Impact of Cell Disintegration Techniques on Curcumin Recovery

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Abstract
In recent years, the improvement of curcumin recovery from turmeric by cell and tissue disintegration techniques has been gaining more attention; these emerging techniques were used for a reproducible and robust curcumin extraction process. Additionally, understanding the material characteristics is also needed to choose the optimized technique and appropriate processing parameters. In this review, an outlook about the distribution of different fractions in turmeric rhizomes is reviewed to explain matrix challenges on curcumin extraction. Moreover, the most important part, this review provides a comprehensive summary of the latest studies on ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), enzyme-assisted extraction (EAE), high-pressure-assisted extraction (HPAE), pulsed electric field-assisted extraction (PEFAE), and ohmic heating-assisted extraction (OHAE). Lastly, a detailed discussion about the advantages and disadvantages of emerging techniques will provide an all-inclusive understanding of the food industry’s potential of different available processes.

Keywords Curcumin extraction · Assisted extraction · Turmeric · Cell disintegration index · Curcuma longa

Introduction

Turmeric is an herb that belongs to the ginger family, located mainly in Asia’s tropical climate [1]. The turmeric rhizome has two parts, the main branch in the central and its laterals, axillary branches [2]. From ancient, turmeric was considered a valuable plant with numerous medical benefits and was used as a coloring in the culinary [3]. The most active compound in turmeric is curcumin, which was first isolated in 1815 and first synthesized by Lampe and Milobedeska in 1913 [4]. In recent years, there has been increasing interest in curcumin research, especially related to medical purposes and medicinal benefits considering curcumin to inhibit intestinal cholesterol absorption [5] and to affect LDL oxidation [6], hemostasis, thrombosis, and coagulation [7], type II diabetes [8] or Alzheimer’s disease [9]. Recently, a few reviews comprehensively covered the health perspective of the curcumin [10], curcumin biological activities [11], purification and applications [12], curcumin production and bioavailability [13]. Therefore, these approaches will not be covered in this review. Other recent approaches gaining attention are emerging methods of extracting curcumin from turmeric and adapting processes to be more efficient, faster, sustainable, and eco-friendly. These modern techniques overcome the stability challenges of curcumin with higher efficiency and purity, adapting its application in the food and pharmaceutical industries.

The primary purpose of this review is to give a summarized and comprehensive overview of turmeric rhizome characteristics and the impact of cell disintegration processes on curcumin extraction efficiency. The emerging technologies overcome the matrix challenges of turmeric cells and enhance extraction efficiency; these technologies included ultrasound-assisted extraction [14–16], pressurized liquid extraction (PLE) [17, 18], enzyme-assisted extraction (EAE) [19, 20], supercritical fluid extraction (SFE) [21, 22], and microwave-assisted extraction [23, 24].

Turmeric Plant Characteristic

Turmeric Plant Cell Structure

The distribution of oleoresin, curcumin, and starch cell in Curcuma amada, C. aromatica, C. longa, and C. zedoaria

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are shown in Fig. 1; these components are varied in different species of turmeric. The comparison of the common turmeric rhizome anatomy is shown in Table 1. The turmeric species have common anatomical features like periderm, the outer zone filled with curcumin cells, oil cells, and the inner zone with starch deposition in vascular bundles. Nevertheless, the number of oil and curcumin cells varies in four species; besides, the starch and pectin content is different from species to species [3]. In general, the optimal turmeric cell for efficient extraction has fewer periderm layers and a larger distribution of vascular bundles containing curcumin cells; besides, it should have plenty of curcumin cells and fewer starch granules.

The amount of curcumin cells in C. longa is higher than three other species (Table 1); therefore, the highest number of publications dealing with curcumin extraction is related to this species [1, 25–28]. There are numerous differences from C. longa to another anatomy of turmeric (Table 1).

The main advantage of C. longa to other types that affects the extraction process is the lower number of periderm layers, the larger distribution of vascular bundles containing curcumin cells, the number of curcumin cells, and the lower number of starch granules.

Different fractions in turmeric could affect curcumin extraction; for example, starch is the barrier that inhibits the diffusion of organic solvent; besides, starch is subjected to swelling and increases the viscosity during thermal treatments. According to Kurmudle et al. [31], α-amylase and glucoamylase are selective and effective enzymes for curcumin extraction. On the other hand, the low content of xylans and cellulose in the turmeric rhizomes do not inhibit the curcumin extraction [31]. The pectin content in the turmeric rhizome is 6.3% w/w [32], and with pectinase treatment, the curcumin recovery could be increased by 53% compared to the untreated sample [33]. In turmeric plant cells, starch and pectin have a noticeable effect on curcumin recovery; numerous studies focused on these components to enhance the efficiency of the extraction process. The efficiency of these approaches will be further discussed in “Evaluation of Structure Modification by Cell Disintegration Index Measurement” and “Effect of Starch Content on the Curcumin Extraction Process.”

Evaluation of Structure Modification by Cell Disintegration Index Measurement

The effect of cell disintegration techniques on turmeric cell structure is shown in Table 2. In order to evaluate the efficiency of pre-treatment on curcumin recovery, cell disintegration index (CDI) was used to reveal the damage of turmeric cells before and after the treatment [33, 41, 42].

The principle of CDI measurement is the difference of impedance measured at the different current frequencies [43]. The difference in material impedance before and after the treatment reveals the damage of the plant cell [44]. According to Shirsath et al. [45], the material matrix is an essential factor affecting the treatment’s efficiency. In the past, mechanical grinding and thermal treatment were used to damage the plant cell. The primary purpose of these techniques was to improve the mass transfer rate due to the plant cell’s increasing permeability [46]. However, these conventional techniques require high-energy usage and long-time treatment [47], which may cause loss of essential components or contamination with undesired compounds. CDI is an important index to compare the efficiency of conventional and non-conventional techniques. According to Luengo et al. [41], an impedance measurement is useful in evaluating plant cell status after the pre-treatment.

In the research of Angersbach et al. [48], the impact of the electroporation induced the formation of pores on the lipid channel but not in the protein channels (Table 2). The frequency area of CDI measurement is in the range of 100 Hz.
to 10 MHz [44, 49]. According to Ando et al. [43], this range has been widely used to evaluate the cell physiological status of the plant tissue after the pre-treatment. The emerging technologies degrade and disrupt the cell membranes, promoting the diffusion of solvent/curcumin and enhancing the recovery [50].

According to Angersbach et al. [51], the plant disintegration index ($p_0$) is described by Eq. (1):

$$p_0 = \frac{\sigma_h^i \times \sigma_l^s - \sigma_h^s \times \sigma_l^i}{\sigma_h^s - \sigma_h^i}$$

(1)

where $p_0$ is the measured electrical conductivity value and the subscripts $i$ and $s$ refer to the conductivities of untreated (initial) and treated (damaged) tissue, respectively; the subscripts $l$ and $h$ refer to low-frequency and high-frequency range. In theory, $p_0 = 0$ for an intact tissue and $p_0 = 1$ for a maximally disintegrated tissue. In most cases, the value of $p_{\text{max}}$ was estimated by measurements of freeze-thawed tissue’s electrical conductivity for two rounds [33]. After such treatment, the electrical conductivity of tissue attained its maximal value.

For CDI measurement, as suggested by Angersbach et al. [51], the impedance was evaluated by parallel plate cylindrical electrodes; the distance between two electrodes was 20 mm [48]. The impedance of the material was measured before and after each treatment; the results at low frequency and high frequency were recorded for the calculation [52]. The low-frequency and high-frequency values were chosen in advance, and they varied on the type of materials. In terms of turmeric cell measurement, these values were 5.5 kHz at low frequency and 1.4 MHz at high frequency [33].

The conductivity of the materials increased after the pre-treatment revealed that the plant cell permeabilization increased or the cell membrane was damaged [51]. According to Hayden et al. [53], the damage out the outer plasma membrane of the plant cells will reduce the impedance of materials.

It is essential to understand the effect of the preparation condition on the impedance result. According to Knirsch et al. [54], the impedance of the material could change when it is measured along or across the slice. The different plant cell arrangements could explain this phenomenon in each orientation [54]. Another point that should be considered is that the impedance measurement should take place right after the pre-treatment due to the changing of moisture content could affect the conductivity of the materials [48]. Besides, the temperature of the measurement should be constant due to impedance of plant tissues could be changed by heat [55, 56].

Besides, the particle size may affect the electrical conductivity of materials; with the smaller size, the conductivity tends to increase. In addition, the particle shape and
orientation also affect the conductivity of the materials [57]. The disintegration of the cell will decrease the impedance of the materials [54]. Based on the literature, there are also numerous reasons for cell impedance reduction, such as tissue shrinkage, dehydration of material, starch gelatinization by thermal treatment, ion concentration, pH value and fat content of materials, and the viscosity of the environment [54, 58, 59].

When applying the pre-treatment, the cellular membrane can be temporarily damaged (reversible) or permanently damaged (irreversible) [60]. The pre-treatment principle and the pre-treatment conditions will decide the cell damage status. In some cases, the reversible damage cells return to normal after stopping the treatment, such as PEFAE [61] and ohmic heating-assisted extraction (OHAE) [59]. Sometimes, the damaging effect could last for hours after the release of the treatment, such as high-pressure-assisted extraction (HPAE) [48]. Especially, the cell plant destruction was also promoted for hours after the treatment stopped [48]. The CDI measurement offers numerous advantages for evaluating the pre-treatment effect on the turmeric plant cells [33].

**Effect of Starch Content on the Curcumin Extraction Process**

Starch grains are in turmeric’s inner and outer cores, with triangular, rod, or spindle shapes (Table 1). The starch content in turmeric could be up to 44.15% w/w [62]. Besides, amylose content in isolated turmeric starch was around 48.4% of total starch [63], making the material become swell and burst under the effect of high temperature. These factors could affect the behavior of the aqueous phase during the thermal process. The interaction between starch and water under the impact of H\(^+\) ion also improves the starch hydrolysis [64], which could reduce the viscosity of the aqueous phase and increase the diffusion of curcumin during the extraction. Interestingly, turmeric starch starts paste and gelatinization at temperatures higher than 70 °C [65]. So, the techniques with a treatment temperature lower than 70 °C could not efficiently break the starch granule and release amylose.

Recently, numerous studies have removed the turmeric starch before curcumin extraction; enzymes such as α-amylase and amyloglucosidase are used to assist curcumin extraction [31, 66].

**Effect of Pectin Content on the Curcumin Extraction Process**

The pectin content in turmeric rhizome is around 6.3% w/w [32]. During thermal pre-treatment, pectin could increase the viscosity of the aqueous phase and become a barrier to curcumin diffusion. In addition, when linked to cellulose, pectin provides rigidity and cohesion to cellular walls [67, 68]. Pectinase increases fruit juice exploitation in the food industry by reducing viscosity and improving filtration efficiency [20]. Pectinase has a more significant application in the food industry than amylase; in addition, some previous studies on curcumin extraction showed the efficiency of pectinase on curcumin extraction [33, 66]. In the recent research of Le-Tan et al. [33], curcumin extraction yield reaches 58% when incubated turmeric with pectinase for 1 h prior to extraction (Table 3).

**Particularities of Curcumin and Curcumin Stability During Extraction**

In turmeric, curcumin is present with demethoxycurcumin (DMC) and bisdemethoxycurcumin (BDMC), which are called curcuminoids; the typical ratio is about 77% of CUR,
### Table 3  Impact of cell disintegration techniques on curcumin extraction

| Techniques | Raw material | Optimized processing conditions | Finding | References |
|------------|--------------|---------------------------------|---------|------------|
| UAE        | Dried powder, material size: <0.18 mm | Power: data not given Amplitude (%): 60 Pulsed duration/interval time: 3/1 Treatment time (min): 10 Amount of sample (g): data not given Temperature: data not given Extraction solvent: ethanol 83% Material/solvent ratio: data not given | Recovery rate: 1.03 g/100 g. The rate constant was 1.55 × 10^{-2} min^{-1} | [91] |
| Dried powder, material size: 0.09–0.85 mm | Power (W): 250 Amplitude (%): data not given Treatment time (min): 60 Amount of sample (g): 3 Temperature (°C): 10 °C Extraction solvent: aqueous phase Material/solvent ratio: 1/10 | Extraction yield: 72%. The system’s temperature cannot be controlled adequately at significantly higher power levels | [45] |
| Dried powder material size: <0.4 mm | Power (W): 50 Amplitude (%): 100 Treatment time (min): 1 Amount of sample (g): 25 Temperature (°C): data not given Extraction solvent: ethanol Material/solvent ratio: 1/2 | Extraction yield as 78.22%. Ultrasound quickly damages the plant cells and decreases the size of materials CDE: 0.35 | [33] |
| Fresh turmeric, material size: 1×10 mm (d×L) | Power (W): 50 Amplitude (%): 100 Treatment time (min): 1 Amount of sample (g): 25 Temperature (°C): data not given Extraction solvent: ethanol Material/solvent ratio: 1/2 | Extraction yield as 41.75% | [33] |
| MAE        | Dried powder, material size: <0.841 mm | Power (W): data not given Amplitude (%): 20 Treatment time (min): 4 Amount of sample (g): data not given Temperature (°C): data not given Extraction solvent: metanol Material/solvent ratio: data not given | 100% (highest in comparison to reference methods) CDE: 1 (in comparison to reference methods) | [34] |
| Dried powder, material size: <0.125 mm | Power (W): 140 Amplitude (%): data not given Treatment time (min): 5 Amount of sample (g): data not given Temperature (°C): data not given Extraction solvent: acetone Material/solvent ratio: 1/3 | Extraction yield 68.57% w/w. The maximum extraction rate constant of 47.49 × 10^{-2} min^{-1} was observed using microwave-assisted acetone extract of water-soaked turmeric rhizomes | [92] |
| Dried powder, material size: <0.18 mm | Power (W): 80 Amplitude (%): data not given Treatment time (min): 10 Amount of sample (g): data not given Temperature (°C): data not given Extraction solvent: ethanol Material/solvent ratio: 1/200 | Extraction yield: 1.01%. The rate constant was 1.46 × 10^{-2} min^{-1} | [91] |
| Dried powder material size: <0.4 mm | Power (W): 50, 100, 150 Amplitude (%): 100 Treatment time (min): 1 Amount of sample (g): 3 Temperature (°C): 10 Extraction solvent: aqueous phase Material/solvent ratio: 1/2 | Extraction yield: 4.42%. The pH 5.0 balances the solubility and stability of curcumin extract in the aqueous phase | [37] |
| Techniques | Raw material | Optimized processing conditions | Finding | References |
|------------|--------------|----------------------------------|---------|------------|
| EAE        | Dried powder, material size: <0.4 mm | Type of enzyme: α-amylase Activity: \(3 \times 10^5\) DU/ml pH: 5 Incubation time (min): 300 Extraction time (min): 480 Temperature (°C): 32 Amount of sample (g): 50 Material/solvent ratio: 1:2.5 | Extraction yield: 3.92%. An increase of 26.04% compared to the control sample | [66] |
|            | Dried powder, material size: <0.4 mm | Type of enzyme: glucoamylase Activity: \(^1\times 10^5\) DU/ml pH: 4.5 Incubation time (min): 300 Extraction time (min): 480 Temperature (°C): 32 Amount of sample (g): 50 Material/solvent ratio: 1:2.5 | Extraction yield: 4.10% (glucoamylase) An increase of 31.83% compared to the control sample | [66] |
|            | Dried powder, material size: <0.177 mm | Type of enzyme: α-amylase and glucoamylase Activity: data not given pH: 5 Incubation time (min): 240 Extraction time (min): 160 Temperature (°C): 65 Amount of sample (g): data not given Material/solvent ratio: 1/200 | Curcumin extraction yield: 4.1%, oleoresin extraction yield: 6.27% | [19] |
|            | Dried powder, material size: <2 mm | Type of enzyme: pectinase Activity: 50,000 U/ml pH: 5 Incubation time (min): 60 Extraction time (min): 15 Temperature (°C): 65 Amount of sample (g): 25 Material/solvent ratio: 1/2 | Extraction yield as 70%. Degradation of curcumin when incubation time longer than 1 h | [33] |
|            | Fresh turmeric, material size: 1×10 mm (d×L) | Type of enzyme: pectinase Activity: 50,000 U/ml pH: 5 Incubation time (min): 60 Extraction time (min): 15 Temperature (°C): 65 Amount of sample (g): 25 Material/solvent ratio: 1/2 | Extraction yield as 53% CDF: 0.16 (pectinase) | [33] |
|            | Dried powder, material size: 0.177–0.4 mm | Type of enzyme: α-amylase and glucoamylase Activity: data not given pH: 5 Incubation time (min): 360 Extraction time (min): 120 Temperature (°C): 65 Amount of sample (g): 1 Material/solvent ratio: 1/10–1/50 | Extraction yield: 5.73%. The mixture of α-amylase and amyloglucosidase enzymes destroys the turmeric cell wall before the extraction process | [37] |
| HPAE       | Dried powder, material size: 0.36 mm | Pressure: 300 MPa Specific energy inputs: 13.9 kJ/kg Power: 80 W Treatment time (min): 5 Amount of sample (g): 3 Material/solvent ratio: 1/10 Extraction solvent: aqueous phase | Extraction yield: 8.39%. CDF: 0.72 | [37] |
17% DMC, and 6% BDMC [69]. The extracts from turmeric consist of all three components (curcuminoids), which need to be further purified for pure curcumin (Fig. 2).

Curcumin is insoluble in water at acidic and neutral pH but dissolves at high alkaline conditions [33]. According to Zheng et al. [70], when pH increases, the deprotonation of hydroxyl groups on curcumin occurs, creating numerous negative charges, increasing hydrophilicity, and the solubility in the aqueous phase. In the research of Rahman et al. [71], curcumin solubility in the aqueous phase is 231 μg/ml at pH 4.0 and increases to 482 μg/ml at pH 8.0. Interestingly, curcumin solubility increases with sodium ions and potassium ions in the aqueous phase [71, 72]. In the report of Le-Tan et al. [37], curcumin recovery increased 25.1% by increasing the pH of the aqueous extraction solvent from 2.0 to 5.0.

Curcumin stability varies depending on the environmental condition. In general, curcumin is stable at high temperatures and in acid conditions but unstable in alkaline conditions and presence of light [72, 73]. The melting point of curcumin is 183 °C [25]. Curcumin is stable at 70 °C when exposed to 10 min in the hydrophilic environment [74]. According to Lestari and Indrayanto [74], curcumin degradation intensively increased at 100 °C. The effect of heat treatment on curcumin stability was studied under different conditions. In the treatments higher than 70 °C for 30 min, the total phenolic content (TPC) in turmeric is significantly reduced [75].

Regarding photo-oxidation, curcumin degradation follows the first-order kinetics [74]. Curcumin photo-degradation begins with the formation of the excited states and singlet oxygen formation, which is responsible for the photodynamic activity of curcumin [76]. According to Lestari and Indrayanto [25], the curcumin stability was different in organic solvents, in which the curcumin half-life degradation followed acetonitrile < chloroform < ethyl acetate < methanol.

Curcumin is not stable in the aqueous phase; the orange-yellow color of curcumin rapidly disappears in the physiological pH conditions [77]. The degradation products of curcumin are vanillin, ferulic acid (FA), and feruloyl methane [78]. In the research of Lestari and Indrayanto [74], vanillin was considered a primary degradation product, and its appearance when incubation was extended.

Curcumin solution changes color in the different pH conditions; at acidic acid, curcumin solution turns red, at pH 1–7, curcumin solution is yellow, and at pH higher than 7.5, the color turns orange-red [72, 79]. The red color at low pH value was due to the presence of curcumin in the protonated form [74], and in the alkaline condition, the formation of degradation products increase the overall absorbance [80]. Interestingly, the curcumin changes solubility in the aqueous phase at different pH conditions, which dissolve at alkaline pH conditions and turn to crystals when pH reduces to acidic value [80].
aqueous solution. Curcumin stabled for at least 20 weeks in the organic solvent at 20 °C [78]. Besides, it was found that curcumin was more stable in the dried/solid state [82]. It is important to understand the effect of curcumin degradation under different solvent conditions (pH, temperature, polarity) to design the processing method in the food industry properly. In the research of Gordon et al. [77], the curcumin degradation could be reduced by adding BDMC and DMC into pure curcumin. According to Gordon et al. [77], DMC and BDMC suffer less from autoxidation than curcumin.

Regarding photo-degradation, curcumin strongly absorbs photons in the visible wavelength [83]. Curcumin photo-degradation starts with the formation of the excited states and singlet oxygen creation [33]. Because of these observations, the process of curcumin extraction should adapt with the criteria such as fast, inhibit of light, less contact time with the alkaline condition, and aqueous phase. It is very important to fully understand the properties of curcumin, raw material, and the mechanism of the pre-treatment techniques.

Efficiency of Assisted Extraction Techniques on the Curcumin Recovery Process

Reference Method

In the literature, the conventional techniques for curcumin extraction have been fully reported, such as soxhlet extraction, maceration, and hydrodistillation. These techniques required high temperature, long extraction time, and organic solvent usage. Furthermore, soxhlet has been known as a reference method with a high extraction yield compared with the newly developed methodology [84]. Soxhlet extraction is a conventional and classical method, using organic solvent at boiling temperature to extract target components [85]. Besides, thermal treatment was combined with maceration to increase the curcumin extraction yield. According to Maskooki and Eshtiaghi [61], the thermal treatment with 70–80 °C in 10–20 min could destroy the plant cell membrane. Moreover, Ade-Omowaye et al. [86] demonstrated that a temperature higher than 70 °C is necessary to improve thermal process extraction.

Nonetheless, conventional such as soxhlet, maceration, or hydrodistillation requires prolonged treatment, high-energy consumption, and organic solvent usage [84, 87]. Moreover, these methods could cause the degradation of sensitive compounds. In recent years, cell disruption methods have been an attractive green technology that applied emerging techniques to change the structure of turmeric cells and increase curcumin recovery yield. Recently, these techniques were successfully applied to increase curcumin recovery, such as ultrasound-assisted extraction [45], microwave-assisted extraction [23], enzyme-assisted extraction [88], high-pressure processing [89], pulsed electric field-assisted extraction [90], and ohmic heating-assisted extraction [37] which strongly impact on the turmeric cell membrane to increase the recovery efficiency with minimum effect on the curcumin degradation.

Two possible application scenarios will be considered for some of the technologies: (i) technology applied as pre-treatment followed by the extraction process and (ii) the technology applied simultaneously during the extraction. Each technique has advantages and disadvantages, which are shown in Table 4. Based on these criteria, the researcher could choose an appropriate procedure that suits individual requirements. The mechanism of these techniques and the process efficiency will be further discussed in the following sections.
Ultrasound-Assisted Extraction

Ultrasound-assisted extraction (UAE) has been known as an effective and intensive technique for assisted essential component extraction [99, 100]. The generation of cavitation bubbles with ultra-high temperature and pressure create microturbulence, high-velocity stream circulation inside the sample, particle collisions, and possible rupture of the tissue [15, 16, 101]. These phenomena accelerate solvent penetration and component diffusion [102], increasing extraction efficiency.

Additionally, ultrasound could reduce the particle size of materials under the effect of micron size cavitation [45]. In recent studies, UAE was proven as a save energy method [101] which could create massive effects in a very short time [16]. UAE improved the extraction efficiency by two mechanisms: (a) the penetration of solvent across the tissue and (b) rinsing the component inside the plant cell after weakening the cell wall [103, 104]. Mason [105] reported that ultrasound waves generate intense shear force, microturbulences, and shock waves. During the treatment, extreme motion energy transforms to heat, which induces mass transfer [84, 101]. The obtained temperature and pressure of the microbubbles could reach 5000 K and 1000 atm, respectively [84, 105, 106]. Interestingly, the heating and cooling rate is above 1010 K/s [106]. In recent years, UAE and microwave-assisted extraction (MAE) were the most common non-conventional techniques used for curcumin extraction [12, 14–17, 19, 45, 92, 107, 108]. Both showed high extraction efficiency, less energy usage, and solvent consumption [12, 13]. The advantages and disadvantages of the UAE are shown in Table 4.

Table 4 Advances and disadvantages of the cell disintegration techniques in curcumin extraction

| No. | Cell disintegration method | Advantages | Disadvantages | References |
|-----|---------------------------|------------|---------------|------------|
| 1   | Conventional method (grinding, maceration, heating) | High extraction yields, Does not require sophisticated equipment | High cost of production (energy, high solvent consumption), Troubles when grinding because of the high oleoresin content in turmeric, Curcumin is sensitive to long exposure time | [12, 13] |
| 2   | Ultrasound-assisted extraction | Rapid, intense, and efficient method for curcumin extraction | Reduce curcumin content by thermal degradation, Requires a small size of the material to get a homogenous effect, Pectin and starch in turmeric might diffuse to the solvent when the cell is destroyed | [14–16, 45] |
| 3   | Microwave-assisted extraction | Simple, fast, and economical method for curcumin extraction | Might cause thermal degradation, Pectin and starch in turmeric might diffuse to the solvent when the cell is destroyed | [23, 34, 91, 93] |
| 4   | Enzyme-assisted extraction | Rapid and efficient extraction with minimal usage of solvents, Selective extraction | High cost of the enzymes, Curcumin is not stable in water | [37, 94] |
| 5   | High-pressure-assisted extraction | Uses non-flammable, non-toxic solvent, Non-thermal process, Low energy usage, Controllable process, minimum effect on curcumin molecules | High cost of instrumentation, Batch processing | [33, 95] |
| 6   | Pulsed electric field-assisted extraction | Extremely fast, High extraction yield, Non-thermal process, Low energy usage | High costs of instrumentation, Treatment of solid material requires immersion in water, but curcumin is not stable in water, Air bubbles must be removed to allow uniform electric field distribution | [52, 60, 96] |
| 7   | Ohmic heating-assisted extraction | Fast (a few minutes) requires the minimum amount of organic solvent, Highly applicable to a laboratory-scale context | High cost of instrumentation, It is challenging to model the thermal process because of the changes in electrical conductivity in turmeric’s inner and outer zones, High starch content in turmeric might promote gelatinization and inhibit curcumin extraction | [97, 98] |
The curcumin extraction by UAE was affected by the material particle size, enzyme content, enzyme activity, the pH condition, incubation temperature, time, and shaking speed [109]. In the report of Shirsath et al. [45], the optimized parameters for curcumin extraction by UAE were 35 °C, solid/liquid ratio of 1:25 (g/ml), US power and frequency at 250 W and 22 kHz, respectively, ethanol as dispersed solvent, and material size was 0.09 mm. The result showed that curcumin recovery was 72% after 1 h, higher than the conventional extraction after 8 h of extraction (62%). Regarding pulsed ultrasound treatment, the curcumin recovery rate was 1.01 g/100 g, and extraction rate constants were 1.46 × 10^{-2} min^{-1} (Table 3). In the recent study of Le-Tan et al. [37], the curcumin extraction by ethanol reached 72% with dried turmeric and 41.73% with fresh turmeric (Table 3). These results are similar to the study of Shirsath et al. [45], and the curcumin extraction yield of dried turmeric reached 72% (Table 3).

Regarding pulsed UAE, the total duration and interval time were the main parameters influencing extraction [91]. According to Li et al. [91], curcumin extraction yield decreases if prolonged interval time. In some cases, the high US power could reduce the extraction yield due to the degradation of sensitive compounds [45]. Hence, it is essential to understand the effect of US on the materials and the properties of the desired compounds. Notable, the temperature during the US treatment could not be controlled fully due to the very intense impact from the ultrasonic wave in a short time [110, 111].

Based on the literature, it is vital to understand the limited use of the UAE for natural products. For instance, the high frequencies at 358–850 kHz or high power (> 750 W) could degrade sensitive compounds [112]. Furthermore, the low frequency at 20 kHz combined with high power of 1500 W was also found to degrade anthocyanin [113]. Moreover, the acoustic cavitation could produce radicals in the material such as OHAE and H radicals, which may trigger degradation chain reactions of the product [114–117].

UAE is a promising technique for curcumin-assisted extraction due to numerous advantages over conventional techniques. However, the extract's quality and drawbacks of the techniques are not fully evaluated [112]. According to Pingret et al. [112], the material matrix and the target extraction components must be carefully considered. Based on recent studies, UAE has been shown as a potential technique to improve curcumin recovery. Compared to conventional extraction methods, the UAE noticeably reduces extraction time energy consumption and improves extraction yield [45]. UAE can be applied in different extraction systems or combined with other methods to increase extraction efficiency [118].

Microwave-Assisted Extraction

MAE has long been known as a rapid and economic-assisted extraction method [119] which requires less energy due to directly heating inside the product [24]. Unlike conventional heating techniques, MAE easily breaks the hydrogen bonds in the materials by electromagnetic effect, resulting in increased solvent penetration and diffusion of soluble compounds into the solvent [107, 108]. According to [120], MAE has been proved a promising assisted extraction technology, which could minimize the thermal degradation of the bioactive compound due to rapid heating mechanism and create fast mass transfer [24]. Yixuan et al. [13] stated that the primary mechanism of MAE is the generation of heat effects by dipole rotation and ion conduction. The transfer of electromagnetic waves induces inside the samples, which significantly improves the mass and heat transfer [120]. Due to microwave irradiation, the cell wall could be degraded by thermal effect, increasing extraction rate and extraction efficiency [92, 121].

Water content in the samples is the prime motivation in the heating process by MAE [108]. The objective of MAE is to heat the moisture in the plant cell, which causes enormous pressure on the cell wall [122]. Based on this effect, the cell wall weakens inside, and cell rupture occurs [123]. Besides, the existing studies suggested that the dielectric susceptibility of the solvent and plant cell matrix play a vital role in MAE utilization [124].

The advantages and disadvantages of MAE are shown in Table 4. The application of MAE in bioactive compound extraction is gaining more attention due to its rapid setup, energy-saving, and feasibility [125]. Besides, MAE could save solvent consumption [126] and, therefore, be considered environmentally friendly technology [12]. Regarding the conventional heating methods, the heat is transferred from the heating wall to the solvent and from the solvent to the material; this process consumes high energy levels and time [122]. However, in terms of MAE, the heated plant cells dramatically increase the temperature due to volumetric heating, leading to cell expansion and cell wall disruption by the internal pressure [119]. As a result, the cell wall opened and released the essential compounds from the plant matrix. Ameer et al. [102] have confirmed the role of radiation waves by MAE, and the rapid heating up of moisture trapped inside the plant matrix could damage the plant matrix. According to Ameer et al. [102], due to the absorption of photonic energy from microwaves, the high temperature was generated from the dehydration of cellulose and created mechanical damage to the cell wall.

In order to decide the optimized parameters for the MAE process, the various levels of microwave power, solvent volume, and treatment time could be investigated [12, 118]. In addition, MAE could be combined with other techniques
like ultrasound [127] or enzyme [128] to increase the efficiency of the process. In the report of Yixuan et al. [13], the combination of UAE and EAE increased the extraction rate and antioxidant activity by 2.89% and 83.95%, respectively. In Wakte et al. [92] report, MAE is more efficient than ultrasound and supercritical CO₂ (scCO₂) in terms of extraction yield and extraction time. Apart from other factors, the material characteristic and aspects played an essential role in curcumin extraction by MAE [102]; this form includes material moisture, particle sized, sieved, or pre-leached. In the literature, the irradiation time of MAE is usually shorter than 10 min (Table 3). The water soaking could increase the extraction yield of curcumin; the extraction yield was 68.57% w/w [92]. With 800 W of power, the extraction rate was 1.01 g/100 g, and the rate constant was 1.46 × 10⁻² min⁻¹ [91]. Notably, in the report of Mandal et al. [34], MAE showed the extraction yield higher than the soxhlet procedure, so the authors considered extraction yield by MAE reached 100% (Table 3).

**Enzyme-Assisted Extraction**

According to Gligor et al. [20], enzyme-assisted extraction (EAE) has gained higher popularity nowadays in bioactive compound extraction due to highly selective extraction and reduction of environmental hazards. Nevertheless, EAE requires a long incubation time, affecting the sensitive compound because of the long exposure time to oxidation [68]. In order to improve the recovery of curcumin, specific enzymes could be added, such as α-amylase, amylglucosidase, cellulase, pectinase, and xylanase (Table 3). These enzymes assisted the extraction yield by breaking the plant cell or hydrolyzing the barriers in the plant tissues (polysaccharide, cellulose) [129].

In recent years, EAE revealed the role of improving extraction yield by enabling efficient contact between enzyme and substrate, increasing cell disintegration index, and inducing mass transfer [130–132]. According to Rosenthal et al. [129], EAE breaks down the cell wall and exposes the solvent’s intracellular components for recovery. In theory, EAE was considered promising for commercial applications [118] due to its environmental and health-friendly techniques and selective extraction [133].

Numerous factors affect EAE application which include particle size of the materials, the ratio between enzyme and the material, the pH of the mixture, the incubation temperature, time, and shaking method [129–131, 133]. In the past few years, some reviews about polyphenol extraction have discussed drawbacks of conventional methods, such as environmental hazards, high consumption of volatile and flammable solvents, high-energy usage, and prolonged exposure time [10, 20, 118, 134]. However, further research on curcumin stability suggested that the soaking of curcumin with water during EAE may degrade the product or promote the oxidation process [11–13]. According to Le-Tan et al. [33], the suitable time for curcumin soaking by EAE was 1 h; a longer incubation time could induce the degradation of the extracts.

By breaking the turmeric starch granules, EAE could significantly improve the oleoresin, curcumin, and volatile oil extraction yield. In the research of Kurmudle et al. [66], α-amylase and glucoamylase increased the yields of oleoresin, curcumin, and volatile oil by 22.50%, 31.83%, and 70.00%, respectively.

Regarding EAE, the appropriate enzyme usage depends on the material characteristics [33]. In the report of Leonel et al. [62], the starch content in turmeric is around 44%, while amylose consists 48.4% of total starch [135]. Due to the high amount of starch, α-amylase and amyloglucosidase were frequently chosen [19, 66]. Turmeric contains 9% w/w of cellulose [62]. The study of Kurmudle et al. [66] showed the curcumin extraction yield was 3.44% with the mixture of xylanase and cellulase (Table 3); according to the authors, this yield was low, and the reason could be due to the low contents of xylans and cellulose in the turmeric rhizomes. The pectin content in turmeric is 6.3% w/w [32]. However, in the literature, less study of pectinase has been used for curcumin extraction. In the recent study of Le-Tan et al. [33], pectinase could improve the curcumin extraction yield by 70% (dried turmeric) and 53% (fresh turmeric). According to Le-Tan et al. [33], pectinase could increase the cell disintegration index to 16%. According to Jiang et al. [12], the maximum yield of curcumin extraction by EAE reached 4.1% under the optimum condition. Besides the enzyme type, it is vital to understand the optimum conditions of the enzyme [66]. In the research of Kurmudle et al. [66], α-amylase and glucoamylase had significantly improved the curcumin extraction yield by 31.83% w/w.

Some studies reveal the efficiency of combining EAE with other emerging techniques such as ionic liquid extraction or three-phase partitioning [88]. In the research of Sahne et al. [88], the combination of EAE and N,N-dipropylammonium-N’,N’-dipropylcarbamate (DPCARB) enhanced curcumin extraction yield to 60%.

**High-Pressure-Assisted Extraction**

High-pressure-assisted extraction (HPAE) is gaining more attention in green extraction technologies because this method requires less treatment time than conventional methods [136] and consumes less energy than other thermal treatments [137]. HPAE disrupts the plant tissue, cellular wall, membrane, and organelles resulting in improved mass transfer and solvent diffusion into the plant structure and soluble compound into the solvent [137]. According to Núñez-Mancilla et al. [138], HPAE could make the cell wall fold and collapse, changing...
the textural properties due to loss of cellular turgor and wall integrity. The treated materials released the extraction compounds rapidly due to the cell wall collapsing [139]. According to He et al. [140], the diffusion would happen faster than the untreated sample and stop when the equilibrium is reached.

In terms of HPAE, the ground turmeric was mixed with extraction solvent in the antipressure container and then tightly sealed in the HPAE treatment. The container was put in the pressure vessel, and the working pressure increased from atmosphere pressure to desired pressure (from 100 to 1000 Mpa) in a short time (several seconds to minutes) [137]. In some reports, the HPAE could reduce the particle size of materials, improve sedimentation behavior, color, and microstructure, inhibit phase separation, and change the rheological behavior [137, 139, 141, 142]. In addition, HPAE consumes 1% of energy compared to traditional heat reflux extraction [137].

Regarding assisted extraction, the appropriate pressure for HPAE treatment was at 100–1000 MPa at room temperature [137]. According to Prasad et al. [95], 400–600 MPa significantly improved the extraction yield than thermal treatment. The possible mechanism of HPAE pre-treatment on assisted extraction is that the associated proteins on the biomembrane would be solubilized during the HPAE treatment; as a result, the membrane permeability improves [48, 143]. In this regard, a significantly detectable membrane disintegration was found after HPAE treatment at 200 Mpa [48].

HPAE pre-treatment is an environmentally friendly technology for curcumin extraction due to the process being implemented in the closed system, rapid, and use less energy consumption (Table 4). This emerging technology is gaining more attention because it has no adverse effects on human health [136] and environmentally approaches for extracting bioactive components from natural sources [137]. In recent years, HPAE was considered a promising technology to assist the extraction of antioxidant compounds [144]. This approach is gaining more attention because of its high efficiency and rapid treatment [60]. In Plaza et al. [145] report, the total phenolic content was increased 15.46% with the HPAE assisted at 400 MPA/1 min. Furthermore, Prasad et al. [95] revealed that the pressure at 400–600 MPa significantly increased TPC than thermal treatment. The study of Angersbach et al. [48] has also stated that the noticeable effect of HPAE treatment at moderate pressure from 200 to 300 MPa could cause an irreversible effect on the subcellular membrane. In the report of Le-Tan et al. [37], HPAE at 300 MPa increased the cell disintegration index of the turmeric to 72.2% (Table 3), resulting in curcumin recovery reaching 8.38%.

**Pulsed Electric Field-Assisted Extraction**

Pulsed electric field-assisted extraction (PEFAE) has been frequently used in biology, biotechnology, and medicine [146]. The mechanism of this technique is applying the external electric field to create charge separation, which could induce pore formation on the membrane [52]. According to Zbinden et al. [96], pore formation is induced by the lipid rearrangement within the bilayer due to electrostatic interactions. Moreover, electroporation plays a crucial role in extraction, increasing the membrane permeability and improving extracts’ diffusion [96].

Existing studies suggested that the appropriate treatment time led to saturation of the cell disintegration index (CDI), which means that cell breakdown would not increase when prolonging the treatment time [41]. Furthermore, the food matrix and material characteristics significantly impact the efficiency of the PEFAE treatment [33]. According to Barsotti and Cheftel [147], the reversible membrane rupture can occur if the treatment remains moderate. However, if the electric field strength and treatment time increase, irreversible changes could happen [148]. In addition, the effect of PEFAE treatment also depends on the other characteristic of PEF protocol, such as pulse shape and pulse duration [149].

The advantages and disadvantages of PEFAE are shown in Table 4. PEFAE is a non-thermal treatment with minimal heat effect on bioactive compounds [61]. Besides, the PEFAE duration is ultra-short (in the range of milliseconds to microseconds) [41]; therefore, the exposure time of curcumin to the solvent will be minimized during the pretreatment-treatment. According to Maskooki and Eshtiaghi [61], PEFAE could limit the changes in food’s sensory and physical properties.

In order to investigate the efficiency of PEFAE treatment with conventional techniques, the comparison may consider different parameters. Regarding time consumption, PEFAE treatment for cell disintegration is ultra-short (≤ 1 min) compared to conventional thermal processing (≥ 10 min) [61]. To completely disintegrate sugar beet cells, the PEFAE treatment consumed 5% energy compared to the conventional thermal treatment, and the diffusion velocity of PEFAE-treated materials was noticeably accelerated [61].

In order to improve the extraction yield, PEFAE could be used as a pre-treatment method before extraction [150]. In the research of Le-Tan et al. [33], the authors used PEFAE as a pre-treatment before rapid shaking extraction by ethanol; the curcumin recovery increased 48.3%. Besides, PEFAE treatment was used to recover valuable compounds from food wastes and food by-products [151–153], which is a promising method to recover curcumin from turmeric wastes.

The curcumin extraction yield by ethanol reached 80% (dried turmeric) and 56% (fresh turmeric) (Table 3). Regarding aqueous extraction, curcumin recovery reaches 9.09 g/100 g at pH 5.0.
**Ohmic Heating-Assisted Extraction**

Ohmic heating is an emerging technology that uses an electric current to internally generate heat based on material electrical resistance [54]. Ohmic heating creates a rapid and uniform heating effect, less thermal damage to the product [154–156]. In addition, ohmic heating-assisted extraction (OHAE) is high-energy efficient compared to conventional heating [157]. According to Castro et al. [158], ohmic heating effects depend on the electric current and resistance of the material. In the research of Knirsch et al. [54], OHAE causes electroporation on the membrane of the cells. It was found that the particles in the liquid would be heated up faster than the continuous phase [54]. The previous study of Sastry and Palaniappan [159] also stated that the heating rate on the particles in a liquid is rapid due to the higher electrical resistance of the particles.

The optimized OHAE condition is that the electrical resistance of the particle is equal to the surrounding fluid [160]. Due to its high heat exchange rate, OHAE could be used as high-temperature short time (HTST) or ultra-high-temperature (UHT) treatment on solids or suspended materials [54, 59]. Based on this theory, OHAE has been developed as an alternative method for conventional pre-treatment, which assists in the extraction process [161]. Recently, numerous studies used OHAE as pre-treatment, such as the report of Pereira et al. [161] and Pereira et al. [39]. Regarding curcumin extraction, Le-Tan et al. [37] used OHAE to support the aqueous extraction of curcumin. Furthermore, OHAE is also appropriate for highly viscous products such as mash of fruit and vegetable [162].

The advantages and disadvantages of OHAE are shown in Table 4. OHAE has less effect on the color of materials [98] and provides rapid and uniform heating [163]. While conventional heating transfers the heat through the interfaces of liquid or solid particles, OHAE could create high-temperature hot spots under the effect of electrical current [54]. Based on these advantages, the heating rate of OHAE treatment lasts from a few seconds to a few minutes [164]. In the non-homogenous material, such as a mixture of the solid foods in the liquid phase, the process could be tough to control due to the fluid conductivity fluctuating in a wide range [165]. The heating rate of OHAE in the food material depends on the system’s relative conductivity and volume [166]. Notably, the heating rate in the particle is higher than the continuous phase [159, 166]. According to Palaniappan and Sastry [165], adding the salt solution might enhance the conductance of the materials and affect the efficiency of OHAE treatment. It was also found that blanching could reduce the electric conductivity of the materials due to shrinkage and porosity loss of the material [54]. It is very important to understand the rate of heat generation and the electrical conductivity of materials in OHAE application [167]. Interestingly, the electrical conductivity of food samples could be changed by numerous parameters such as field strength, amount and properties of fat in materials, and cell structure [145, 168, 169]. OHAE has been gaining more attention in recent years [170–172]. In curcumin extraction, the most recent research of Le-Tan et al. [37] on curcumin extraction by the aqueous phase showed that the curcumin recovery was 7.84 g/100 g at pH 5.0, while untreated materials had 2.68 g/100 g (Table 3).

To provide a comprehensive understanding of the matrix challenges in the turmeric material and emerging techniques used for curcumin-assisted extraction, an overview picture is seen in Fig. 2.

**Outlook**

The exploitation of curcumin by emerging technologies is a promising trend. By understanding the characteristics of turmeric rhizome, and the amount and distribution of main fractions in the turmeric tissue and cells, a better understanding of the curcumin extraction process will result. Besides, knowledge about curcumin stability in different conditions will help to enhance the quality of extracts. Furthermore, tailored recovery concepts will have the potential to help in improving the purity of released curcumin. Applying emerging technologies for curcumin recovery may have the advantage of providing a rapid extraction, less energy usage, and high efficiency, which may also result in an improved extraction process for commercial purposes. Future investigations are needed to expand the currently available processes, particularly to enhance current curcumin recovery levels further.

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**Declarations**

**Conflict of Interest** The authors declare no competing interests.

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