IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Curcumin Bioextraction And Functional Uses: A Review Of Methods And Applications

Dr. Sharad K. Awate
Assistant Professor
South Indian Children's Education Society's
Degree College of Arts, Science & Commerce,
Jambhul Phata Chikloli Ambernath (W)

Abstract

Curcumin, the principal bioactive compound derived from *Curcuma longa* (turmeric), has garnered significant attention due to its potent pharmacological properties, including antioxidant, anti-inflammatory, antimicrobial, and anticancer activities. This review comprehensively examines the advancements in curcumin extraction and purification techniques from plant materials, highlighting both conventional methods and emerging green technologies such as ultrasound-assisted, microwave-assisted, and supercritical fluid extraction. A critical comparison of these methods is provided based on extraction efficiency, environmental impact, and scalability. Furthermore, the review explores the diverse functional applications of curcumin across pharmaceuticals, nutraceuticals, food industries, cosmetics, and agriculture. Challenges associated with curcumin's low bioavailability and chemical stability are also discussed, along with potential strategies like nanoencapsulation and formulation improvements. The paper concludes with future prospects in bioengineering and industrial-scale production, emphasizing curcumin's role as a sustainable, multifunctional natural compound.

Keywords

Curcumin; *Curcuma longa*; Bioextraction; Green extraction methods; Purification; Pharmacological applications; Food additives; Nanoformulation; Antioxidant; Natural products

1. Introduction

Curcumin, a natural polyphenolic compound, is the primary bioactive ingredient found in the rhizomes of Curcuma longa, commonly known as turmeric. With a long-standing history in traditional Ayurvedic and Chinese medicine, curcumin has gained global attention for its diverse therapeutic properties, including antioxidant, anti-inflammatory, antimicrobial, anticancer, and neuroprotective effects. These bioactivities make curcumin a promising agent for applications across pharmaceuticals, nutraceuticals, cosmetics, and functional food industries.

Turmeric, the most abundant source of curcumin, belongs to the Zingiberaceae family. Other species within the Curcuma genus, such as Curcuma aromatica and Curcuma zedoaria, also contain curcuminoids, albeit in varying concentrations. The yield and purity of curcumin depend significantly on the species, geographic origin, cultivation conditions, and processing methods used. Given the increasing global demand for curcumin-based products, developing efficient, sustainable, and scalable extraction and purification technologies is essential.

This review aims to provide a comprehensive overview of curcumin bioextraction from plant materials, focusing on both traditional and advanced extraction techniques. Additionally, the paper discusses purification strategies, characterization approaches, and the functional applications of curcumin across multiple sectors. By critically analyzing current practices and emerging innovations, the review intends to identify key challenges and propose future directions for optimizing curcumin utilization as a multifunctional natural compound.

2. Curcumin: Chemistry and Properties

2.1 Chemical Structure and Molecular Formula

Curcumin is a polyphenolic compound derived from the rhizomes of Curcuma longa (turmeric). Its chemical structure consists of two aromatic ring systems containing o-methoxy phenolic groups, connected by a seven-carbon linker consisting of an α,β-unsaturated β-diketone moiety. The molecular formula of curcumin is C21H20O6, and its structure allows for various chemical modifications to enhance its pharmacokinetic properties and therapeutic efficacy. (Slika & Patra, 2019), (Ahmed et al., 2024), (Abd El-Hack et al., 2021)

2.2 Physical and Chemical Properties

Curcumin is characterized by its yellow-orange color and is poorly soluble in water (<8 μg/mL), which limits its application in aqueous environments (Salem et al., 2014), (Suresh & Nangia, 2018). It is more soluble in organic solvents such as ethanol, methanol, and acetone. Curcumin is chemically unstable in alkaline conditions (pH ≥7), where it undergoes rapid degradation, while it tends to crystallize out in acidic solutions (pH <7) (Kharat et al., 2017), (Salem et al., 2014). The compound is sensitive to light, heat, and oxygen, which can further contribute to its degradation. In emulsions and encapsulated forms, curcumin demonstrates improved stability, especially under acidic conditions and at lower temperatures. (Peng et al., 2018),

2.3 Bioavailability and Stability Issues

Curcumin suffers from poor oral bioavailability due to several factors: low water solubility, limited absorption in the gastrointestinal tract, rapid metabolism, and quick systemic elimination (Slika & Patra, 2019), (Ahmed et al., 2024), (Tsuda, 2018), (Salem et al., 2014), (Suresh & Nangia, 2018), (Dei Cas & Ghidoni, 2019) After oral administration, only a small fraction is absorbed, and it is rapidly metabolized in the liver and excreted, resulting in low plasma concentrations (Suresh & Nangia, 2018) Chemical instability, especially in alkaline environments, further reduces its effective concentration in biological systems (Kharat et al., 2017), (Salem et al., 2014)

To address these challenges, various strategies have been developed, including encapsulation in nanoparticles, emulsions, and complexation with proteins or other bioactive compounds. These approaches have been shown to significantly enhance curcumin's solubility, stability, and bioavailability. For example, saponin-coated curcumin nanoparticles increased in vitro bioaccessibility by 3.3-fold and in vivo bioavailability by 8.9-fold compared to free curcumin2. Emulsion-based delivery systems and solid-state formulations (such as cocrystals and coamorphous forms) also improve curcumin's physicochemical properties and oral bioavailability (Kharat et al., 2017), (Salem et al., 2014), (Suresh & Nangia, 2018) (Abd El-Hack et al., 2021).

Table no. 1. Curcumin: Chemistry and Properties

Sr.No.	Property	Description
1	Chemical Structure	Polyphenol, $C_{21}H_{20}O_6$, two aromatic rings with o-methoxy phenols, β-diketone linker
2	Solubility	Poor in water (<8 μg/mL), better in organic solvents
3	Stability	Unstable in alkaline pH, degrades with light/heat/oxygen, improved in emulsions/nanoparticles
4	Bioavailability Issues	Low absorption, rapid metabolism, quick elimination, low plasma levels
5	Enhancement Strategies	Nanoparticles, emulsions, protein/compound complexation, solid-state forms

3. Sources of Curcumin

Curcumin is the main bioactive compound found in turmeric, primarily sourced from the rhizomes of Curcuma longa. The content of curcumin varies widely due to differences in species, geographic origin, and cultivation practices. Curcumin levels are highly influenced by both genetic and environmental factors, as well as by specific cultivation and harvest methods.

3.1 Botanical Origins

Curcuma longa is the primary botanical source of curcumin, widely cultivated in Asia, especially India, which is a center of turmeric diversity(Kocaadam & Şanlier, 2017), (El-Saadony et al., 2023). Other Curcuma species, such as Curcuma aeruginosa, also contain curcumin and related curcuminoids, but typically at lower or more variable levels (Nurcholis et al., 2019)

3.2 Variability in Curcumin Content

There is significant variability in curcumin content among different turmeric genotypes and accessions, with reported ranges from as low as 0.4% up to 7.2% depending on the region and genotype (Akbar et al., 2016), (Kocaadam & Şanlier, 2017), (Dudekula et al., 2022) Studies show that both genotype (genetic makeup) and environment (location, climate, soil) play major roles in determining curcumin levels. Some genotypes are more stable and consistently high in curcumin across environments, while others are more sensitive to environmental changes (Aarthi et al., 2020), (Anandaraj et al., 2014) (Akbar et al., 2016) (Dudekula et al., 2022). In Curcuma aeruginosa, even when grown in the same environment, different accessions showed some variability in curcumin and related compounds, though less pronounced than in C. longa (Nurcholis et al., 2019)

3.3 Influence of Cultivation and Harvest Methods

Environmental factors such as altitude, soil pH, nitrogen, potassium, temperature, and humidity significantly affect curcumin content in turmeric (Sandeep et al., 2016), (Akbar et al., 2016) Specific cultivars and genotypes respond differently to these factors, with some being more stable and others more variable in curcumin production across different agroclimatic zones (Aarthi et al., 2020) (Anandaraj et al., 2014). Optimizing cultivation practices and selecting suitable genotypes for specific environments can help maximize curcumin yield and quality (Dudekula et al., 2022)

4. Extraction Techniques

4.1 Solvent Extraction:

Extraction techniques are essential for isolating valuable compounds from plant and other biological materials. Conventional methods such as solvent extraction, Soxhlet extraction, and maceration have been widely used, but they often require large amounts of solvents, longer extraction times, and may have lower selectivity and efficiency. Modern extraction methods—including ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), and enzyme-assisted extraction—have been developed to address these limitations, offering higher yields, improved purity, reduced processing times, and lower environmental impact (Macias-Frotto et al., 2024)

4.2 Soxhlet Extraction

Soxhlet extraction is a widely used conventional technique that allows continuous extraction with fresh solvent. It generally provides higher yields than simple maceration but is time-consuming (often several hours) and requires significant solvent volumes. Soxhlet is effective for exhaustive extraction but is less environmentally friendly due to solvent use and energy consumption. (Chuo et al., 2020), (Anandaraj et al., 2014), (Haido et al., 2024)

4.3 Ultrasound-Assisted Extraction (UAE)

UAE uses ultrasonic waves to enhance mass transfer, resulting in higher extraction yields and shorter processing times compared to conventional methods. UAE is considered a green technique as it reduces solvent and energy consumption and can improve selectivity and purity of extracts. (Nurcholis et al., 2019), (Chuo et al., 2020), (Mwaurah et al., 2019)

4.4 Microwave-Assisted Extraction (MAE)

MAE employs microwave energy to rapidly heat the solvent and plant matrix, significantly reducing extraction time and solvent usage. MAE often achieves higher yields and better purity in a matter of minutes, making it one of the most efficient and sustainable extraction methods available. (Nurcholis et al., 2019), (Chuo et al., 2020), (Mwaurah et al., 2019), (MEHRA, 2023) & (Haido et al., 2024)

4.5 Supercritical Fluid Extraction (SFE)

SFE, often using supercritical CO_2, is a modern technique that offers high selectivity, minimal solvent residues, and is environmentally benign. SFE can achieve high yields and purity, especially for non-polar compounds, but requires specialized equipment and higher initial investment. (Chuo et al., 2020), (Mwaurah et al., 2019), (MEHRA, 2023)

4.6 Enzyme-Assisted Extraction

Enzyme-assisted extraction uses specific enzymes to break down cell walls, enhancing the release of target compounds. This method can improve yield and purity while operating under mild conditions, reducing the need for harsh chemicals and high temperatures, thus supporting sustainability. (Mwaurah et al., 2019),

4.7 Green Extraction Techniques and Sustainability

Modern extraction methods such as UAE, MAE, SFE, and enzyme-assisted extraction are designed to be greener and more sustainable. They minimize solvent and energy consumption, reduce hazardous waste, and often use renewable or biodegradable solvents. These advancements not only improve extraction efficiency and product quality but also align with environmental and regulatory demands for sustainable industrial practices

Table no. 2 Comparison of Methods: Yield, Purity, Time, and Environmental Impact

Sr.No.	Method	Yield & Purity	Time Required	Environmental Impact
1	Solvent Extraction	Moderate yield, variable purity	Long	High solvent use, less sustainable
2	Soxhlet Extraction	High yield, good purity	Long (hours)	High solvent/energy use
3	UAE	High yield, high purity	Short (minutes)	Low solvent/energy use, green
4	MAE	Highest yield, high purity	Very short (minutes)	Low solvent/energy use, green
5	SFE	High yield, high purity (non-polar)	Moderate	Minimal solvent, green
6	Enzyme-Assisted	High yield, high purity	Moderate	Mild conditions, green

5. Purification and Characterization

Purification and characterization are essential steps in the development and quality assurance of pharmaceuticals, natural products, and food compounds. These processes rely on a combination of purification methods, advanced analytical techniques, and strict quality control standards to ensure product purity, identity, and consistency.

5.1 Purification Methods

- **Chromatography:**

Column chromatography, especially reversed-phase high-performance liquid chromatography (RP-HPLC), is widely used for purification due to its simplicity, automation, and ability to handle complex mixtures. The choice of column is critical, as different columns offer varying selectivity and performance, necessitating careful selection based on the analyte and sample complexity(Manheim et al., 2024), (Žuvela et al., 2019), (Ionut Avrămia et al., 2024), (Tibo De Saegher et al., 2023) & (Seger et al., 2013).

- **Crystallization:**

While not detailed in the abstracts, crystallization is a traditional method for purifying compounds, often used in conjunction with chromatographic techniques.

- **Workflow Optimization:**

Automated LC screening and in silico modeling can expedite the development of purification methods, allowing rapid identification of optimal conditions and reducing manual labor. (Manheim et al., 2024)

5.2 Analytical Techniques

- **HPLC:**

High-performance liquid chromatography is the preferred method for both purification and quantitative analysis, especially for vitamins, peptides, proteins, and small molecules. Advances include the use of smaller particle columns and integrated platforms (e.g., HPLC-MS, HPLC-NMR) for improved resolution and sensitivity. (Manheim et al., 2024), (Žuvela et al., 2019), (Ionut Avrămia et al., 2024), (Tibo De Saegher et al., 2023) & (Seger et al., 2013).

- **UV-Vis and FTIR:**

UV-Vis and Fourier Transform Infrared Spectroscopy are used for qualitative and quantitative fingerprinting, enabling the assessment of sample similarity and consistency, particularly in herbal and food products (Li et al., 2021), (Amorim et al., 2022), (Móricz et al., 2020) & (Kirchert & Morlock, 2020).

- **NMR and MS:**

Nuclear Magnetic Resonance and Mass Spectrometry are high-end detectors used for structural characterization, purity verification, and identification of isomers and unknown compounds. Hyphenated techniques (HPLC-MS, HPLC-NMR) provide comprehensive profiling and authentication. (Amorim et al., 2022), (Móricz et al., 2020) & (Kirchert & Morlock, 2020).

5.3 Quality Control Standards

- **Fingerprinting and Consistency Evaluation:**

Combining spectral (UV, FTIR) and chromatographic (HPLC) fingerprints allows for robust quality consistency evaluation, distinguishing between product grades and ensuring batch-to-batch uniformity. (Li et al., 2021)

- **Process Analytical Technologies:**

Real-time monitoring and advanced control strategies (e.g., in-line UV, on-line HPLC, NIR, MALS) enhance process robustness and enable rapid quality assessment during manufacturing, supporting regulatory compliance and product release. (Armstrong et al., 2021)

6. Functional Applications of Curcumin

Curcumin, the main active compound in turmeric, is widely recognized for its diverse applications across pharmacology, food, cosmetics, agriculture, and veterinary medicine. Its multifunctional properties—

especially anti-inflammatory, antioxidant, and antimicrobial effects—support its use in health, industry, and personal care.

6.1 Pharmacological Uses

Curcumin exhibits strong anti-inflammatory, antioxidant, anticancer, antimicrobial, antidiabetic, and neuroprotective activities. It is being explored for the prevention and treatment of diseases such as cancer, cardiovascular and neurodegenerative disorders, infections, and metabolic syndromes. (Sharifi-Rad et al., 2020), (Abd El-Hack et al., 2021) & (Hu et al., 2023).

Its low toxicity and broad therapeutic potential make it a promising candidate for modern drug development, though challenges like low bioavailability are being addressed through advanced delivery systems such as nanoencapsulation. (Rafiee et al., 2019), (Hao et al., 2023)

6.2 Food Industry Applications

Curcumin is used as a natural coloring agent, food preservative, and nutraceutical ingredient due to its vibrant yellow color and health-promoting properties. (Rafiee et al., 2019), (Sharifi-Rad et al., 2020), (El-Saadony et al., 2023), (Jikah & Edo, 2024)

It enhances food appeal and shelf life by providing antioxidant and antimicrobial benefits, and is incorporated into functional foods and supplements for health support. Rafiee et al., 2019), (Sharifi-Rad et al., 2020), (El-Saadony et al., 2023), (Jikah & Edo, 2024)

6.3 Cosmetic and Personal Care

Curcumin is included in skin-care and anti-aging products for its antioxidant, anti-inflammatory, and pigmentation-regulating effects.

Its ability to protect skin from oxidative stress and inflammation supports its use in cosmetic formulations. (Rafiee et al., 2019) & (Jikah & Edo, 2024)

6.4 Agricultural and Veterinary Applications

Curcumin's antimicrobial and immunomodulatory properties are being explored for use in agriculture and veterinary medicine, such as in animal health products and as a natural additive to improve disease resistance. (Jikah & Edo, 2024)

Its role in regulating metabolic and immune functions may benefit both plant and animal health. (Hu et al., 2023)

7. Challenges and Limitations

Poor solubility, low bioavailability, degradation, stability issues, and regulatory challenges are major obstacles in the development and delivery of many drugs and bioactive compounds. These limitations can significantly reduce therapeutic effectiveness and complicate product development and approval.

7.1 Solubility and Bioavailability Challenges

Many drugs and phytochemicals have poor water solubility, which leads to low and variable bioavailability after oral administration, limiting their clinical effectiveness. (Zheng et al., 2020), (Hu, Lin, et al., 2023)

The Biopharmaceutics Classification System (BCS) highlights that poor solubility is a common cause of drug development failures and requires extensive investigation and risk assessment. (Censi & Di Martino, 2015) & (Bou-Chacra et al., 2017)

Enhancing solubility and bioavailability can be achieved through formulation strategies such as solid dispersions, encapsulation (e.g., nanoparticles, liposomes), and chemical modifications, but these approaches have practical and technical limits. (Zupančič et al., 2015) & (Kim et al., 2015)

7.2 Degradation and Stability Issues

Many compounds are chemically unstable, degrading under certain pH, temperature, or humidity conditions, which affects their shelf life and therapeutic potency. (Lehmkemper et al., 2016)

For example, trans-resveratrol is stable in acidic conditions but degrades rapidly at higher pH and temperatures, emphasizing the need for careful formulation and storage. (Zupančič et al., 2015)

Amorphous solid dispersions and polymer-based formulations can improve stability, but long-term physical stability and prevention of recrystallization remain concerns. (Liao et al., 2024).

7.3 Regulatory and Standardization Challenges

Regulatory agencies like the FDA and ICH require comprehensive screening and characterization of all polymorphic forms of a drug to ensure consistent quality, safety, and efficacy(Censi & Di Martino, 2015).

There is a lack of universal standards for measuring solubility, dissolution, and bioavailability, leading to inconsistencies and confusion, especially for globally marketed products. (Kim et al., 2015)

Harmonization of guidelines and standardization of testing methods are needed to streamline regulatory approval and ensure reliable product performance. (Bou-Chacra et al., 2017)

8 Conclusion

Curcumin, the principal bioactive compound of Curcuma longa, holds significant promise due to its wide-ranging therapeutic properties, including antioxidant, anti-inflammatory, antimicrobial, anticancer, and neuroprotective activities. However, the practical application of curcumin is constrained by challenges related to its low aqueous solubility, chemical instability, and poor bioavailability. This review has highlighted the critical factors influencing curcumin yield and purity, including botanical origin, genotype variability, and environmental and cultivation practices.

Moreover, it has comprehensively examined conventional and advanced extraction methods, from solvent-based approaches to green technologies such as UAE, MAE, SFE, and enzyme-assisted extraction. These modern methods not only improve efficiency, yield, and purity but also align with global sustainability goals. Purification strategies like RP-HPLC and complementary analytical techniques further ensure curcumin's quality for industrial and therapeutic applications.

The integration of emerging extraction technologies with optimized cultivation strategies and bioavailability enhancement methods, such as nanoparticle encapsulation and emulsion systems, offers a pathway toward maximizing the functional potential of curcumin. Future research should focus on scaling up green extraction methods, standardizing purification protocols, and developing novel delivery systems to fully harness curcumin's multifaceted benefits across pharmaceutical, nutraceutical, and food industries.

References

Aarthi, S., Suresh, J., Leela, N. K., & Prasath, D. (2020). Multi environment testing reveals genotype-environment interaction for curcuminoids in turmeric (Curcuma longa L.). *Industrial Crops and Products*, *145*, 112090. https://doi.org/10.1016/j.indcrop.2020.112090

Abd El-Hack, M. E., El-Saadony, M. T., Swelum, A. A., Arif, M., Abo Ghanima, M. M., Shukry, M., Noreldin, A., Taha, A. E., & El-Tarabily, K. A. (2021). Curcumin, the active substance of turmeric: its effects on health and ways to improve its bioavailability. *Journal of the Science of Food and Agriculture*, *101*(14), 5747–5762. https://doi.org/10.1002/jsfa.11372

Adeeyo, A. O., Oyetade, J. A., Alabi, M. A., Adeeyo, R. O., Samie, A., & Makungo, R. (2023). Tuning water chemistry for the recovery of greener products: pragmatic and sustainable approaches. *RSC Advances*, *13*(10), 6808–6826. https://doi.org/10.1039/d2ra06596g

Ahmed, M., Basheer, S., AL, M. H., Iqbal, D. N., Qamar, S., Saeed, A., Rida Batool, Mudassar Sanaullah, Raza, H., & Hussain, R. (2024). Structural development of curcumin: A natural product arsenal for diverse therapeutic targets- seizing opportunities through serendipity and rational design. *Journal of Molecular Structure*, 140815–140815. https://doi.org/10.1016/j.molstruc.2024.140815

Akbar, A., Kuanar, A., Joshi, R. K., Sandeep, I. S., Mohanty, S., Naik, P. K., Mishra, A., & Nayak, S. (2016). Development of Prediction Model and Experimental Validation in Predicting the Curcumin Content of Turmeric (Curcuma longa L.). *Frontiers in Plant Science*, *7*. https://doi.org/10.3389/fpls.2016.01507

Amorim, A. das G. N., Vasconcelos, A. G., Souza, J., Oliveira, A., Gullón, B., de Souza de Almeida Leite, J. R., & Pintado, M. (2022). Bio-Availability, Anticancer Potential, and Chemical Data of Lycopene: An Overview and Technological Prospecting. *Antioxidants*, *11*(2), 360. https://doi.org/10.3390/antiox11020360

Anandaraj, M., Prasath, D., Kandiannan, K., Zachariah, T. J., Srinivasan, V., Jha, A. K., Singh, B. K., Singh, A. K., Pandey, V. P., Singh, S. P., Shoba, N., Jana, J. C., Kumar, K. R., & Maheswari, K. U. (2014). Genotype by environment interaction effects on yield and curcumin in turmeric (Curcuma longa L.). *Industrial Crops and Products*, *53*, 358–364. https://doi.org/10.1016/j.indcrop.2014.01.005

Armstrong, A., Horry, K., Cui, T., Hulley, M., Turner, R., Farid, S. S., Goldrick, S., & Bracewell, D. G. (2021). Advanced control strategies for bioprocess chromatography: Challenges and opportunities for intensified processes and next generation products. *Journal of Chromatography A*, *1639*, 461914. https://doi.org/10.1016/j.chroma.2021.461914

Bou-Chacra, N., Melo, K. J. C., Morales, I. A. C., Stippler, E. S., Kesisoglou, F., Yazdanian, M., & Löbenberg, R. (2017). Evolution of Choice of Solubility and Dissolution Media After Two Decades of Biopharmaceutical Classification System. *The AAPS Journal*, *19*(4), 989–1001. https://doi.org/10.1208/s12248-017-0085-5

Censi, R., & Di Martino, P. (2015). Polymorph Impact on the Bioavailability and Stability of Poorly Soluble Drugs. *Molecules*, *20*(10), 18759–18776. https://doi.org/10.3390/molecules201018759

Chuo, S. C., Nasir, H. M., Mohd-Setapar, S. H., Mohamed, S. F., Ahmad, A., Wani, W. A., Muddassir, Mohd., & Alarifi, A. (2020). A Glimpse into the Extraction Methods of Active Compounds from Plants. *Critical Reviews in Analytical Chemistry*, 1–30. https://doi.org/10.1080/10408347.2020.1820851

Dei Cas, M., & Ghidoni, R. (2019). Dietary Curcumin: Correlation between Bioavailability and Health Potential. *Nutrients*, *11*(9), 2147. https://doi.org/10.3390/nu11092147

Dudekula, M. V., Kandasamy, V., Balaraman, S. S., Selvamani, S. B., Muthurajan, R., Adhimoolam, K., Manoharan, B., & Natesan, S. (2022). Unlocking the genetic diversity of Indian turmeric (Curcuma longa L.) germplasm based on rhizome yield traits and curcuminoids. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.1036592

El-Saadony, M. T., Yang, T., Korma, S. A., Sitohy, M., Abd El-Mageed, T. A., Selim, S., Al Jaouni, S. K., Salem, H. M., Mahmmod, Y., Soliman, S. M., Mo'men, S. A. A., Mosa, W. F. A., El-Wafai, N. A., Abou-Aly, H. E., Sitohy, B., Abd El-Hack, M. E., El-Tarabily, K. A., & Saad, A. M. (2023). Impacts of turmeric and its principal bioactive curcumin on human health: Pharmaceutical, medicinal, and food applications: A comprehensive review. *Frontiers in Nutrition*, *9*. https://doi.org/10.3389/fnut.2022.1040259

Haido, M. H., Matti, A. H., & Taher, S. M. (2024). Optimization of Extraction Conditions of Bioactive Compounds From Kurdistan Species Urtica dioica. *Cureus*. https://doi.org/10.7759/cureus.61146

Hao, M., Chu, Y., Lei, J., Yao, Z., Wang, P., Chen, Z., Wang, K., Sang, X., Han, X., Wang, L., & Cao, G. (2023). Pharmacological Mechanisms and Clinical Applications of Curcumin: Update. *Aging and Disease*, *14*(3), 716–749. https://doi.org/10.14336/AD.2022.1101

Hu, P., Li, K., Peng, X., Kan, Y., Yao, T.-J., Wang, Z., Li, Z., Liu, H., & Cai, D. (2023). Curcumin derived from medicinal homologous foods: its main signals in immunoregulation of oxidative stress, inflammation, and apoptosis. *Frontiers in Immunology*, *14*. https://doi.org/10.3389/fimmu.2023.1233652

Hu, Y., Lin, Q., Zhao, H., Li, X., Sang, S., McClements, D. J., Long, J., Jin, Z., Wang, J., & Qiu, C. (2023). Bioaccessibility and bioavailability of phytochemicals: Influencing factors, improvements, and evaluations. *Food Hydrocolloids*, *135*, 108165. https://doi.org/10.1016/j.foodhyd.2022.108165

Ionut Avrămia, Mircea-Adrian Oroian, & Radu-Cristian Oiţă. (2024). A review of current trends of vitamin identification and quantification by chromatography from food samples. *Journal of Food Composition and Analysis*, *131*, 106244–106244. https://doi.org/10.1016/j.jfca.2024.106244

Jikah, A. N., & Edo, G. I. (2024). Turmeric (Curcuma longa): an insight into its food applications, phytochemistry and pharmacological properties. *Vegetos*. https://doi.org/10.1007/s42535-024-01038-4

Kharat, M., Du, Z., Zhang, G., & McClements, D. J. (2017). Physical and Chemical Stability of Curcumin in Aqueous Solutions and Emulsions: Impact of pH, Temperature, and Molecular Environment. *Journal of Agricultural and Food Chemistry*, *65*(8), 1525–1532. https://doi.org/10.1021/acs.jafc.6b04815

Kim, R.-Y., Yoon, J.-K., Kim, T.-S., Yang, J. E., Owens, G., & Kim, K.-R. (2015). Bioavailability of heavy metals in soils: definitions and practical implementation—a critical review. *Environmental Geochemistry and Health*, *37*(6), 1041–1061. https://doi.org/10.1007/s10653-015-9695-y

Kirchert, S., & Morlock, G. E. (2020). Orthogonal Hyphenation of Planar and Liquid Chromatography for Mass Spectrometry of Biomarkers out of the Bioassay Matrix (NP-HPTLC-UV/vis/FLD-Bioassay-RP/IEX-HPLC-UV/vis-ESI-MS). *Analytical Chemistry*, *92*(13), 9057–9064. https://doi.org/10.1021/acs.analchem.0c01251

Kocaadam, B., & Şanlier, N. (2017). Curcumin, an active component of turmeric (Curcuma longa), and its effects on health. *Critical Reviews in Food Science and Nutrition*, *57*(13), 2889–2895. https://doi.org/10.1080/10408398.2015.1077195

Lehmkemper, K., Kyeremateng, S. O., Heinzerling, O., Degenhardt, M., & Sadowski, G. (2016). Long-Term Physical Stability of PVP- and PVPVA-Amorphous Solid Dispersions. *Molecular Pharmaceutics*, *14*(1), 157–171. https://doi.org/10.1021/acs.molpharmaceut.6b00763

Li, X., Zhang, F., Wang, X., & Sun, G. (2021). Evaluating the quality consistency of Rong'e Yishen oral liquid by UV + FTIR quantum profilings and HPLC fingerprints combined with 3-dimensional antioxidant profiles. *Microchemical Journal*, *170*, 106715–106715. https://doi.org/10.1016/j.microc.2021.106715

Liao, Y., Sun, L., Fan, D., Xu, W., Zelikman, M. V., & Qiao, P. (2024). Enhancing the Solubility, Stability, and Bioavailability of Retinol Acetate through Mechanochemistry. *Biomacromolecules*, *25*(6), 3831–3839. https://doi.org/10.1021/acs.biomac.4c00440

Macias-Frotto, B., Rostro-Alanís, M., Escobedo-Avellaneda, Z., & Welti-Chanes, J. (2024). Conventional and Innovative Methods for Pectin Extraction from Agro-industrial By-products. *Food Engineering Reviews*. https://doi.org/10.1007/s12393-024-09390-6

Manheim, J., Singh, A. N., Aggarwal, P., Fatima Naser Aldine, & Ahmad. (2024). An improved workflow for the development of MS-compatible liquid chromatography assay purity and purification methods by using automated LC Screening instrumentation and in silico modeling. *Analytical & Bioanalytical Chemistry (Print)*. https://doi.org/10.1007/s00216-023-05118-3

MEHRA, N. (2023). A COMPARATIVE STUDY ON CONVENTIONAL AND ADVANCE TECHNIQUES FOR PLANT EXTRACTION AND EFFECT ON THE EXTRACT YIELD: REVIEW. *Current Perspectives on Medicinal and Aromatic Plants (CUPMAP)*. https://doi.org/10.38093/cupmap.1365128

Móricz, Á. M., Lapat, V., Morlock, G. E., & Ott, P. G. (2020). High-performance thin-layer chromatography hyphenated to high-performance liquid chromatography-diode array detection-mass spectrometry for characterization of coeluting isomers. *Talanta*, *219*, 121306. https://doi.org/10.1016/j.talanta.2020.121306

Mwaurah, P. W., Kumar, S., Kumar, N., Attkan, A. K., Panghal, A., Singh, V. K., & Garg, M. K. (2019). Novel oil extraction technologies: Process conditions, quality parameters, and optimization. *Comprehensive Reviews in Food Science and Food Safety*, *19*(1), 3–20. https://doi.org/10.1111/1541-4337.12507

Nurcholis, W., Khumaida, N., Syukur, M., & Bintang, M. (2019). Variability of Curcumin, Demethoxycurcumin and Bisdemethoxycurcumin Contents in Ethanolic Extract from Ten Curcuma aeruginosa Roxb. Cultivated in West Java, Indonesia. *Asian Journal of Chemistry*, *31*(11), 2461–2465. https://doi.org/10.14233/ajchem.2019.22128

Peng, S., Li, Z., Zou, L., Liu, W., Liu, C., & McClements, D. J. (2018). Improving curcumin solubility and bioavailability by encapsulation in saponin-coated curcumin nanoparticles prepared using a simple pH-driven loading method. *Food & Function*, *9*(3), 1829–1839. https://doi.org/10.1039/c7fo01814b

Rafiee, Z., Nejatian, M., Daeihamed, M., & Jafari, S. M. (2019). Application of curcumin-loaded nanocarriers for food, drug and cosmetic purposes. *Trends in Food Science & Technology*, *88*, 445–458. https://doi.org/10.1016/j.tifs.2019.04.017

Salem, M., Rohani, S., & Gillies, E. R. (2014). Curcumin, a promising anti-cancer therapeutic: a review of its chemical properties, bioactivity and approaches to cancer cell delivery. *RSC Advances*, *4*(21), 10815–10829. https://doi.org/10.1039/C3RA46396F

Sandeep, I. S., Kuanar, A., Akbar, A., Kar, B., Das, S., Mishra, A., Sial, P., Naik, P. K., Nayak, S., & Mohanty, S. (2016). Agroclimatic zone based metabolic profiling of turmeric (Curcuma Longa L.) for phytochemical yield optimization. *Industrial Crops and Products*, *85*, 229–240. https://doi.org/10.1016/j.indcrop.2016.03.007

Seger, C., Sturm, S., & Stuppner, H. (2013). Mass spectrometry and NMR spectroscopy: modern high-end detectors for high resolution separation techniques – state of the art in natural product HPLC-MS, HPLC-NMR, and CE-MS hyphenations. *Natural Product Reports*, *30*(7), 970–987. https://doi.org/10.1039/C3NP70015A

Sharifi-Rad, J., Rayess, Y. E., Rizk, A. A., Sadaka, C., Zgheib, R., Zam, W., Sestito, S., Rapposelli, S., Neffe-Skocińska, K., Zielińska, D., Salehi, B., Setzer, W. N., Dosoky, N. S., Taheri, Y., El Beyrouthy, M., Martorell, M., Ostrander, E. A., Suleria, H. A. R., Cho, W. C., & Maroyi, A. (2020). Turmeric and Its Major Compound Curcumin on Health: Bioactive Effects and Safety Profiles for

Food, Pharmaceutical, Biotechnological and Medicinal Applications. *Frontiers in Pharmacology*, *11*(33041781). https://doi.org/10.3389/fphar.2020.01021

Slika, L., & Patra, D. (2019). A short review on chemical properties, stability and nano-technological advances for curcumin delivery. *Expert Opinion on Drug Delivery*, *17*(1), 61–75. https://doi.org/10.1080/17425247.2020.1702644

Suresh, K., & Nangia, A. (2018). Curcumin: pharmaceutical solids as a platform to improve solubility and bioavailability. *CrystEngComm*, *20*(24), 3277–3296. https://doi.org/10.1039/c8ce00469b

Tibo De Saegher, Vercammen, J., Boyana Atanasova, Van, K. M., Jeriffa De Clercq, Verberckmoes, A., & Jeroen Lauwaert. (2023). Efficient mapping of lignin depolymerization product pools and quantification of specific monomers through rapid GPC-HPLC-UV/VIS analysis. *Analytica Chimica Acta*, *1278*, 341738–341738. https://doi.org/10.1016/j.aca.2023.341738

Tsuda, T. (2018). Curcumin as a functional food-derived factor: degradation products, metabolites, bioactivity, and future perspectives. *Food & Function*, *9*(2), 705–714. https://doi.org/10.1039/c7fo01242j

Zheng, D., Ruan, Y.-T., Yin, Z.-P., & Zhang, Q.-F. (2020). A Comparison of Solubility, Stability, and Bioavailability between Astilbin and Neoastilbin Isolated from Smilax glabra Rhizoma. *Molecules*, *25*(20), 4728–4728. https://doi.org/10.3390/molecules25204728

Zupančič, Š., Lavrič, Z., & Kristl, J. (2015). Stability and solubility of trans-resveratrol are strongly influenced by pH and temperature. *European Journal of Pharmaceutics and Biopharmaceutics*, *93*, 196–204. https://doi.org/10.1016/j.ejpb.2015.04.002

Žuvela, P., Skoczylas, M., Jay Liu, J., BączekT., Kaliszan, R., Wong, M. W., & Buszewski, B. (2019). Column Characterization and Selection Systems in Reversed-Phase High-Performance Liquid Chromatography. *Chemical Reviews*, *119*(6), 3674–3729. https://doi.org/10.1021/acs.chemrev.8b00246