuestos antioxidantes y antimicrobianos. La investigación, realizada a través de la plataforma ScienceDirect y MDPI en diciembre de 2024, permitió identificar nueve estudios relevantes. Los resultados sugieren que los subproductos agrícolas, como cáscaras, pulpas y semillas, son fuentes valiosas de compuestos bioactivos capaces de aportar funcionalidad a los envases, lo que resulta en una mayor vida útil y una reducción del uso de aditivos sintéticos. La técnica de fundición se utilizó ampliamente en los estudios, demostrando su eficacia en la integración de aditivos naturales. A pesar de los avances significativos, pocos estudios han probado la aplicación directa de las películas a los alimentos, lo que pone de manifiesto una brecha en la validación práctica de estas tecnologías. No obstante, los hallazgos refuerzan el potencial de estos materiales como una alternativa viable y respetuosa con el medio ambiente a los envases de plástico convencionales.

Palabras clave: Envases Biodegradables. Residuos de Fruta. Compuestos Bioactivos. Sostenibilidad.

1 INTRODUCTION

In the food industry, packaging plays a key role, being a decisive element in the consumer's purchase intention, as it represents the first point of contact with the product. In addition to influencing consumer perception and transmitting essential information, packaging also ensures the protection of food against chemical, physical, and biological agents, preserving its quality and integrity during storage and transportation (Dirpan, Ainani, & Djalal, 2023; Cheng, et al. 2024).

In the face of contemporary environmental challenges, the choice of material for packaging manufacturing has become a growing concern in the food industry. Petroleum-based synthetic plastics stand out as the most widely used materials due to their strength, low cost, and durability. However, it is estimated that more than 300 million tons of plastic waste are generated annually worldwide, with a significant portion coming from single-use food packaging. This high volume of waste represents a serious environmental threat, since these materials degrade slowly, accumulate in ecosystems, and generate microplastics that contaminate soils, water bodies, and fauna (Cheng, et al. 2024).

In this scenario, the search for more sustainable solutions for packaging has intensified, driving research and innovations in the food industry. Biodegradable packaging has emerged as a sustainable alternative to conventional plastics. In addition, active packaging has gained prominence for its ability to interact with food, contributing to the increase of shelf life, the preservation of organoleptic characteristics and the improvement of the mechanical properties of the films. This is given by the incorporation of bioactive compounds in the matrix or surface of the material, such as antioxidant and antimicrobial agents, which act to control microbial growth and reduce oxidation, ensuring greater safety and quality of packaged foods (Dirpan, Ainani, Djalal, 2023; Kola & Carvalho, 2023; Soleimanzadeh, et al. 2024).

In this context, several natural sources, often considered agro-industrial waste, have been explored as sustainable and effective alternatives to improve the functionality of food packaging. Studies indicate that components extracted from fruits, seeds, peels, and pulps, often classified as waste, represent rich sources of polyphenols, flavonoids, tocopherols, and others. These molecules have antioxidant and antimicrobial properties that can be incorporated into packaging, reducing or even eliminating the need for artificial preservatives in food. This approach not only adds value to industrial by-products but also contributes to the reduction of waste and the development of more sustainable and efficient packaging systems (Soleimanzadeh, et al. 2024; Gupta, et al. 2024; Rather, et al. 2023).

Thus, the present work aimed to research, compile and analyze scientific advances on the use of fruits and their residues in active packaging, highlighting the form of application of antioxidant and/or antimicrobial compounds, the incorporation methods, the challenges faced and the future perspectives for the development of more sustainable and effective solutions in the food industry.

2 MATERIALS AND METHODS

This article presents an exploratory literature review conducted in December 2024, using the ScienceDirect and MDPI platform. The following descriptors were used in the search "Application fruit film", "Active packaging fruit" and "Application fruit antioxidant packaging", considering articles published in the last 10 years. After the initial screening, 10 articles that were in accordance with the researched theme were selected, and the others were discarded from the analysis. The research focused on identifying promising results related to the development of active packaging, the varieties of fruits and residues used, the application of antioxidant and/or antimicrobial compounds from the product, and the form of application.

3 RESULTS AND DISCUSSIONS

At first, this work provides an overview of the theme considering the main sub-items, as follows. Soon after, a specific item is pointed out about the application of waste in packaging, which is the main focus of this research.

3.1 AGRO-INDUSTRIAL WASTE AND BY-PRODUCTS

Despite advances in reducing food waste, it is estimated that approximately 33% of global food production is lost or wasted annually, totaling about 1.6 billion tons, according to the FAO (Food and Agriculture Organization of the United Nations) (Gupta, et al. 2024).

Food losses and waste occur in various stages of processing and can be classified as by-products or agro-industrial waste. In relation to the processing of horticultural products, the residues comprise between 25 and 30% of peels, seeds, crushed pulp, among others (Rifna; Misra & Dwivedi, 2021; Gupta, et al. 2024).

However, these by-products have promising applications in food engineering due to the presence of phenolic compounds, flavonoids, carotenoids, and anthocyanins, which confer antioxidant and antibacterial properties, making them potential alternatives for application in the food industry, especially in the development of biodegradable packaging (Gupta, et al. 2024; Yun, et al. 2023).

3.2 ACTIVE AND MECHANICAL PROPERTIES

Natural polymers are fundamental for the composition and functioning of packaging, providing mechanical resistance and efficient barriers against oxygen and moisture, but alone they do not have bioactive functions. On the other hand, the inclusion of fruits and/or their by-products offers active properties, due to the presence of bioactive compounds, such as antioxidants and antimicrobial agents. These compounds not only improve food preservation, but also make the films ideal for sustainable packaging. In addition, they stand out for their mechanical strength, biodegradability, and bioactive properties (Gupta, et al. 2024; Ali, et al. 2024).

Antioxidant properties are responsible for inhibiting food oxidation and the generation of free radicals, which triggers food degradation. Similarly, antimicrobial compounds limit the growth of undesirable microorganisms. These properties favor food preservation and reduce the use of food preservatives (Gupta, et al. 2024; Munekata, et al. 2023).

3.2.1 Application of food waste in packaging

Table 1 presents the comparison between the studies analyzed according to the type and amount of fruit analyzed, the technique used, the form of application and some mechanical properties of the films. Regarding the technique used, all the articles developed the films by the casting technique, which consists of the preparation of a film-forming solution, that is, a solvent and biopolymeric materials are used, such as polysaccharides (cellulose, chitosan and starch), proteins (gelatin and casein) and lipids (waxes and fatty acids). After preparation the solution is poured onto a flat surface, the solvent is evaporated by drying, which results in the formation of the film. This technique also allows for the creation of functional layers and the addition of additives (lipids, antimicrobials, and plasticizers) (Cheng, et al. 2024; Prakoso, Indiarto & Utama, 2023).

The studies researched the enrichment of biodegradable films with different fruits and forms of application. In general, the articles sought to use fruits rich in bioactive properties and the applications varied from extract and direct application of dry residue (ground or freeze-dried powder). For example, Kurek, et al. (2021) used blackcurrant residue as an antioxidant source and anthocyanins for the films. While, Yun, et al. (2023) used freeze-dried peels of citrus fruits such as orange, pomelo, lemon, and tangerine and Santos, et al. (2023) used typical Brazilian fruits as a way to add value to by-products and produce an alternative to plastic packaging. In addition, the application of myrtle, pomegranate, papaya and jackfruit, banana peel, avocado residues, jatoba pulp, blackberry pulp, prickly pear peel and pulp can also be mentioned. The amounts of fruit applied varied according to the form of application, the fruit used and the formulation used.

Table 1

Comparison between fruits and waste used, form of application and quantity applied in biodegradable films

Applied Fruit	Form of application	Technique used	Amount of fruit applied	Film thickness (mm)	Water vapour permeability ($^{10\text{-}10}$g m^{-1} s-1 $^{Pa\text{-}1}$)[a] or (g mm/m^2 day kPa)[b]	Author
Chilean myrtle fruit (*Ugni Molinae*)	Extract obtained with 50% ethanol. Final concentration of 100 mg myrtle/mL	Casting	2.5 mL of extract to methylcellulose weight ratio (0.25:1)			Dicastillo, et al. 2016
Residue of blackcurrant (*Ribes Nigrum*)	Freeze-dried and sieved residue (180 microns)	Casting	10-20 % of the bagasse used in relation to FSS (film-forming suspensions)	0.047 - 0.145	2.82 - 3.97A	Kurek, et al. 2021
Pomegranate, papaya and jackfruit peels	Peels dried at 30 °C for 24 h, ground and sieved	Casting	0-9 % (w/v)	0.11 - 0.25		Hanani. et al. 2018
Citrus peels: Orange (*C. sinensis), lemon (C. limon*),	Freeze-dried, ground and sieved peels	Casting	4.6 g of each fruit	0.124 - 0.157	1.34 - 1.92A	Yun, et al. 2023

pomelo (*C. maxima*) and tangerine (*C. reticulate Blanco*)	(100 mesh)					
Residue of araçá (*Psidium cattleianum*), guabiroba (*Campomanesia xanthocarpa*), butiá (*Butia eriospatha*) and uvaia (*Eugenia uvalha*)	Extract: the residues were lyophilized (20 g) and extracted with 100 mL of 80 % ethanol. The extract was passed through the rotaevaporator and centrifuge.	Casting	10 mL	0.11 - 0.20		Santos, et al. 2023
Banana peel	Banana peel extract: the peels were frozen in liquid nitrogen and pulverized. The extract was prepared using 100 g of powder with 500 mL of ethanol and 0.1 % of HCl and a rotary evaporator.	Casting	4, 8 and 12 %	0.051 - 0.080	1.05 - 1.67a	Zhang, Li & Jiang. 2020
Jatoba Pulp	Dried and crushed Jatoba pulp	Casting	5-7 g/0.1 mL solution	0.09 - 0.021	0.32 - 4.05b	Alves-Silva, Romani & Martins, 2022
Blackberry pulp	Fresh blackberry pulp	Casting	0, 20, 30 and 40 % (mass of solids/mass of dry starch)	0.065 - 0.133	3.62 - 4.60b	Nogueira, et al. 2019
Peel and pulp of prickly pear (*Opuntia-ficus indica*)	Added to the movie in two ways: -Directly: Dried and ground peels and pulps (10%, w/v)	Casting	10 %	53.73 - 108.20	2.37 - 4.81a	Kurek, et al. 2021

	-Extract: the pulp and peel powder has been dissolved in acetic acid (1%, w/v) or water					
Camu-camu residue	Extract of camu-camu residue dried at 50°C for 24h. Two concentrations were applied 0.25 and 0.5 g	Casting	0.25-0.5g	0,02-0,08	1.146-2.712b	Naves, et al. 2024

Yun et al. (2023) produced biodegradable films using freeze-dried citrus peels (orange, lemon, pomelo, and tangerine) as a polymer and antioxidant agent. They studied its application in edible oils in order to evaluate the oxidation stability. The films showed good mechanical properties and low permeability of water vapor and oxygen, high antioxidant and antimicrobial capacity, since it delayed the oxidation of corn oil. The films produced with tangerine peel stood out due to their high antioxidant capacity, barrier against light and oxidation.

Kurek et al. (2021) enriched chitosan and pectin films with lyophilized residue of blackcurrant, observed that the antioxidant activity of the films increased by up to 30 times, while the tensile strength and elongation at break decreased due to the insoluble particles of the residue.

Naves et al. (2024) produced films using camu-camu residue extract and obtained satisfactory results of antioxidants. In addition, he observed that the increase in the concentration of the extract in the film directly implies an increase in the permeability of water vapor, which can be justified by the glucose molecule present in the fruit, which has a high affinity for water. On the other hand, the samples enriched with the extract showed higher degradability in the 30-day period, compared to the others.

In another study, when incorporating pomegranate, papaya and jackfruit peel powder into gelatin/polyethylene bilayer film, Humani et al. (2018) observed that films from pomegranate peel powder had higher antioxidant and antimicrobial activities compared to the others. The thickness and moisture of the film increased, while the water solubility decreased. On the other hand, Zhang, Li & Jiang (2020) analyzed chitosan-based films with the addition of banana peel extract and found reductions in moisture, water solubility, and water vapor permeability. The films have also demonstrated high antioxidant activity, making it a sustainable and promising alternative as active packaging.

Using Brazilian fruit extract applied in biodegradable films, Santos et al. (2023) analyzed that films produced with butiá extract had reduced mechanical resistance and greater elongation, while films with uvaia had less impact on mechanical properties. The authors also observed a release of the film's antioxidants, which they said favors food preservation. In addition, the films showed antimicrobial activity against Listeria monocytogenes, L. inoccua, B. cereus and S. aureu. This shows that the native Brazilian fruit is a viable alternative for the extraction of bioactive compounds and for the production of active films.

Alves-Silva, Romani & Martins (2022) investigated the mechanical properties of glycerol-based films enriched with jatoba pulp. The increase in the concentration of jatoba promoted a significant improvement in tensile strength, with a 4-fold and 1.7-fold increase in elongation. Another important point is the biodegradability analysis, the films demonstrated a complete degradation in a period of seven days when exposed to different environments, such as seawater, soil and beach sand, evidencing its potential as a biodegradable material.

Nogueira et al. (2019) noted an increase in thickness, elongation, water vapor permeability, solubility, and decreased tensile strength in films produced with arrowroot starch enriched with blackberry pulp Fresh.

Kurek, et al. (2021) applied extract and powder of Opuntia-ficus indica In chitosan and pectin films, they observed that the films enriched with extract had higher antioxidant potential (1000 mg AGA/100 g), with some mechanical changes, but the films enriched with the powder had more significant changes in thickness, moisture, solubility, oxygen permeability and water vapor.

In view of these results, the potential of horticultural by-products as raw material for the development of active packaging is evident, promoting a sustainable and functional alternative to conventional packaging. The incorporation of these by-products into biodegradable films has demonstrated significant benefits, such as improved antioxidant and antimicrobial properties, favoring food preservation, and reducing the need for synthetic additives. In addition, the diversification of the sources of waste used, covering different fruits and extraction techniques, expands the possibilities of application and optimization of formulations.

Another point analyzed is that, in addition to the importance of biodegradability analysis to effectively prove the degradation of packaging in a short period of time and under different environmental conditions, the relevance of carrying out tests of direct application of packaging in food products is highlighted. Such tests are essential to evaluate the actual performance of the films under practical conditions of use, including their efficacy in food preservation, physicochemical stability, release of bioactive compounds, and possible interactions with the food matrix. However, it was observed that, among the articles selected in this review, only one study performed the practical application of active films in foods, more specifically in edible oils, evaluating the oxidative stability of the product. The scarcity of applied studies highlights an important gap in the literature, since most research remains restricted to the development and physicochemical and mechanical characterization of films under controlled laboratory conditions. Thus, the inclusion of application tests in real foods is essential to validate the technological potential of these materials and ensure their functional and commercial viability, in addition to contributing to regulation and acceptance by industrial sectors and consumers.

In this context, it is essential to continue research aimed at characterizing the by-products used, in order to understand their chemical composition, structure and behavior in different polymeric matrices. This information is fundamental for the development and optimization of biodegradable film formulations, allowing the improvement of their mechanical, functional and bioactive properties. In addition, studies that evaluate the practical applicability of these materials, especially in direct contact with food, are essential to validate their performance and feasibility in real contexts of use, contributing to the consolidation of sustainable solutions in the packaging industry.

4 CONCLUSION

The incorporation of fruit waste in the production of biodegradable films and active ingredients represents a promising alternative to conventional plastic packaging, combining sustainability with the valorization of agro-industrial by-products. These residues are rich sources of bioactive compounds, which confer antioxidant and antimicrobial properties to the films, favoring food preservation.

According to the studies, the casting technique proved to be effective for the incorporation of these compounds, allowing the obtaining of films with good functional properties. However, the scarcity of applied studies and biodegradability analyses in real conditions highlights the need for future research that evaluates the practical performance of these materials, aiming at their technological and commercial viability.

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