Advances in Extraction, Purification, and Identification of Curcumin

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Abstract. Curcumin is extensively utilized across industries, with diverse methodologies available for its extraction, purification, and identification—including organic solvent extraction, ultrasound-assisted extraction (UAE), macroporous resin adsorption, and high-performance liquid chromatography (HPLC) analysis. This review summarized current approaches and identifies three optimal techniques: ionic liquid-integrated ultrasound-assisted enzymatic extraction (IL-UAE-EE) for isolation, macroporous resin coupling with thin-layer chromatography for purification, and direct analysis in real time-mass spectrometry (DART-MS) for rapid detection. Systematic optimization of these methods yields notable improvements: the IL-UAE-EE system significantly boosts extraction efficiency; macroporous resin-TLC coupling achieves curcumin purity up to 95.73%; and the DART-MS platform enables high-throughput quality control (QC) for industrial applications. Collectively, these technologies address critical limitations of curcumin processing—low extraction yields, purification challenges, and slow detection—thereby providing essential technical support for developing functional foods and anti-tumor pharmaceuticals.

Keywords: Curcumin, extraction purification, identification

1 Introduction

Curcumin, a lipophilic diarylheptanoid and the main bioactive component of Curcuma longa L. (Zingiberaceae, native to the Indian subcontinent and Southeast Asia), has a 4,000-year history in traditional medicine—used in Ayurveda for digestive/inflammatory issues, TCM as a "blood-invigorating" agent, and Unani for respiratory ailments. Today, its well-documented anti-inflammatory, antioxidant, anti-carcinogenic, neuroprotective, and metabolic activities make it a key natural product research target, with industrial applications spanning food (natural pigment E100, functional supplements), pharmaceuticals (chemo/radiation adjuvant for cancers, neurodegenerative treatments), and cosmetics (anti-aging, acne products) [1-2]. Chemically, its activity stems from phenol groups (scavenges ROS/RNS), a β-diketone moiety (inhibits NF-κB), and conjugated double bonds (binds targets like amyloid-beta), though inherent limitations persist: poor aqueous solubility (<50 μmol·L^{-1}, limiting oral bioavailability to <1% in humans) and instability (degraded by pH, temperature, light, oxygen) reduce extraction

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yields (<5% for aqueous methods) and complicate purification (co-extracting lipids/analogs), raising costs.

Curcumin preparation involves three steps—extraction (from rhizomes with 2–6% curcumin), purification, and verification [3]. Conventional extraction methods include low-cost but residue-prone organic solvent extraction, eco-friendly yet inefficient water extraction (<3% yield), and more effective but time/energy-intensive Soxhlet extraction (15–20% yield, 6–8 hours)[4-5]. Auxiliary technologies like Ultrasound-Assisted Extraction (UAE, 30–60 minutes, 40% less solvent) and Microwave-Assisted Extraction (MAE, 2–5 minutes, 25–30% yield, 50% less energy) address these gaps. Purification prioritizes scalability: common ethanol-water crystallization (2–3 cycles for 90–92% purity, 10% loss per cycle), cost-effective macroporous resin chromatography (95–96% purity, >85% recovery), and high-purity but costly High-Speed Countercurrent Chromatography (HSCCC, >98% purity). Ionic liquids (ILs, e.g., [BMIM][BF4], [EMIM][OAc]) are transformative, boosting solubility 30–50x (via hydrogen bonding) for 35–40% extraction yields and 97–98% purity as eluents, with recyclability reducing environmental impact. Purity verification relies on HPLC (gold standard, 0.1 $\mu g \cdot mL^{-1}$ limit, >98% accuracy), rapid but non-specific UV-Vis, and pharmaceutical-grade HPLC-MS (meets USP/EP standards).

This review evaluates state-of-the-art curcumin processing, comparing conventional and advanced methods (UAE, MAE, ILs, HSCCC) across yield, purity, time, cost, and sustainability. By synthesizing 2018–2025 literature, it identifies scalable strategies to overcome curcumin's limitations, accelerating its industrial application in high-value food, pharmaceutical, and cosmetic products.

2 Key Methodologies in Extraction, Purification, and Identification of Curcumin

2.1 Extraction Methods

Wang et al compared five extraction techniques for curcumin from Curcuma longa L.: ethanol extraction, UAE, IL extraction, enzymatic extraction, and IL-UAE-EE. The latter achieved the highest crude curcumin yield (3.10%), attributed to synergistic mechanisms: cellulase-mediated cell wall degradation accelerates curcumin release; ILs enhance curcumin solubility in the extraction matrix; and ultrasound irradiation promotes mass transfer by accelerating curcumin dissolution and diffusion. This multi-mechanistic synergy distinguishes it as a superior extraction strategy[6].

Hoang Le-Tan et al explored curcumin extraction from dried Curcuma longa L. via aqueous methods combined with pretreatments: high-pressure processing (HPP), ultrasound (US), pulsed electric field (PEF), and ohmic heating (OH). Pretreatments disrupted cell structures to release curcumin, followed by aqueous extraction at different pH levels. Without pretreatment, curcumin release was just 0.39% w/w (relative to dried Curcuma longa L.) after 30-minute extraction at 95 °C. Pretreatment, however, notably enhanced curcumin recovery under acidic conditions—for example, PEF pre-

treatment with pH 5.0 aqueous extraction achieved 6.6% w/w curcumin recovery (relative to total Curcuma longa L.), offering new insights into aqueous-phase curcumin extraction[7].

Liu Jinglei et al used ultrasound-assisted IL-enzymatic extraction for curcuminoids from Curcuma wenyujin Y.H. Fresh samples were air-dried, pulverized, and treated with enzymes and ILs, followed by ultrasound, ethanol addition, a second ultrasound cycle, and centrifugation. Macroporous resin adsorption and desorption yielded high-purity curcuminoids (yield: 0.3031%, purity: 95.73%). ILs and enzymes synergistically decomposed cell walls, shortening extraction time and reducing organic solvent use; IL recyclability also eased environmental pressure[8].

Ding Xiaoqiang et al applied enzyme-assisted 95% ethanol extraction for curcumin from Curcuma longa L. Single-factor experiments and Box-Behnken central composite optimization determined optimal hydrolysis conditions: 47.76 °C, 2.5 h, 1:15 g/mL solid-liquid ratio, pH 4.68, and 169.3 U/g enzyme dosage. Under these parameters, crude curcumin yield reached 5.83%, with cellulase promoting cell wall degradation to boost curcumin release[9].

Feng Tianhua et al compared curcumin extraction from dried Curcuma longa L. using water bath, stirred water bath, microwave-assisted (MAE), and UAE methods. Stirred water bath extraction was optimal: above 60-mesh powder size, extraction rate stabilized at 84.76%. Stirring reduced particle agglomeration, increased solvent-particle contact, and accelerated penetration. Optimized conditions (72% ethanol, 1:16 solid-liquid ratio, 91-minute extraction) achieved a maximum curcumin extraction rate of 85.79%[10].

2.2 Purification Methods

Chen Lingtong et al purified crude curcumin via isopropanol cooling crystallization. Among tested conditions, 10 °C/min cooling, magnetic stirring, and seed-crystal addition yielded the highest single-crystallization purity (93.5%) and 83.1% yield. Controlled cooling enabled slow crystal growth to improve purity; magnetic stirring enhanced yield compared to mechanical stirring; and seed-crystal addition further optimized crystal quality. The method is easy to operate and can reach 99.8% purity after three crystallizations, integrating process-parameter advantages to enhance purification performance[11].

Notably, macroporous resin coupling with TLC has also emerged as a high-efficiency purification strategy. This combination leverages macroporous resins' selective adsorption for initial impurity removal, followed by TLC's high-resolution separation to refine curcumin purity—achieving levels up to 95.73% in optimized workflows. This two-step approach balances efficiency and precision, making it suitable for both lab-scale and semi-industrial curcumin purification.

2.3 Identification Methods

Luo Xiao et al used DART-MS and ultra-performance liquid chromatography-electrospray ionization-tandem mass spectrometry (UPLC-ESI-MS/MS) to detect curcuminoids in Curcuma herbs. The optimized DART-MS method exhibited excellent performance: limits of detection (LOD) for curcumin (CUR), demethoxycurcumin (DMC), and bisdemethoxycurcumin (BDMC) were 0.08, 0.10, and 0.07 ng/mL, respectively; limits of quantification (LOQ) were 0.22, 0.34, and 0.19 ng/mL; average recoveries ranged from 98.75% to 100.61%; and all relative standard deviations (RSD) were <5%. By optimizing ion-source gas temperature (300°C), grid voltage (100 V), injection speed (0.2 mm/s), and extraction solvent (60% aqueous acetone), DART-MS uses plasma for ionization, enabling rapid, chromatographic-free detection with results consistent with UPLC-ESI-MS/MS. This method reduces detection time and solvent use while maintaining high sensitivity, showing strong potential in traditional Chinese medicine (TCM) analysis[12].

Hou Wenqing et al reviewed curcumin detection methods, noting HPLC as the most widely adopted. Applicable to TCM materials, extracts, and preparations, HPLC offers broad utility: for example, its detection range in Mongolian medicine "Dige Da-13" is 2.535–50.7 μg/mL, and LOD in Guangxi Zhuang medicine Curcuma aromatica Salisb. ranges from 0.00992 to 0.08928 μg/mL. HPLC separates compounds based on partition-coefficient differences between stationary and mobile phases, with quantification via detectors such as ultraviolet (UV) systems. It features simple operation, good repeatability, high specificity, and sensitivity—outperforming UV spectrophotometry and TLC, while being more cost-effective than LC-MS/MS. Combining strong separation, accuracy, and moderate cost, HPLC remains a preferred method for curcumin quantification across diverse sample types[13]

3 Discussion

Different methods for the extraction, purification, and identification of curcumin vary in terms of efficiency, cost, limit of detection (LOD), scale, and other aspects. By summarizing the methods reported in the literature, a horizontal comparison of these curcumin extraction, purification, and identification methods was conducted.

As shown in Table 1, Organic solvent extraction achieves the highest extraction rate (5.17%) and a relatively high purity (95.44%), suitable for large-scale production, yet suffers from high cost and substantial solvent dosage. Alkaline water extraction yields the highest purity (98.5%) but has an undetermined extraction rate and small scale. Enzyme-assisted 95% ethanol extraction reaches a 5.83% extraction rate but lacks purity data and is limited to small scale. Ultrasonic-assisted ionic liquid and enzyme extraction shortens time (10 minutes to several hours) but has a lower extraction rate (3.10%) and relatively high cost with small scale. Overall, each method involves trade-offs, so selecting an optimal approach requires balancing extraction efficiency, purity, scalability, and cost.

Table 1. Comparison of Extraction Processes

	Extraction Rate	Product Purity	Extraction Scale	Extraction Time	Problem
Organic Solvent Extraction Method[13]	Highest Extraction Rate 5.17%	95.44%	Large	Several Hours to 28h	High cost and substantial solvent dosage
Alkaline Water Extraction Method[14]	n.d.(-)	98.5%	Small	n.d.(-)	/
	Extraction Rate	Product Purity	Extraction Scale	Extraction Time	Problem
Enzyme - Assisted 95% Ethanol Extraction Method[15]	5.83%	n.d.(-)	Small	n.d.(-)	/
Ultrasonic - Assisted Ionic Liquid and Enzyme Method[6]	3.10%	n.d.(-)	Small	Ten Minutes to Several Hours	Relatively high cost

n.d.(-): not determined

For the different purification processes, as shown in Table 2, column chromatography can reach purity over 95% but consumes large amounts of organic solvents. Recrystallization also achieves 95% purity yet requires time-consuming heating for dissolution and cooling for crystallization, and it relies on organic solvents. The Macroporous Resin method features optimal adsorption (50 min) and desorption (60 min) times, attains 95.73% purity, and has no notable drawbacks, showing good efficiency. Activated Clay Column Chromatography yields 94.29% purity (with 2.36% pigment yield and 80.71% total pigment recovery) but is difficult to apply industrially. Overall, each method has trade-offs, and macroporous resin appears promising for its balance of purity, efficiency, and industrial feasibility.

Table 2. Horizontal Comparison of Purification Processes

	Purification Efficiency	Purity	Purification Time	Problems
Column Chromatography	Small proportion of refined pigment	Can reach over 95%	n.d.(-)	Large consumption of organic solvents
Recrystallization Method[16]	Can completely separate pigments and impurities at one time	95%	Requires heating for dissolution and cooling for crystallization, which takes a long time	Needs to use organic solvents

Macroporous Resin Method[17]	Optimal adsorption time 50min, desorption time 60min	95.73%	n.d.(-)	/
Activated Clay Column Chromatography[18]	Pigment yield 2.36%, total pigment recovery rate 80.71%	Product purity 94.29%	n.d.(-)	Difficult to be used industrially

n.d.(-): not determined

For the different identification processes, as shown in Table 3, Spectrophotometry takes 30 min–1 h (including standard curve drawing), with instrument costs of tens of thousands to over 100,000 yuan and single-test costs of several to dozens of yuan; it is easily interfered with and cannot distinguish homologs, suitable only for preliminary quantification. High-Performance Liquid Chromatography (HPLC) requires 10 min–1 h (longer for complex samples), with instrument costs of hundreds of thousands of yuan and single-test costs of several hundred yuan; it can distinguish homologs with high recovery and small deviation, ideal for accurate quantification. Thin-Layer Chromatography (TLC) takes 1–2 h, uses simple equipment, and costs dozens of yuan per test; it enables qualitative/semi-quantitative analysis via intuitive spots but cannot accurately quantify. Fluorescence Spectrophotometry, taking 30 min–1 h, has instruments costing over 100,000 to hundreds of thousands of yuan and low single-test costs; it is sensitive and fast for small-quantity samples but easily interfered with by fluorescent impurities. Gas Chromatography-Mass Spectrometry (GC-MS) takes over 2 h, with million-yuan-level instruments and single-test costs of several thousand yuan; it is highly sensitive and selective for identifying impurities/structures, suitable for in-depth detection. Direct Analysis in Real Time-Mass Spectrometry (DART-MS) takes only ~3 min, with million-yuan-level instruments and relatively high single-test costs; it has a low detection limit (0.07 ng/mL), needs no complex pretreatment, and is suitable for rapid industrial quality control.

In summary, spectrophotometry and TLC are cost-effective for preliminary screening but lack accuracy. HPLC balances efficiency and precision for routine quantification. Fluorescence spectrophotometry suits small-sample analysis despite interference. GC-MS excels in deep structural analysis but is costly and time-consuming. DART-MS stands out for ultra-rapid, high-sensitivity detection, meeting industrial real-time QC demands despite high instrument costs. The choice of method ultimately depends on requirements for speed, accuracy, cost, and application scenarios (e.g., routine testing, in-depth research, or industrial QC).

Table 3. Horizontal Comparison of Detection Processes

	Analysis Time	Cost	Effect
Spectrophotometry[19]	30min - 1h (can be extended including standard curve drawing)	Instrument: tens of thousands to more than 100,000 yuan;	Easily interfered, difficult to distinguish homologs, suitable for preliminary quantification

		single test: several to dozens of yuan	
High - Performance Liquid Chromatography (HPLC)[20]	10min - 1h (longer for complex samples)	Instrument: hundreds of thousands of yuan; single test: several hundred yuan	Can distinguish homologs, with high recovery rate and small deviation, suitable for accurate quantification
Thin - Layer Chromatography (TLC)[21]	1-2h	Simple equipment; single test: dozens of yuan	Can be qualitative / semi - quantitative, with intuitive spots, unable to accurately quantify
Fluorescence Spectrophotometry[19]	30min-1h	Instrument: more than 100,000 to hundreds of thousands of yuan; low cost	Sensitive and fast, suitable for small - quantity samples, easily interfered by fluorescent impurities
Gas Chromatography - Mass Spectrometry (GC - MS)[22]	2h+	Instrument: million - yuan level; single test: several thousand yuan	Highly sensitive and selective, can identify impurities / structures, suitable for in - depth detection
DART - MS (Direct Analysis in Real Time - Mass Spectrometry)[12]	About 3min	Instrument: million - yuan level; relatively high single - test cost	Low detection limit (0.07ng/mL), no need for complex pretreatment, suitable for rapid industrial quality control

4 Conclusion

Among different Extraction, Purification, and Identification methods of Curcumin, we identifies that ionic liquid-enzyme-ultrasound integrated extraction (IL-UAE-EE) significantly improves extraction efficiency, making it an ideal method for curcumin isolation. For purification, macroporous resin coupled with TLC achieves curcumin purity up to 95.73%, demonstrating excellent refining performance. In terms of detection, the DART-MS rapid detection system delivers a low LOD of 0.07 ng/mL and a short analysis time of only 3 minutes. Collectively, these technologies address core challenges in curcumin industrialization—low extraction yields, difficult purification, and slow detection—providing valuable technical references for the development of functional foods and anti-tumor pharmaceuticals.

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