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Review

Acceleration of microwave-assisted extraction processes of food components by integrating technologies and applying emerging solvents: A review of latest developments

Flora-Glad Chizoba Ekezie [a, b, c], Da-Wen Sun [a, b, c, d, *], Jun-Hu Cheng [a, b, c, **]

[a] School of Food Science and Engineering, South China University of Technology, Guangzhou 510641, China
[b] Academy of Contemporary Food Engineering, South China University of Technology, Guangzhou Higher Education Mega Center, Guangzhou 510006, China
[c] Engineering and Technological Research Centre of Guangdong Province on Intelligent Sensing and Process Control of Cold Chain Foods, Guangzhou Higher Education Mega Center, Guangzhou 510006, China
[d] Food Refrigeration and Computerized Food Technology (FRCFT), Agriculture and Food Science Centre, University College Dublin, National University of Ireland, Belfield, Dublin 4, Ireland

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ABSTRACT

Background: Microwave-assisted extraction (MAE) have gained enormous popularity as a preferred method for the recovery of various active compounds from food materials. They proffer benefits such as the reduction of extraction time, environmental friendliness, low cost and enable automation or on-line coupling to other analytical procedures. Recently, newer add-ons or technological modifications have been incorporated into MAE systems, in an effort to continuously improve extraction efficiency and ensure a greener implementation.
Scope and approach: The core pathways of such meliorations include integrating microwave extraction with other technologies, *e.g.,* ultrasound assisted extraction (UAE), negative pressure cavitation (NPC), enzyme assisted extraction (EAE), hydrodiffusion extraction (HDE), and supercritical fluid extraction (SFE) or replacement of extraction medium with suitable alternatives including ionic liquids, deep eutectic solvents, non-ionic surfactants, *etc.* This review confers their underlying principles and mechanisms, equipment and apparatuses, practicalities, as well as resultant benefits such as increased yield, intensification of mass transfer and reduction of energy consumption, in a manner not achievable by MAE alone or previous intermediary modifications.
Key findings and conclusions: It is hoped that this paper reinforces the need to initiate more studies focused on process validation and optimization of such emerging MAE systems, in furtherance of their scale-up, sustainability and robust adoption by the food industry.

1. Introduction

Like drying (Cui, Sun, Chen, & Sun, 2008; Pu & Sun, 2016; Yang, Sun, & Cheng, 2017), cooling (McDonald, Sun, & Kenny, 2000; Sun, 1997; Sun & Brosnan, 1999; Sun & Hu, 2003; Sun & Wang, 2000; Wang & Sun, 2002a, 2002b; Wang & Sun, 2004; Zheng & Sun, 2004) and freezing (Cheng, Sun, & Pu, 2016; Cheng, Sun, Zhu, & Zhang, 2017; Kiani, Zhang, Delgado, & Sun, 2011; Ma et al., 2015; Pu, Sun, Ma, & Cheng, 2015; Xie, Sun, Xu, & Zhu, 2015; Xie, Sun, Zhu, & Pu, 2016), extraction is a common processing method used in the food industry. Driven by technical, scientific and economical impediments associated with traditional extraction techniques, such as high energy cost, residual solvent impurities and thermal degradation, in the past decade, the food industry has experienced a revolution in the development of greener technologies for the recovery of active ingredients (Alexandre, Castro, Moreira, Pintado, & Saraiva, 2017; Barba, Zhu, Koubaa, Sant'Ana, & Orlien, 2016; Chemat, Rombaut, Fabiano-Tixier, Pierson, & Bily, 2015; Zhu et al., 2016). Such novel methods for the screening, separation and extraction of various food components includes microwave-assisted extraction (MAE), enzyme-assisted extraction (EAE),

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* Corresponding author. School of Food Science and Engineering, South China University of Technology, Guangzhou 510641, China.
** Corresponding author. School of Food Science and Engineering, South China University of Technology, Guangzhou 510641, China.
E-mail address: dawen.sun@ucd.ie (D.-W. Sun).
URL: http://www.ucd.ie/refrig, http://www.ucd.ie/sun

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high-voltage electrical discharges (HVED), pulsed electric field (PEF), ultrasound-assisted extraction (UAE), high pressure processing (HPP), pulsed ohmic heating (POH), supercritical fluid extraction (SFE) and their combinations, coupled with various advances in extraction solvents/mediums. Among them, microwave-assisted extraction (MAE) is the most diffused method for the recovery of food constituents due to its high extraction efficiency, eco-friendliness, low-cost, reduced recovery time and ease of assembling in large or small scale (Felkai-Haddache et al., 2016; Pap et al., 2013).

The recovery of organic constituents by microwave irradiation was first documented in a study by Ganzler, Salgo, and Valkó (1986). Since then, several enhancement attempts have been made and implemented, in furtherance of MAE sustainability and operational effectuality. In a typical MAE procedure, microwave irradiation penetrates a material, interact with polar compounds and produce voluminous heating via ionic conduction or dipole rotation thereby inducing high yield (Deo et al., 2015). However, in order to assure continuality, certain constraints such as the need to remove the solvent from the material upon process termination and its limitation to polar extractants should be vanquished (Chan, Yusoff, Ngoh, & Kung, 2011). In addition, studies propose that to further promote extraction efficacy, the elementary closed system and open MAE systems, which were previously in existence, can be modified with various add-ons or synergistically used with other technologies. For instance, MAE can be combined simultaneously or sequentially with other techniques such as UAE, SFE, EAE, hydrodiffusion *etc.* Correspondingly, the conventionality was to employ organic solvent or water as extractant in MAE systems, but nowadays, various hydrotropic liquids, two-phase solutions, miscellars, *etc.* are employed (Chen, Liu et al., 2016; Chen, Zhang et al., 2016; Li et al., 2016; Liu, Chen et al., 2016; Liu, Yu et al., 2016; Tang et al., 2017; Xie et al., 2017; Zhang, Liu et al., 2016; Zhang, Yao et al., 2016). These approaches provide a greener implementation strategy through minimizing solvent usage and less toxicity, reducing waste production or the emission of CO_2 released into the atmosphere and minimal energy consumption. In addition, some of these hybrid modes such as MHG ensure recyclability of solvents, re-use of extraction residues for subsequent operations and promote overall extraction efficiency (Boukroufa, Boutekedjiret, Petigny, Rakotomanomana, & Chemat, 2015).

Considering the sundry number of reviews (Chan et al., 2011; Mandal & Tandey, 2016; Tatke & Jaiswal, 2011; Wang, Ding, & Ren, 2016; Zhang, Yang, & Wang, 2011) published in the past on MAE systems, which clearly demonstrates the intensity of attention bestowed on the extraction setup. However, an up-close analysis of these reviews and findings from recent experimental investigations indicates that the engineering of MAE systems have long evolved from elementary systems or their intermediary modifications into employment of greener solvent-based MAE systems and integration with other advanced or newer techniques, which remarkably improves the overall process efficiency in an unprecedented manner. Although, Wang et al. (2016) pointed out some of these advancements are in the area of using greener analytical solvents, it becomes imperative to thoroughly update information available on these newly developed hybrid modes of MAE systems and eco-friendly solvents in order to substantiate their potentiality and buttress the need for process validation and optimization in a stepwise approach. Therefore, this review presents a collation of recently published studies focused on fresh modifications/ameliorations to MAE systems/procedures. Specifically, from the viewpoint of alternative extractants, combination modes and subsequent applications during extraction of target compounds from food matrix are discussed. Additionally, the principles and mechanisms as well as equipment setup/configuration are highlighted, and MAE technological modification trajectory experienced over the years and future directions are elucidated. It is hoped that the current review will promote their potency, popularity and transition from lab-bench to industrial utilization.

2. Fundamentals of microwave-assisted extractions

2.1. Principles and mechanism of MAE

The rationale of microwaves during extraction lies in the transfer of energy by electrical field via two coinciding mechanisms. Firstly, dipole rotation occurs by the interaction of dipoles with polar components, and engendering the dipoles to realign with the applied field, which causes coerced molecular movements that produces heat (Adetunji, Adekunle, Orsat, & Raghavan, 2017; Chan et al., 2011). Secondly, ionic conduction induces the movement of charged ions inside the solvent when electromagnetic radiation is applied and generates a resistance within the solution, resulting in friction and consequently heat is released. Notwithstanding, the aptitude of the food matrix to absorb microwave irradiation and produce heat is dependent on its dielectric loss. Hence, the absorbed energy is derived from the dissipation factor (δ) equation, expressed as follows:

$$\tan\delta = \varepsilon'' \Big/ \varepsilon' \tag{1}$$

where ε'' represents the efficiency of transforming microwave irradiation into heat and called dielectric loss factor, while ε' conveys the capacity of an irradiated molecule to become polarized by the electric field. Meanwhile, the transformation of electrical energy into thermal energy is expressed as:

$$P = K.f\varepsilon' E^2 \ \tan\delta \tag{2}$$

where $\tan\delta$ is termed as dielectric loss tangent, E is called the electric field strength, ε' is the dielectric constant, f denotes the frequency employed, K is a known constant and P represents microwave power dissipation per unit volume. When microwave heat comes in contact with tiny traces of moisture inside the cell matrix, evaporation occurs and builds intense pressure on the cell wall, which ruptures and causes the release of the active constituents. Higher throughputs can be achieved by careful selection of operating conditions such as temperature, since increase in temperature promotes faster penetration of solvent into the cell matrix. Likewise, considering the existence of a permanent dipole moment that interacts with microwaves, polar molecules and ionic mixtures facilely absorbs microwave energy. However for non-polar solvents, *e.g.*, hexane, the solvents do not heat up spontaneously when they are in contact with microwaves. Other parameters influencing the performance of MAE systems include solid-to-liquid ratio, extraction duration, microwave power, nature of samples, and stirring. The effects of these parameters have previously been reviewed and the details can be found elsewhere (Chan et al., 2011).

2.2. Configuration and instrumentation in MAE systems

Typically, a basic MAE system comprises of a magnetron, an isolator, a wave guide, a cavity and a mode stirrer (Routray & Orsat, 2012). The magnetron generates microwave energy, propagating through the wave guide into the cavity and the mode stirrer disperses the energy via several routes. The cavity is used to confine energy pending complete absorption by the material matrix. The isolator is used to prevent reflected energy from reaching the magnetron, otherwise power output would be diminished, *i.e.*,