Ultrasound-assisted extraction for food and environmental samples

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In recent years, ultrasound-assisted extraction (UAE) has attracted growing interest, as it is an effective method for the rapid extraction of a number of compounds from food and environmental samples, with extraction efficiency comparable to that of classical techniques. In particular, recently, numerous analytical applications of this technique dealt with the extraction of natural compounds and pollutants from food and environmental samples.

This review gives a brief presentation of the theory of UAE, discusses recent advances that influence its efficiency, and summarizes the main results in selected applications published in the period 2010–12. There is discussion of the advantages and the disadvantages of UAE and the possibility of coupling UAE with other analytical techniques.

Keywords: Analytical application; Contaminant; Environmental matrix; Environmental sample; Extraction; Food sample; Natural compound; Pollutant; Ultrasound-assisted extraction (UAE); Ultrasound-assisted emulsification microextraction (UAEME)

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1. Introduction

For many years, the use of ultrasound energy in liquid and solid media has been extensive in food-processing applications and has created growing interest in sample treatment [1]. This technique is an efficient tool for large-scale commercial applications (e.g., emulsification, homogenization, extraction, crystallization, dewatering, low-temperature pasteurization, degassing, defoaming, activation and inactivation of enzymes, particle-size reduction and changing viscosity) [2,3]. Much attention has been given to the application of ultrasound for the extraction of natural products that typically needed hours or days to reach completion with conventional methods [3–7].

The classical techniques used in food industry for solvent extraction of bioactive compounds are based upon the correct choice of solvent coupled with the use of heat and/or agitation. Solvent extraction of organic compounds contained within the bodies of plants and seeds is significantly improved by using the power of ultrasound. The mechanical effects of ultrasound provide a greater solvent penetration into cellular materials and improve mass transfer due to the effects of micro-streaming. This is combined with an additional benefit of using ultrasound in extractive processes – disruption of biological cell walls to release the cell contents [8].

Overall, ultrasound-assisted extraction (UAE) is recognized as an efficient extraction technique that dramatically reduces working times, increasing yields and often the quality of the extract [8]. Several studies have reviewed different industrial applications of ultrasound in the intensification of extraction of bioactive materials from herbs, oils from seeds and proteins from soy [9–11]. Thus, in the past few years, numerous compounds have been extracted by UAE from several matrices, with special emphasis on the commercial production of bioactive compounds in the food industry.

UAE is also gradually becoming a matter of routine practice in analytical chemistry, which uses this energy for a variety of purposes in relation to sample preparation, mostly sample extraction. Currently, any critical review of recent advances in sample preparation includes a section dedicated to UAE [12–17]. Over 80% of analysis time is still spent on the sample and sample preparation, and UAE can speed up many procedures that are appropriate in other respects [12,15,17].

There were recently some review articles about UAE [4] and its applications to microwave [18], lesser known

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heterogeneous sample-preparation procedures [19] and green chemistry [20], and the determination of heavy metals [21] and organic food contaminants [22].

But, to the best of our knowledge, there is no single review that addresses the UAE applications to extract any type of compound in food and environmental matrices. Consequently, this article reviews the application of ultrasound energy to the extraction of organic, organometallic and inorganic compounds from environmental and food matrices (soils, sediments, vegetables, animal tissues, and water) for their analytical determination. The principle of the technique is first presented, together with the commercially available systems. Then, the main parameters and operations are discussed, before the presentation of the experimental conditions that allow the extraction of numerous compounds. The aim of this review is to describe different aspects of recent interesting applications of UAE published since 2010. Finally, the performance of the technique is compared to that of other techniques, either classical or recent.

2. Principles of ultrasound extraction

Ultrasound comprises mechanical waves that need an elastic medium to spread. The difference between sound and ultrasound is the frequency of the wave; sound waves are at human hearing frequencies (16 Hz to 16–20 kHz) while ultrasound has frequencies above human hearing but below microwave frequencies (from 20 kHz to 10 MHz). For the classification of ultrasound applications, the amount of energy generated, characterized by sound power (W), sound intensity (W/m^2) or sound energy density (W/m^3), is the key criterion. The uses of ultrasound are broadly distinguished into two groups: high intensity and low intensity [11,23,24].

Low-intensity ultrasound – high frequency (100 kHz–1 MHz) low power (typically <1 W/cm^2) – is involved in non-destructive analysis, particularly for quality assessment. This technique is most commonly applied as an analytical technique to provide information on the physicochemical properties of food (e.g., firmness, ripeness, sugar content, and acidity). Nevertheless, high-intensity ultrasound – low frequency (16–100 kHz) high power (typically 10–1000 W/cm^2) – can alter food properties physically or chemically [8,9,23]. High-intensity ultrasound is used, among other applications, to speed up and to improve the efficiency of sample preparation.

2.1. Effects of ultrasound

During the sonication process, longitudinal waves are created when a sonic wave meets a liquid medium, thereby creating regions of alternating compression and rarefaction waves induced on the molecules of the medium (Fig. 1) [11]. In these regions of changing pressure, cavitation occurs and gas bubbles are formed. These bubbles have a larger surface area during the rarefaction (expansion) cycle, which increases the diffusion of gas, causing the bubble to expand. A critical point is reached during the compression cycle in which the ultrasonic energy provided is not sufficient to retain the vapor phase in the bubble. As a consequence, rapid condensation occurs and large amounts of energy are released [11,23,24]. The condensed molecules collide violently, creating shock waves. These shock waves create regions of very high temperature and pressure, reaching up to 5500°C and 50 MPa [11,24]. Cavitation can result in micro-streaming, which can enhance heat and mass transfer. This creates hotspots that can dramatically accelerate the chemical reactivity in the medium. When these bubbles collapse onto the surface of a solid material, the high pressure and temperature released generate microjets directed towards the solid surface. These microjets are responsible for the degreasing effect of ultrasound on metallic surfaces, which is widely used for cleaning materials [8,9].

Another application of microjets in food industry is the extraction of vegetal compounds, because this allows improved solvent penetration into the plant body and can also break down cell walls [11]. As shown in Fig. 2, a cavitation bubble can be generated close to the plant material surface (a), then, during a compression cycle, this bubble collapses (b) and a microjet directed toward the plant matrix is created (b and c). The high pressure and temperature involved in this process destroy the cell walls of the plant matrix, and its content can be released into the medium (d). This is a very interesting tool for extraction of ingredients from natural products [24]. As a consequence, employing UAE has benefits in increased mass transfer, better solvent penetration, less dependence on solvent use, extraction at lower temperatures, faster extraction rates and greater yields of product [11,23,24].

The ability of ultrasound to cause cavitation depends on the characteristics of ultrasound (e.g., frequency and intensity), product properties (e.g., viscosity and surface tension) and ambient conditions (e.g., temperature and pressure). This technique requires a liquid medium, an energy generator and a transducer, which transforms the electric, magnetic or kinetic energy into acoustic energy [23].

2.2. Commercial devices

Ultrasonication can be applied in analytical chemistry in two ways: directly to the sample, or indirectly through the walls of the sample container using a water bath, which is the most available and cheapest source of ultrasound irradiation. However, there are other more efficient designs [e.g., horns (indirect or direct) or ultrasonic probes (direct to the sample)] able to develop