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Valorization of food industry by-products: bioactive compounds including phenolic flavonoids, alkaloids, and their biological activities for sustainable applications

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Abstract

Food products are among the most widely consumed products worldwide , resulting in the generation of enormous quantities of by-products and waste, such as peels, seeds, and pulp. These materials are often regarded as mere waste to be disposed of, despite containing high-value bioactive compounds such as phenolic compounds, flavonoids, and alkaloids that exhibit diverse biological properties.

Through a comprehensive review of the scientific literature, this work addresses the valorization of food industry by-products as sustainable and rich sources of bioactive compounds with multiple biological properties, including antioxidant, antimicrobial, and anti-inflammatory activities, as well as neuroprotective potential and prebiotic properties. It also reviews the most important green extraction techniques used to recover these compounds as sustainable and environmentally friendly alternatives to conventional extraction methods. To illustrate the significance of this approach, three case studies drawn from published scientific articles are presented, focusing on the extraction of bioactive compounds from spent coffee grounds, citrus peels, and red onion skins using various green extraction techniques.

The findings demonstrate that food industry by-products represent valuable sources of bioactive compounds with promising applications in the food, pharmaceutical, cosmetic, and other sectors. These results confirm the importance of valorizing such waste and converting it into value-added products, thereby contributing to the reinforcement of circular economy principles and the achievement of sustainable development goals.

Keywords: by-product valorization, bioactive compounds, phenolic compounds, flavonoids, alkaloids, green extraction, circular economy, sustainable development.

Résumé

L’industrie alimentaire est l’un des secteurs les plus consommateurs à l’échelle mondiale, ce qui entraine la production de quantités considérables de sous-produits et de déchets, tels que les pelures, les graines et les pulpes. Ces matières sont souvent considérées comme de simples déchets à éliminer, bien qu'elles contiennent des composés bioactifs de grande valeur, tels que les composés phénoliques, les flavonoïdes et les alcaloïdes, qui se distinguent par diverses propriétés biologiques.

À travers une revue bibliographique exhaustive, ce travail aborde la valorisation des sous-produits des industries alimentaires en tant que sources durables et riches en composés bioactifs aux multiples propriétés biologiques, notamment les activités antioxydantes, antimicrobiennes et anti-inflammatoires, ainsi que leurs potentiels neuroprotecteurs et leurs propriétés prébiotiques. Ce travail passe également en revue les principales techniques d'extraction vertes utilisées pour récupérer ces composés, en tant qu'alternatives durables et respectueuses de l'environnement par rapport aux méthodes d'extraction traditionnelles. Pour illustrer l'importance de cette approche, trois études de cas issues d'articles scientifiques publiés ont été présentées, portant sur l'extraction de composés bioactifs à partir de marc de café usagé, d'écorces d'agrumes et d'écorces d'oignon rouge, à l'aide de différentes techniques d'extraction vertes.

Les résultats ont montré que les sous-produits des industries alimentaires représentent des sources précieuses de composés bioactifs, offrant des applications prometteuses dans les domaines alimentaire, pharmaceutique, cosmétique et autres. Ces résultats confirment l'importance de valoriser ces déchets et de les transformer en produits à valeur ajoutée, contribuant ainsi au renforcement des principes de l'économie circulaire et à la réalisation des objectifs de développement durable.

Mots-clés : valorisation des sous-produits, composés bioactifs, composés phénoliques, flavonoïdes, alcaloïdes, extraction verte, économie circulaire, développement durable.

ملخص

تُعدّ الصناعات الغذائية من أكثر المنتجات استهلاكًا ، مما يؤدي إلى إنتاج كميات هائلة من المنتجات الثانوية والمخلّفات، مثل القشور والبذور واللبّ .وغالبًا ما تُعتبر هذه المواد مجرد نفايات يتم التخلص منها، رغم احتوائها على مركبات حيوية فعّالة ذات قيمة عالية، مثل المركبات الفينولية والفلافونويدات والقلويدات، والتي تتميز بخصائص بيولوجية متنوعة.

من خلال مراجعة شاملة للأدبيات العلمية، يتناول هذا العمل تثمين المنتجات الثانوية للصناعات الغذائية باعتبارها مصادر مستدامة وغنية بالمركبات الحيوية الفعّالة ذات الخصائص البيولوجية المتعددة، بما في ذلك الأنشطة المضادة للأكسدة، والمضادة للميكروبات، والمضادة للالتهابات، بالإضافة إلى إمكاناتها الوقائية العصبية وخصائصها البريبيوتيكية .كما يستعرض هذا العمل أهم تقنيات الاستخلاص الخضراء المستخدمة لاسترجاع هذه المركبات باعتبارها بدائل مستدامة وصديقة للبيئة مقارنةً بطرق الاستخلاص التقليدية .ولتوضيح أهمية هذه المقاربة، تم عرض ثلاث دراسات حالة مستخلصة من مقالات علمية منشورة، تناولت استخلاص المركبات الحيوية من بقايا القهوة، وقشور الحمضيات، وقشور البصل الأحمر باستخدام تقنيات استخلاص خضراء مختلفة.

وقد أظهرت النتائج أن المنتجات الثانوية للصناعات الغذائية تمثل مصادر قيّمة للمركبات الحيوية الفعّالة، ذات تطبيقات واعدة في المجالات الغذائية والدوائية والتجميلية وغيرها .وتؤكد هذه النتائج أهمية تثمين هذه المخلفات وتحويلها إلى منتجات ذات قيمة مضافة، بما يساهم في تعزيز مبادئ الاقتصاد الدائري وتحقيق أهداف التنمية المستدامة.

الكلمات المفتاحية :تثمين المنتجات الثانوية، المركبات الحيوية الفعّالة، المركبات الفينولية، الفلافونويدات، القلويدات، الاستخلاص الأخضر، الاقتصاد الدائري، التنمية المستدامة.

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1. Introduction

The context of this narrative is set within a dynamic global market, shaped by agricultural expansion and mounting environmental concerns. Due to the intensification of production and the evolution of household goods, a substantial volume of by-products is generated throughout the value chain, extending to the final consumption process. This situation has led to systemic challenges, including significant issues in waste management, pollution, and various ecological stressors. As natural resources are depleted, the urgent need to minimize the environmental footprint is driving a decisive shift toward more sustainable and circular production models.

The circular economy concept emerges as an indispensable solution, aiming to reintegrate by-products into the production cycle by the second year at the latest. Furthermore, scientific research shows that these materials are rich in bioactive compounds, such as polyphenols, flavonoids, and alkaloids, which possess valuable biological properties(Ingallina et *al.*, 2025) This shift is driving significant growth across various industries, including agriculture, pharmaceuticals, and cosmetics(Yadav et *al.*, 2024).

This initiative exists at the intersection of environmental, economic, and scientific disciplines. Its primary aspiration is to develop innovative solutions that facilitate resource valorization, transforming raw materials and by-products into high-value assets. By bridging these sectors, we can optimize the utility of our resources and devices, ultimately providing a robust framework for sustainable development.

For decades, the agricultural industry has been defined by a linear production model centered on a "producer, consumer, disposal" cycle. This system generates massive quantities of standardized products with minimal added value, leading to severe economic, environmental, and sanitary constraints. Today, a fundamental paradigm shift is required—one that moves beyond treating residues simply as wasteand instead recognizes them as strategic resources rich in bioactive compounds. Extensive research into agri-food by-products, such as peels, seeds, cocoa husks, and rice cakes, has revealed significant concentrations of polyphenols, flavonoids, alkaloids, carotenoids, tannins, and vitamins. These molecules possess remarkable biological properties, including antioxidant and anti-inflammatory activities, which are highly valuable for industrial success. The valorization of

these by-products involves extracting, purifying, and exploiting these functional compounds for use as active principles in the pharmaceutical sector and natural active ingredients in the cosmetics industry. This approach significantly reduces the depletion of natural resources and minimizes waste generation. By aligning innovation with the logic of a circular economy, we transform environmental challenges into sources of wealth and creativity, contributing to the more rational and responsible management of resources. These bioactive agents serve as essential integrators across different sectors, providing functional ingredients for the agri-food industry and active components for specialized devices. Ultimately, this integration creates new economic value chains that limit the over-exploitation of the natural environment while maximizing the utility of every cell of biological matter.(Zhao et *al*., 2018).

The agricultural industry inevitably leads to the formation of by-products such as peels, seeds, cores, pulp, and processing residues which serve as a rich source of bioactive compounds. These natural molecules exert beneficial effects on human health and possess significant potential for industrial application. Polyphenols, including flavonoids and phenolic acids, are the principal compounds identified for their essential antioxidant, anti-inflammatory, and antimicrobial properties. These are highly concentrated in the peels of fruits such as citrus, apples, and pomegranates (Ajila et *al*., 2007).

Furthermore, these by-products include alkaloids, which are nitrogenous molecules with diverse biological and pharmacological activities, ranging from analgesic and stimulant effects to potential anti-cancer properties. Other bioactive substances found in high concentrations include carotenoids, tannins, and vitamins (specifically vitamins C and E), alongside various dietary fibers. These compounds play a fundamental role in protecting the body against oxidative stress and preventing various chronic diseases.(Silva et *al*., 2014).

The richness and diversity of these compositions in food by-products are essential for valorization across multiple domains, including the formulation of functional food ingredients, the development of pharmaceutical products, and the design of natural cosmetics. However, the success of these applications depends on the implementation of specialized extraction and stabilization methods, which must be carefully adapted to safeguard the biological activity and overall efficiency of these molecules.(Joseph et *al*., 2023).

Although the agri-food industry generates a significant volume of by-products rich in bioactive compounds such as polyphenols, flavonoids, and alkaloids these resources remain largely underutilized and are frequently dismissed as waste. This underutilization stems from

several critical limitations, including a lack of extraction procedures that are simultaneously efficient, economical, and environmentally friendly. Furthermore, the inherent variability in chemical composition, influenced by the raw material source and processing conditions, complicates the path toward standardization. Beyond these technical hurdles, proper industrial policies are often lacking, and the compounds themselves face regulatory hurdles regarding stability and bioavailability that inhibit large-scale application. Consequently, it is essential to develop integrated strategies for the recovery, characterization, and valorization of these substances. By converting these by-products into high-value resources, we can effectively address the dual challenges of sustainable development and the transition to a circular economy.

Research Aim and Objectives

The purpose of this study is summarized as follows:

Identification and Characterization: To determine and describe the primary bioactive compounds present in various food by-products.

Biological Assessment: To evaluate their functional capabilities, specifically focusing on their antioxidant and antimicrobial properties.

Optimization of Extraction: To identify and refine effective, eco-friendly extraction techniques that minimize environmental impact.

Industrial Application Research: To investigate potential applications across the agri-food, pharmaceutical, and cosmetic sectors.

Circular Integration: To contribute to a circular economy by successfully incorporating these by-products into a sustainable value chain

This research aims to facilitate the sustainable valorization of food by-products by investigating their potential as sources of bioactive compounds, specifically polyphenols, flavonoids, alkaloids, and other molecules of interest. The primary objective is to identify and profile these compounds using relevant physicochemical analysis, followed by an evaluation of their biological characteristics, with a particular focus on antioxidant and antimicrobial activities.

Furthermore, the research seeks to establish and refine extraction systems that are effective, eco-friendly, and cost-effective, ensuring maximum yield and stability of the active substances. The study also explores practical opportunities for incorporating these

extracts into the agri-food, pharmaceutical, and cosmetic industries. Ultimately, the goal is to transform overlooked waste into high-value resources, aligning with the core principles of a circular economy and global sustainable development.