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REVIEW ARTICLE

Extraction methods of bioactive compounds: a sustainability approach

Métodos de extracción de compuestos bioactivos: un enfoque hacia la sostenibilidad

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Abstract This article provides an overview of various extraction methods used to obtain bioactive compounds from plant materials, highlighting the process conditions, extract properties, and potential applications. Methodologies such as ultrasonic-assisted extraction (UAE), Soxhlet, supercritical fluids extraction (SFE), and green or environmentally friendly methods were studied. Each technique was evaluated in terms of efficiency, cost, environmental impact, and application, considering factors such as the type of compounds extracted (antioxidants, flavonoids, essential oils) and their use in the food, cosmetic, and pharmaceutical industries. The advantages and limitations of each process were discussed, providing a framework for selecting the most suitable method based on specific extraction and sustainability needs.

Keywords extraction methods, green extraction processes, bioactive compounds, environmental sustainability, antioxidants, flavonoids.

Resumen Este artículo ofrece una visión de diversos métodos de extracción utilizados para obtener compuestos bioactivos a partir de materiales vegetales, destacando las condiciones del proceso, las propiedades de los extractos y sus aplicaciones potenciales. Se estudiaron metodologías como la extracción asistida por ultrasonido (EAU), Soxhlet, fluidos supercríticos (SFE), y métodos verdes o ambientalmente amigables. Cada técnica se evaluó en términos de eficiencia, costo, impacto ambiental y aplicación, considerando factores como el tipo de compuestos extraídos (antioxidantes, flavonoides, aceites esenciales) y su uso en las industrias alimentaria, cosmética y farmacéutica. Se señalaron las ventajas y limitaciones de cada proceso, proporcionando un marco para la selección del método más adecuado según las necesidades específicas de extracción y sostenibilidad.

Palabras clave métodos de extracción, procesos de extracción verde, compuestos bioactivos, sostenibilidad ambiental, antioxidantes, flavonoides.

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PUBLIS EDITORIAL

Introduction

The bioactive compounds in natural matrices such as plants, fruits, algae, and microorganisms have gained attention due to their antioxidant, anti-inflammatory, and antimicrobial benefits. The extraction methods for these compounds affect their characteristics and application in food, pharmaceutical, and cosmetic products. Evaluating these methods is necessary to optimize the performance of industrial processes.

This work analyzes different extraction techniques, such as ultrasound-assisted extraction, microwave extraction, supercritical fluids, and green methods, to provide a comprehensive view of how these technologies contribute to improving efficiency and sustainability in obtaining high-quality extracts for various industries.

This work's objective was to compare the main extraction methods for bioactive compounds from plant materials, with emphasis on their principles, advantages, limitations, and potential applications. It will also explore the environmental impact of these methodologies and their role in developing more sustainable extraction solutions for bioactives.

Traditional extraction methods

Maceration extraction

Principle

Maceration is a solid-liquid extraction method based on passive diffusion, where the bioactive compounds from a plant matrix dissolve in an appropriate solvent, such as ethanol or water. This process is typically carried out at room temperature or slightly elevated temperatures to prevent thermal degradation of sensitive compounds. Parameters such as the particle size of the sample and the contact time between the matrix and the solvent directly affect the extraction efficiency. Its simplicity makes it ideal for preliminary chemical composition tests on natural samples (Martins et al., 2023; Usman et al., 2023).

Advantages

Maceration is economical and easy to implement, requiring no specialized equipment, making it an accessible technique, especially in preliminary studies.

Limitations

Among the disadvantages are the prolonged time required to achieve high yields and low efficiency in extracting compounds of low polarity or from complex matrices. The use of large volumes of solvents can pose environmental and economic concerns. Compared to advanced methods like ultrasound-assisted extraction, its efficiency is relatively low, especially for difficult-to-extract compounds (Martins et al., 2023; Usman et al., 2023).

Applications

Maceration is widely used to extract thermally stable compounds such as polyphenols, flavonoids, and tannins, which are important in the pharmaceutical, food, and cosmetic industries. It is also used to extract antioxidants from medicinal plants and traditional botanical products. In current research, this method remains a useful option in laboratory settings and as a baseline for comparing the effectiveness of more advanced techniques in the extraction of bioactive compounds (Martins et al., 2023; Usman et al., 2023).

Soxhlet Extraction

Principle

Soxhlet extraction uses a continuous reflux system where a volatile solvent repeatedly passes through a solid sample contained in a porous cartridge. This process ensures a complete extraction of the compounds soluble in the chosen solvent. The principle is based on the condensation of the heated solvent, which, upon dissolving the compounds, accumulates in the siphon until it is emptied, allowing the cycle to repeat. It is particularly useful for obtaining non-polar bioactive compounds, such as lipids and terpenes, due to its ability to maintain a constant solvent saturation during the extraction (El Maaiden et al., 2022).

Advantages

One of the main advantages of the Soxhlet method is its efficiency in extracting non-polar compounds with high purity. Additionally, it allows for more precise control of extraction conditions, contributing to its ability to extract large amounts of bioactive compounds compared to conventional methods like maceration. For example, in a study on green coffee beans, the Soxhlet extraction produced high levels of total phenolic compounds and flavonoids, the main contributors to antioxidant activity (Palmieri et al., 2020).

Limitations

However, the Soxhlet method has significant limitations. It consumes large volumes of solvents and requires prolonged extraction, resulting in high energy consumption. These drawbacks limit its environmental sustainability and economic viability on an industrial scale. Also, prolonged heat exposure can degrade certain thermosensitive compounds, reducing their applicability in specific cases (Gligor et al., 2023).

Applications

Soxhlet is widely used to extract bioactive compounds from plants and natural products for food, pharmaceuticals, and cosmetics. For example, it has proven effective in extracting antioxidant compounds from thyme and coriander, where the obtained extracts showed strong antioxidant activity in FRAP and ABTS assays. Additionally, it is useful for obtaining lipids and sterols from raw materials such as oilseeds, which are used in functional foods and supplements (Palmieri et al., 2020; Gligor et al., 2023).

Hydrodistillation

Principle

Hydrodistillation is a technique used to extract volatile compounds, especially essential oils, from plant materials. It works by injecting steam into the plant matrix, facilitating volatile compounds' release. These vapors are condensed and collected, allowing for the separation of the essential oil from the water. This method is based on the differences in volatility and solubility of the compounds, which allows the oils to be carried with steam. At the same time, other substances remain in the plant matrix. This approach is widely used due to its ability to preserve the integrity of the volatile compounds during the extraction process despite the high temperatures used (Machado et al., 2022; Oubannin et al., 2024).

Advantages

Hydrodistillation is recognized for its efficiency in extracting essential oils from various plants. One of its main advantages is that it does not require chemical solvents, making it a more eco-friendly and safe option for industrial and cosmetic applications. Furthermore, this method is relatively simple and can be applied on a large scale without expensive equipment. Hydrodistillation also allows for extracting multiple components from a sample, expanding its usefulness in industries such as pharmaceuticals, food, and cosmetics (Fernández et al., 2024; Semerdjieva et al., 2019).

Limitations

However, this method is not without limitations. Hydrodistillation is unsuitable for heat-sensitive compounds, as high temperatures can degrade specific components, altering their chemical profile and reducing their quality. Additionally, the process can be slow, with limited yields depending on the quantity and type of plant material used. Precise control of operational conditions, such as temperature and distillation time, is also required to ensure efficient extraction and minimize losses of key compounds (Semerdjieva et al., 2019; Fernández et al., 2024).

Applications

Hydrodistillation is widely used to extract essential oils in the cosmetic industry, where these compounds are used in fragrances, soaps, and personal care products. Essential oils extracted through this method are employed as natural flavorings and preservatives in the food industry due to their antimicrobial properties. In the pharmaceutical field, they are used for their therapeutic properties, such as antioxidant activity and anti-inflammatory effects. This method is also key in scientific research for the characterization of new essential oils and their bioactive potential (Machado et al., 2022; Fernández et al., 2024).

Modern and sustainable methods

Ultrasound-assisted extraction

Principle

Ultrasound-assisted extraction (UAE) is based on acoustic cavitation, a phenomenon generated by high-frequency ultrasonic waves in a liquid medium. These waves create microbubbles that collapse violently, generating high temperatures and local pressures that break the cell walls of plant materials. This process facilitates the release of bioactive compounds, such as polyphenols, flavonoids, and carotenoids, improving extraction efficiency compared to traditional methods. Furthermore, it reduces processing times while maintaining high quality in the obtained extracts (Ranjha et al., 2021; Lavenburg et al., 2021).

Advantages

One of the main advantages of ultrasound-assisted extraction (UAE) is its speed and efficiency, as it significantly reduces extraction time compared to traditional methods. This method also requires less solvent, making it more environmentally friendly. UAE is highly adaptable to different bioactive compounds and substrates, and its ability to operate at lower temperatures minimizes the degradation of heat-sensitive compounds. Moreover, it is considered a "green" technique due to its low environmental impact and compatibility with sustainability standards in the food and pharmaceutical industries (Teixeira et al., 2024; Ranjha et al., 2021).

Limitations

Despite its advantages, UAE has certain limitations, such as the possible degradation of bioactive compounds sensitive to ultrasound or the heat generated during the process. Additionally, large-scale implementation may be expensive due to the specialized equipment required.

Applications

Ultrasound-assisted extraction is widely used to extract polyphenols from fruits, carotenoids from vegetables, and flavonoids from various medicinal plants. It is also a promising technique for obtaining essential oils and antioxidants for the food, cosmetic, and pharmaceutical industries (Ranjha et al., 2021; Lavenburg et al., 2021).

Microwave-Assisted Extraction (MAE)

Principle

Microwave-assisted extraction (MAE) uses high-frequency electromagnetic waves that interact with the polar molecules of the sample and the solvent, generating rapid heating. This process increases the cell pressure, breaking their walls and releasing bioactive compounds into the solvent medium. The effectiveness of this method lies in the ability of microwaves to distribute heat evenly, promoting efficient extraction of target substances such as polyphenols, flavonoids, and carotenoids (Dobrinčić et al., 2020; Moretto et al., 2022).

Advantages

MAE stands out for its speed and lower use of solvents compared to traditional methods. This reduces processing time and improves environmental sustainability. The direct heating by microwaves minimizes the loss of bioactive compounds sensitive to prolonged thermal processes, preserving their chemical integrity. It is effective in obtaining extracts rich in antioxidant compounds, which greatly interest food and pharmaceutical applications (Dobrinčić et al., 2020; Moretto et al., 2022).

Limitations

Despite its advantages, Microwave-Assisted Extraction (MAE) has limitations. One of the main issues is the initial investment required for specialized equipment, which can be prohibitive for some facilities. Additionally, this method presents challenges when working with non-polar compounds, as they rely less on interacting with microwaves. There is also the risk of degradation of heat-sensitive compounds if extraction parameters, such as temperature and exposure time, are not adequately controlled (Dobrinčić et al., 2020; Moretto et al., 2022).

Applications

MAE is widely used to extract bioactive compounds from plant and marine materials, including polyphenols from olive leaves and fatty acids from microalgae. In the case of microalgae, this method has been used to extract lipids intended to produce high-quality biodiesel. The efficiency of MAE in recovering compounds such as oleuropein, hydroxytyrosol, and carotenoids makes it a preferred technique in industries such as food, cosmetics, and energy (Dobrinčić et al., 2020; Moretto et al., 2022).

Supercritical Fluid Extraction (SFE)

Principle

Supercritical Fluid Extraction (SFE) uses supercritical fluids, particularly carbon dioxide (CO_2), to dissolve and extract bioactive compounds. Under temperature and pressure conditions exceeding the critical point of CO_2, it acquires both liquid and gas properties, efficiently penetrating solid matrices and dissolving specific substances. This method is adjusted based on parameters such as pressure, temperature, and, in some cases, the use of cosolvents to enhance the selectivity and efficiency of the process (Uwineza & Waśkiewicz, 2020; Alcázar-Alay & Gallón-Bedoya, 2023).

Advantages

One of the main advantages of Supercritical Fluid Extraction (SFE) is its ability to extract without leaving residues of toxic solvents, making it ideal for food, pharmaceutical, and cosmetic applications. It is also highly selective, allowing the extraction of specific compounds such as antioxidants, carotenoids, and essential oils. Furthermore, by using CO_2, a safe and economical gas, SFE is environmentally friendly and provides an efficient method for thermolabile compounds, as the temperature can be kept low during the process (Uwineza & Waśkiewicz, 2020; Alcázar-Alay & Gallón-Bedoya, 2023).

Limitations

Despite its benefits, SFE has limitations, such as high equipment initial costs and operational expenses due to the pressure requirements and precise control of process conditions. Additionally, the method's efficiency may be limited for non-polar compounds if appropriate cosolvents are not used, which can increase the system's complexity and cost (Uwineza & Waśkiewicz, 2020; Alcázar-Alay & Gallón-Bedoya, 2023).

Applications

SFE (Supercritical Fluid Extraction) is widely used to obtain high-purity food, cosmetics, and pharmaceutical extracts. Notable examples include the extraction of antioxidants from agro-industrial waste, essential oils from aromatic plants, and natural pigments such as carotenoids. Additionally, SFE is frequently combined with emerging technologies to optimize the recovery of bioactive compounds, highlighting its role in the valorization of biomass and industrial waste (Uwineza & Waśkiewicz, 2020; Alcázar-Alay & Gallón-Bedoya, 2023).

Green or environmentally friendly extraction

Principle

Green or environmentally friendly extraction refers to methods that minimize environmental impact and improve sustainability compared to conventional techniques. Among these methods, subcritical water extraction, ionic liquids, and deep eutectic solvents stand out. Subcritical water extraction uses water at high temperatures and pressures without reaching its critical point, allowing for efficient dissolution of bioactive compounds without the problems associated with using organic solvents. On the other hand, ionic liquids and deep eutectic solvents are characterized by their low toxicity and their ability to dissolve a wide range of compounds, making them particularly useful for extracting bioactive compounds such as phenols and essential oils (Almohasin et al., 2023; Martins et al., 2023).

Advantages

One of the main advantages of green extraction methods is their lower environmental impact, as they reduce the use of conventional solvents, which are toxic and non-renewable. Additionally, these techniques contribute to sustainability, as many of the solvents used come from renewable sources or are not harmful to the environment. Green extraction strategies aim to optimize extraction performance, improve energy efficiency, minimize waste, and promote the circular economy in industrial processes. The limited availability of some of these solvents and the need for process optimization still represent significant challenges in the widespread adoption of these methods.

Limitations

Despite their advantages, green extraction methods have certain limitations. The availability of ionic liquids and deep eutectic solvents is still restricted, which may hinder their large-scale implementation. The optimization of these processes remains an active area of research, and it is necessary to find the most suitable conditions to maximize the efficiency and selectivity of bioactive compound extraction. The continuous development of biorefineries and research in green chemistry pave the way for the refinement of these methods and their integration into more sustainable industrial processes. Table 1 summarizes the characteristics of the comparison of extraction methods.

Table 1. Comparison of methods

Method	Efficiency	Cost	Sustainability	Applications
Maceration	Low	Low	Low	Thermostable compounds
Soxhlet	Moderate	Moderate	Low	Fats and oils
UAE	High	Moderate	Alta	Antioxidants and flavonoids
SFE	Very high	High	Very high	High-purity extracts

Table 2 compares bioactive compound extraction methods concerning process conditions, extract properties, and potential applications.

Table 2. Extraction methods for bioactive compounds: process conditions, extract properties, and potential applications

Reference	Extraction method	Plant material	Process conditions	Extract properties	Potential application
Wong et al. (2020)	UAE	Fruit and vegetable waste	Time: 20-30 min, Temperature: 40-60 °C, Solvent: Ethanol/water	Antioxidants (phenols and flavonoids)	Natural preservatives in processed foods
Borges et al. (2020)	Soxhlet and microwave	Green and black tea leaves	Soxhlet: 3 hours, Microwave: 15 minutes, Solvent: Water/Ethanol	Antioxidant and antimicrobial	Preservatives in beverages and meat products

Reference	Extraction method	Plant material	Process conditions	Extract properties	Potential application
Aldughaylib et al. (2022)	Liquid-liquid extraction	Grape seeds	Methanol maceration for 24 hours, partitioning with hexane and ethyl acetate	Antioxidant properties (flavonoids)	Enrichment of vegetable oils
Kothari et al. (2012)	Ultrasound	Cardamom seeds	Time: 30 minutes, Temperature: 50 °C, Solvent: Ethanol	Antioxidants (total phenols) and antimicrobial agents	Natural preservatives in processed foods
Gonelimali et al. (2018)	Agar diffusion	Thyme essential oil	Steam distillation extraction, Evaluation: MIC (Minimum Inhibitory Concentration)	Significant antimicrobial activity	Antimicrobial additives for cheeses
Mahmood et al. (2019)	UAE	Moringa leaf	Time: 40 minutes, Temperature: 45°C, Solvent: Ethanol	Potent antioxidant and antimicrobial activity	Fortification of functional beverages
Junsathian et al. (2022)	Solid-liquid extraction	Edible plant leaves from Thailand	Time: 2 hours, Temperature: 60 °C, Solvent: Water	Antioxidants (flavonoids, tannins) and antimicrobial agents	Preservatives in dairy products and snacks
Altemimi et al. (2017)	UAE	Plants with bioactive compounds such as polyphenols, flavonoids, carotenoids	Use of ultrasound to induce cavitation, with controlled temperature and time	Higher extraction yield, better quality of bioactive compounds	Extraction of antioxidants, essential oils, pigments
Naviglio et al. (2023)	EAM	Plant material rich in phenolic compounds, essential oils	Rapid heating using microwaves, with temperature control and solvents	High extraction efficiency, reduced time, and solvents	Antioxidant extracts, oils, bioactive compounds
Altemimi et al. (2017)	EFS	Aromatic plants, spices, medicinal herbs	Use of CO_2 in a supercritical state at controlled temperatures and pressures	Pure extracts without solvent residues, high selectivity	Essential oils, antioxidants, lipophilic compounds
Naviglio et al. (2023)	Green or environmentally friendly extraction	Various plants, especially those with antioxidant or pharmacological properties	Use of ionic liquids, deep eutectic solvents, or subcritical water	Reduction of environmental impact, lower use of conventional solvents	Natural products, pharmacological extracts, cosmetics

Environmental impact of extraction methodologies and their role in the development of sustainable solutions for bioactive extraction

The methodologies for extracting bioactive compounds from plant sources have a variable environmental impact, depending on the process used. Traditionally, methods such as extraction with organic solvents have raised concerns due to their high solvent consumption and the potential environmental contamination resulting from the waste of these compounds. Technological advancements have developed more sustainable techniques that minimize this impact.

Methods such as UAE (Ultrasound-Assisted Extraction) and MAE (Microwave-Assisted Extraction) are known for their efficiency in reducing extraction times and using smaller amounts of solvents, contributing to a smaller ecological footprint. Although EFS (Supercritical Fluid Extraction) is costly, it does not leave solvent residues, making it more environmentally friendly than conventional techniques (Naviglio et al., 2023; Altemimi et al., 2017).

Green or environmentally friendly methods include subcritical water extraction, ionic liquids, or deep eutectic solvents; these methodologies are designed to reduce toxic solvents and energy consumption, which aligns with sustainability principles. These techniques have a reduced environmental impact and enhance the efficiency of bioactive compound extraction, resulting in less waste of natural resources. Some of these methods are in the optimization phase. They are not as widely used as other established techniques, but their potential to contribute to developing more eco-friendly extraction processes is promising (Naviglio et al., 2023; Altemimi et al., 2017).

The role of these technologies in transitioning to a more sustainable industry extends beyond waste reduction and energy use. Their ability to produce high-purity extracts with fewer toxic residues decreases pollution associated with the natural extract industry. Implementing these methodologies improves extraction efficiency and facilitates the production of safer and more eco-friendly products to meet the growing demand for natural and sustainable solutions across all sectors of life (Naviglio et al., 2023).

Conclusions

Modern extraction methods offer advantages in terms of efficiency, sustainability, and control over extraction conditions. Their implementation depends on the balance between costs and benefits and the nature of the target compounds. The current trend is towards green technologies that minimize environmental impact and maximize the safety of the final products. Combining techniques (hybrid) and developing even more sustainable technologies are recommended, along with integrating computational tools to optimize extraction conditions. This will allow expanding the applications of bioactive compounds in innovative sectors.

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Conflicts of interest
The authors declare that they have no conflicts of interest.

Author contributions
Yanelis Chongo: Conceptualization, research, methodology, visualization, writing the original draft, writing, review and editing.

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