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REVIEW ON GREEN EXTRACTION TECHNIQUES: PRINCIPLES, APPLICATIONS, AND FUTURE PROSPECT

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ABSTRACT

Green extraction techniques have emerged as sustainable alternatives to conventional extraction methods, addressing environmental concerns and improving the efficiency of recovering bioactive compounds from natural sources. This review provides a comprehensive overview of major green extraction methods including supercritical fluid extraction (SFE), microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), pressurized liquid extraction (PLE), enzyme-assisted extraction (EAE), and the use of green solvents such as deep eutectic solvents (DES). The principles, advantages, limitations, and industrial applications of each technique are discussed. A comparative analysis highlights the energy efficiency, environmental impact, and economic viability of these approaches. Finally, challenges and future directions are outlined to guide research and industrial adoption toward sustainable extraction processes.

KEYWORDS: The principles, advantages, limitations, and industrial applications of each technique are discussed.

1. INTRODUCTION

Extraction of bioactive compounds from plants and natural materials is fundamental in pharmaceuticals, food, cosmetics, and nutraceutical industries. Traditional extraction methods often rely on large volumes of organic solvents, long extraction times, and high energy consumption, leading to environmental pollution and safety concerns. The growing awareness of sustainability and regulatory pressures have accelerated the development of *green extraction techniques* that minimize environmental footprint while enhancing extraction efficiency.

Green extraction is defined by the principles of reducing solvent toxicity, lowering energy use, increasing selectivity and yield, and ensuring safer working conditions. This review aims to summarize recent advances in green extraction methods, critically compare their performance, and highlight practical applications and future prospects.[1]

2. Principles of Green Extraction

Green extraction emphasizes:

- Use of renewable, biodegradable solvents (e.g., water, ethanol, DES)
- Minimization of solvent volume and waste
- Reduction of energy consumption through innovative technologies
- Maximizing selectivity and yield to reduce downstream processing

The goal is to replace hazardous solvents and energy-intensive processes with eco-friendly, cost-effective alternatives without compromising product quality.[2]

3. Overview of Green Extraction Techniques

3.1 Supercritical Fluid Extraction (SFE)

Principle

Supercritical fluids occur when a substance is above its critical temperature and pressure, exhibiting unique properties between liquids and gases. Carbon dioxide (CO_2) is most commonly used due to its relatively low critical point (31.1 °C, 73.8 bar), non-toxicity, non-flammability, and ease of removal post-extraction.

In SFE, supercritical CO_2 penetrates the plant matrix like a gas but dissolves compounds like a liquid. The solvating power can be tuned by adjusting pressure and temperature. Co-solvents such as ethanol may be added to increase polarity for extracting polar compounds.

Applications

- Extraction of essential oils and flavors (e.g., lavender, rosemary).
- Decaffeination of coffee and tea.
- Recovery of lipids and antioxidants from seeds and herbs.

Advantages

- Solvent-free extracts — no toxic residues.
- Mild operating temperatures preserve thermolabile compounds.
- Tunable selectivity by controlling pressure and temperature.
- Environmentally benign with CO_2 recycling.

Limitations

- High capital and operational costs for pressure-resistant equipment.
- Limited solvating power for highly polar compounds unless co-solvents are used.
- Scale-up requires complex process optimization.[3]

3.2 Microwave-Assisted Extraction (MAE)

Principle

MAE uses microwave radiation (300 MHz to 300 GHz) to cause rapid heating of polar molecules inside plant tissues and solvents through dipole rotation and ionic conduction. This rapid heating disrupts cell walls and accelerates solvent penetration, enhancing the release of target compounds.

Applications

- Extraction of polyphenols, flavonoids, alkaloids from plant material.
- Recovery of natural pigments such as anthocyanins.
- Extraction of essential oils and fatty acids.

Advantages

- Significantly reduces extraction time (minutes instead of hours).
- Lowers solvent and energy consumption.
- Compatible with aqueous and organic solvents.
- Simple and easy to operate, scalable with batch or continuous modes.

Limitations

- Risk of localized overheating causing degradation of sensitive compounds.
- Uneven heating if the microwave distribution is not uniform.
- Limited penetration depth in dense matrices, which may require sample size optimization.[4]

3.3 Ultrasound-Assisted Extraction (UAE)

Principle

Ultrasound waves (20 kHz – 100 kHz) generate acoustic cavitation in the extraction solvent: microscopic bubbles form, grow, and implode violently. This produces localized high temperature and pressure microenvironments that disrupt plant cell walls, increase solvent penetration, and enhance mass transfer.

Applications

- Extraction of antioxidants, polysaccharides, essential oils.
- Isolation of bioactive compounds from seeds, leaves, roots.
- Increasing yields of phenolic and flavonoid compounds from herbs.

Advantages

- Operates at low to moderate temperatures, preserving heat-sensitive compounds.
- Short extraction times (minutes).
- Reduced solvent use and energy consumption.
- Equipment is relatively low cost and simple.

Limitations

- Potential generation of free radicals during cavitation, which may oxidize sensitive molecules.
- Challenges in scaling up uniformly due to attenuation of ultrasound waves.
- Effectiveness varies with solvent type and matrix.[5]

3.4 Pressurized Liquid Extraction (PLE)

Principle

Also known as accelerated solvent extraction (ASE), PLE involves applying elevated pressure (usually 10–15 MPa) and moderate temperatures (50–200 °C) to keep solvents in the liquid state above their boiling point. This increases solvent diffusivity and solubility of analytes, speeding up extraction kinetics.

Applications

- Extraction of lipids, pesticides, phenolics from soils, food, and plants.
- Preparation of samples for analytical chemistry.
- Isolation of pharmacologically active compounds.

Advantages

- Fast extraction and reduced solvent volumes compared to Soxhlet.
- Compatible with water, alcohols, and their mixtures as solvents.
- Closed system reduces solvent evaporation and exposure.

Limitations

- Higher temperatures may degrade thermolabile compounds.
- Equipment cost is relatively high.
- Optimization of pressure and temperature is needed for each matrix.[6]

3.5 Enzyme-Assisted Extraction (EAE)

Principle

EAE leverages specific enzymes such as cellulase, pectinase, hemicellulase, and protease to hydrolyze plant cell wall components, facilitating the release of intracellular compounds. This biological pretreatment enhances the efficiency and yield of extraction with mild solvents (usually aqueous).

Applications

- Extraction of pectin, polysaccharides, and dietary fibers.
- Recovery of phenolics and flavonoids from fruit peels and seeds.
- Oil extraction from seeds and nuts with enhanced yield.

Advantages

- Mild processing conditions (temperature, pH) maintain compound integrity.
- Highly selective due to enzyme specificity.
- Reduced energy consumption.
- Can be combined with other green extraction methods (e.g., UAE + EAE).

Limitations

- Enzyme cost and activity stability can be limiting factors.
- Extraction times can be longer than physical methods.
- Requires careful control of pH, temperature, and enzyme concentration.[7]

3.6 Use of Green Solvents: Deep Eutectic Solvents (DES) and Ionic Liquids (ILs)

Principle

Green solvents are designed to replace traditional organic solvents with less toxic, biodegradable alternatives. DES are mixtures of hydrogen bond donors and acceptors (e.g., choline chloride + glycerol) that form eutectic mixtures with melting points lower than either component. ILs are salts liquid at or near room temperature, composed of organic cations and inorganic/organic anions.

Applications

- Extraction of alkaloids, phenolics, organic acids, and other polar compounds.
- Solubilization of biomass for biorefinery applications.
- Recovery of pharmaceuticals and natural products.

Advantages

- Low volatility, reducing VOC emissions.
- Tunable polarity and solvating properties by altering components.
- Biodegradable and often non-toxic (especially some DES).
- Potential to recycle and reuse solvents.

Limitations

- Toxicity profiles of many ILs are not fully understood.
- High viscosity can reduce mass transfer rates.
- Cost and scalability remain concerns.a
- Regulatory acceptance still evolving.[8]

4. Comparative Analysis

Technique	Energy Efficiency	Solvent Use	Selectivity	Environmental Impact	Cost	Scale-up Potential
SFE	Moderate	Low (CO_2)	High	Low	High	Industrial ready
MAE	High	Low	Moderate to High	Low	Moderate	Medium
UAE	High	Low	Moderate	Low	Low	Medium
PLE	Moderate	Moderate	High	Moderate	High	Medium
EAE	Low to Moderate	Low	High (enzyme-specific)	Low	Moderate	Medium
DES/ILs	Variable	Low	High	Potentially Low	Moderate to High	Emerging

This table shows that each technique has strengths and trade-offs, and selection depends on target compounds, scale, and sustainability goals.[9]

5. Applications in Industry

Green extraction methods have been adopted in various industries.

- **Food:** Extraction of antioxidants, flavors, and pigments using SFE and MAE.
- **Pharmaceuticals:** Isolation of alkaloids, terpenes with SFE and EAE.
- **Cosmetics:** Recovery of essential oils and polyphenols via UAE and green solvents.
- **Nutraceuticals:** Extraction of bioactive compounds with MAE and PLE.

  Adoption is driven by regulations on solvent residues, consumer demand for natural products, and environmental standards.[10]

6. Challenges and Future Perspectives

- **Challenges**
  - High capital costs for specialized equipment.
  - Scale-up difficulties for certain techniques.
  - Need for standardization and toxicity assessment of green solvents.
  - Optimization of parameters for different matrices.

- **Future Directions**
  - Integration of hybrid methods (e.g., MAE + UAE).
  - Development of biodegradable, low-cost green solvents.
  - Process intensification via continuous extraction.
  - Lifecycle assessments to quantify environmental benefits.
  - Regulatory harmonization to promote adoption.[11]

7. CONCLUSION

Green extraction techniques present a promising pathway toward sustainable and efficient recovery of bioactive compounds. While each method offers distinct advantages, challenges remain in scaling and cost-effectiveness. Continued research and innovation will enable wider industrial adoption, aligning extraction processes with environmental and economic sustainability.

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