INTERNATIONAL JOURNAL OF PHARMACEUTICAL SCIENCES
[ISSN: 0975-4725; CODEN(USA): IJPS00]
Journal Homepage: https://www.ijpsjournal.com

Review Article

Extraction Techniques

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ARTICLE INFO

Published: 20 Apr 2026
Keywords:
microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), accelerated solvent extraction (ASE), supercritical fluid extraction (SFE), solid phase extraction (SPE), and solid phase micro-extraction (SPME),maceration, infusion, decoction, percolation, Soxhlet extraction, and reflux techniques
DOI:
10.5281/zenodo.19673531

ABSTRACT

The extraction of bio-active compounds from medicinal plants is a critical step in the development of pharmaceuticals, nutraceutical, and cosmetic products. Conventional approaches such as maceration, infusion, decoction, percolation, Soxhlet extraction, and reflux techniques have been widely utilized for decades. However, these methods often involve excessive solvent consumption, long processing times, and degradation of thermolabile compounds. Because of recent progress in science, new methods have been adopted such as microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), accelerated solvent extraction (ASE), supercritical fluid extraction (SFE), solid phase extraction (SPE), and solid phase micro-extraction (SPME). This review provides a comprehensive discussion of the working principles, instruments, applications, advantages, limitations, and future prospects of both conventional and modern extraction methods. We are highlighting their importance in drug manufacturing and connected industries, and also covering the latest eco-friendly methods for getting them out of their source.

INTRODUCTION

Extraction is the process by which medicinally active molecules are separated from plant or animal tissues using solvents of appropriate polarity. The principle guiding extraction is “like dissolves like”, meaning that polar solvents (such as water, ethanol, methanol) extract polar constituents, whereas non-polar solvents (hexane, chloroform, ether) target lipophilic compound The choice of extraction technique significantly

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Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

influences the yield, purity, and stability of the final product. In the pharmaceutical field, extraction enables the recovery of phytochemicals such as alkaloids, flavonoids, terpenoids, tannins, and phenolic acids, which serve as drug leads or therapeutic agents.

2. Pre-Extraction Sample Preparation: Optimizing the Matrix

The initial stage of material processing, known as pre-extraction preparation, is crucial for preserving the biomolecules and enhancing extraction efficiency.

2.1 Sample State: Fresh versus Dried Materials

While both fresh and dried plant materials are utilized, the dried state is often preferred for experimental work due to the fragile nature of fresh samples and their tendency to deteriorate quickly. However, the drying method itself can influence the content of specific phytochemicals; for instance, dried Moringa oleifera(drumstick tree) dry leaves showed higher flavonoid content but no significant difference in total phenolics compared to fresh samples.

2.2 Particle Size Reduction: Grinding and Powdering

The particle size of the sample is a major factor influencing extraction efficiency, particularly in processes like enzyme-assisted extraction. Reducing particle size increases the surface area for contact between the sample matrix and the extraction solvent, thus facilitating mass transfer.

Optimal Size: A particle size smaller than 0.5 mm (or 400~\mu\text{m}) is often considered ideal for efficient extraction.

Nanoparticles: Further reduction to the nanoscale, such as with a Planetary Ball Mill (PBM), has been shown to yield significantly higher extracts (e.g., 82.09% higher yield for Centella asiatica) compared to micro-powder.

2.3 Thermal and Non-Thermal Drying Techniques

Drying removes moisture and helps preserve phytochemicals, but the method must be carefully chosen based on the target compounds' stability.

1. Air-Drying:-

Principle:- Exposure to ambient air and temperature over a long period (days to months).

Limitation:- It is a lengthy process and the samples may be susceptible to contamination in unstable temperature environments.

2. Oven-Drying:-

Principle:- Uses thermal energy for rapid moisture removal Strength:

Easy and rapid thermal processing.

Limitation:- While rapid processing can preserve overall antioxidant activity, specific bioactive phytochemicals, such as sinensetin and rosmarinic acid, have shown sensitivity to elevated temperatures from oven- or sunlight-drying.

3. Microwave-Drying:-

Principle:- Employs electromagnetic radiation, where the electric field causes simultaneous heating through dipolar rotation (alignment of molecules with a dipole moment, such as water or solvents) and ionic induction. The resulting oscillation and collision of molecules leads to fast, simultaneous heating.

Strength:- Significantly shortens drying time.

Limitation:- High temperatures can sometimes cause the degradation of heat-sensitive phytochemicals.

4. Freeze-Drying (Lyophilization):-

Principle:- Based on sublimation, where a frozen solid is converted directly into the gas phase without entering the liquid phase. The sample is frozen (e.g., at -80^{\circ}\text{C}) before being lyophilized.

Strength:- Excellent for preserving the integrity of biomolecules and heat-labile compounds due to the very low-temperature operation

Proper sample handling is crucial to maintain phytochemical integrity.

3. Conventional Extraction Techniques/ Traditional methods

Traditional methods are foundational in research settings and manufacturing, providing reliable, albeit sometimes inefficient, separation.

1. Maceration

Principle:

The simplest traditional method, involving the steeping of the solid plant material in a liquid solvent (usually water or ethanol) for an extended period, allowing the solvent to penetrate and dissolve the target compounds. The powdered plant material (drug) is soaked in a suitable solvent at room temperature for a specific time (usually 3–7 days) with occasional stirring. The solvent penetrates into the cell wall, dissolves active constituents, and the solution is filtered to obtain the extract.

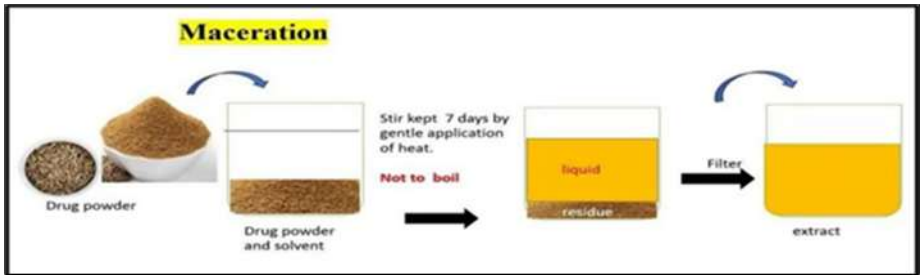

Fig.1 Maceration

Stepwise Working / Process:-

1. Drug is coarsely powdered.

2. Transferred into a stoppered container with solvent.

3. Kept for defined period with occasional shaking.

4. Filtration → extract obtained

Instrumentation:- Glass container with stopper Filter paper or muslin cloth Stirring rod

Applications:-

- Extraction of heat-sensitive compounds such as flavonoids , volatile oils .
- Preparation of tinctures and extracts (e.g. Ipecac tincture) .

Advantages:-

- Simple, economical, no heating needed.
- Ideal for thermolabile compounds.
- Widely used in SMEs.

Disadvantages:-

- Time consuming process that can require days or weeks for complete extraction.
- Large amount of solvent required.
- Risk of microbial growth during long soaking

2. Infusion & Decoction

A. Infusion:-

Quick soaking of plant material in warm/cold water (like making tea).

Principle: A fresh extract is prepared by soaking plant material in hot or cold water for a short time (like making tea).

Stepwise Working:-

1. Drug placed in water.

2. Allowed to steep for 15–30 minutes.

3. Filtration → used directly.

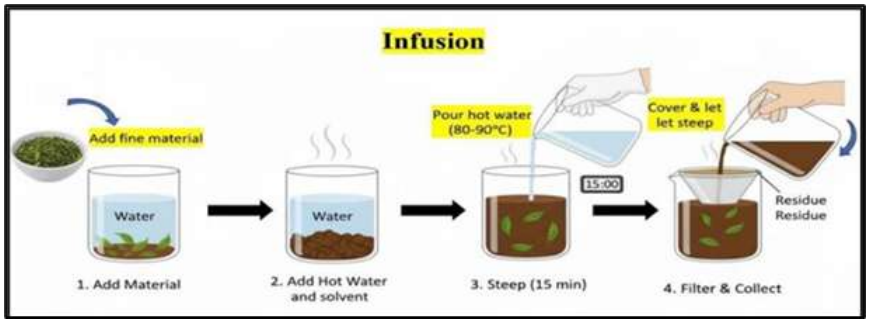

Fig. 2 Infusion

Instrumentation:- Beaker or kettle, Filter paper / cloth

Applications:

Used in herbal teas, light extracts, soft tissues (flowers, leaves). Example: Infusion of Senna.

Advantages:-

Quick, convenient , No complex equipment, Inexpensive

Disadvantages:-

- Not suitable for insoluble or less soluble compounds.
- Extract is unstable

B. Decoction:-

Boiling tough parts like bark and roots in water for extended time.

Boiling the drug in water for a specific time to soften tough plant parts and extract active constituents.

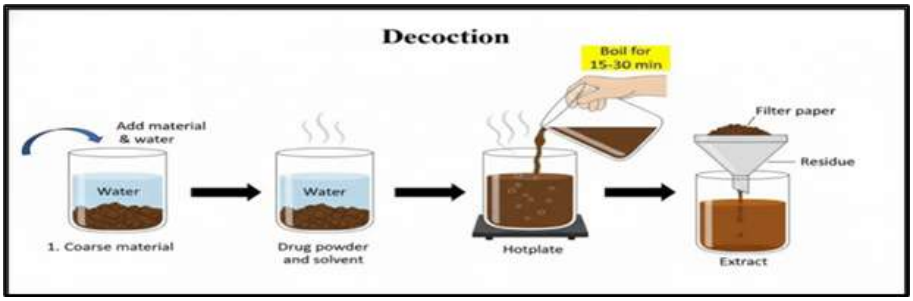

Fig. 3 Decoction

Stepwise Working:-

1. Coarse powder of drug is added to water.

2. Boiled for 15–30 minutes.

3. Filtered → extract collected.

Instrumentation:- Boiling flask / kettle, Heat source

Applications:-

- Used for roots, barks, hard seeds (e.g., Liquorice root decoction).
- Traditional Ayurvedic and Chinese medicine.

Advantages:-

- Good for hard plant parts.
- No expensive solvents.

Disadvantages:-

- Destructive for volatile oils and heat-sensitive compounds.
- Requires energy (boiling).

3. Percolation:-Continuous Flow Dynamics

Principle:

Similar to chromatography, the solvent is continuously flowed through a packed column of plant material. The constant flow of fresh solvent maintains a steep concentration gradient at the solid-liquid interface, driving the extraction to completion faster than static maceration.

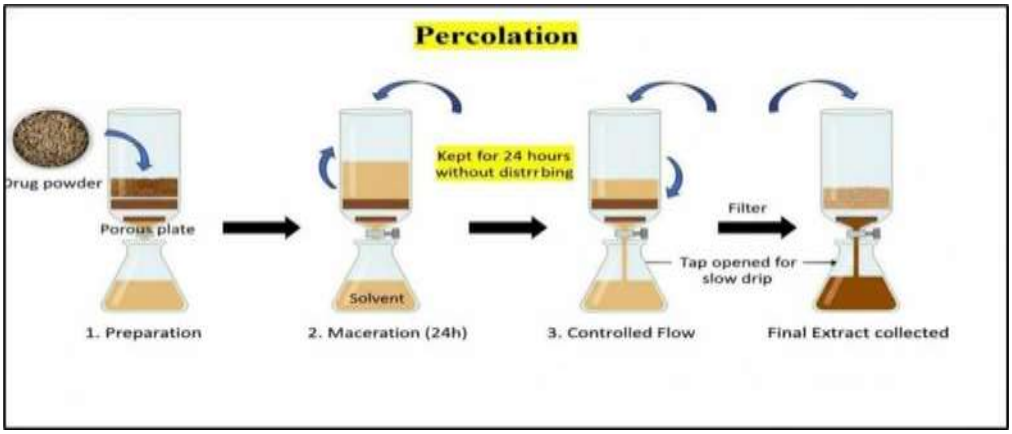

Fig. 4 Percolation

Stepwise Working:-

1. Drug packed in a percolator (conical container with stopcock).

2. Solvent poured on top → flows through the powder.

3. Extract collected at bottom

Instrumentation:- Percolator (glass / stainless steel), Filter system

Applications:-

- Large-scale preparation of tinctures and standardized extracts.
- Example: Extraction of opium alkaloids.

Advantages:-

- Achieves high efficiency and purity, but requires careful control of the flow rate to prevent channeling.
- continuous process.

- Get More concentrated extract compared to maceration.
- Percolation can be scaled up for industrial use.

Disadvantages:-

- Careful packing required to avoid "channeling" (solvent bypassing).
- Setup is more complex than infusion or maceration.
- Time consuming.

4. Soxhlet Extraction:-

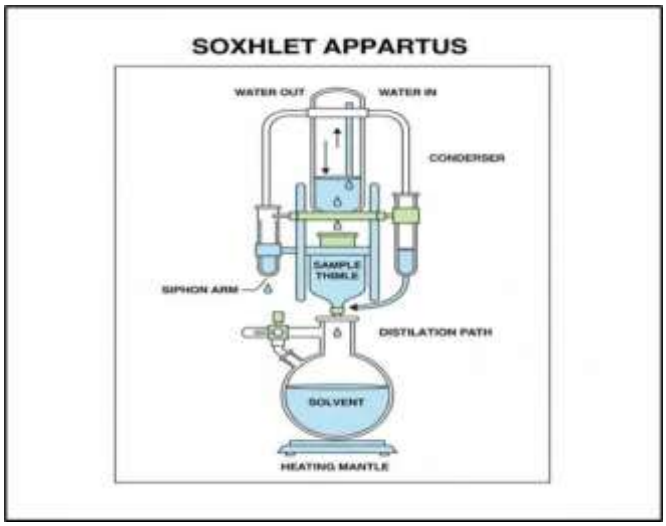

Fig. 5 Soxhlet apparatus

Principle of Operation:-

The Soxhlet apparatus operates as a continuous extraction system. The sample is packed into a thimble and continuously saturated with fresh, concentrated, distilled solvent vapor. As the liquid level in the chamber rises, a siphon mechanism pumps the extract-laden solvent back into the distillation flask, where the solvent is recycled, and the non-volatile target extract accumulates.

SE is versatile, used to:-

- Extract organic compounds from sediments and soils, offering improved analytical results due to enhanced solvent-analyte matrix interaction.
- Remove lipid components (e.g., oil from biomass) using non-polar organic solvents like n-hexane.
- Extract essential oils, such as geranium oil used in perfumes and cosmetics.

The process faces significant criticism due to several drawbacks:-

- Thermal Degradation Risk:-The sample is exposed to the boiling temperature of the solvent for a prolonged time, increasing the risk of thermal damage to sensitive compounds.
- Time-Consuming:- Extraction time is long, often requiring careful and lengthy manipulations, which limits sample throughput.
- High Solvent Use: - It typically consumes a large volume of solvent, contributing to cost and environmental impact.

Stepwise Working:-

1. The solvent in the round-bottom flask is heated and starts boiling.

2. Solvent vapour's rise up through the distillation arm.

3. Vapour's enter the condenser where cold water circulates.

4. Vapour's condense into liquid solvent and drip into the thimble.

5. The thimble contains the solid sample, which gets soaked by the hot solvent.

6. Solvent dissolves the soluble components from the sample.

7. The chamber fills with solvent until it reaches the top of the siphon tube.

8. The siphon tube automatically drains the extract-rich solvent back into the boiling flask.

9. The thimble becomes empty, ready for the next extraction cycle.

10. Boiling–condensing–extraction–siphoning cycles repeat continuously, ensuring complete extraction.

11. After sufficient cycles, most of the soluble compounds collect in the boiling flask.

12. Solvent is evaporated to obtain the final concentrated extract.

Instrumentation:-

Soxhlet apparatus (round-bottom flask, condenser, siphon tube, thimble).

Applications:-

- Large-scale preparation of tinctures and standardized extracts.
- Example: Extraction of opium alkaloids

Advantages:-

- Efficient, continuous process.
- More concentrated extract compared to maceration.
- Efficient solvent recycling, handles large sample quantity.

Disadvantages:-

- Careful packing required to avoid "channeling" (solvent bypassing).
- Time consuming.
- Unsuitable for thermolabile compound.

5. Heat Reflux Extraction: Controlled Thermal Contact

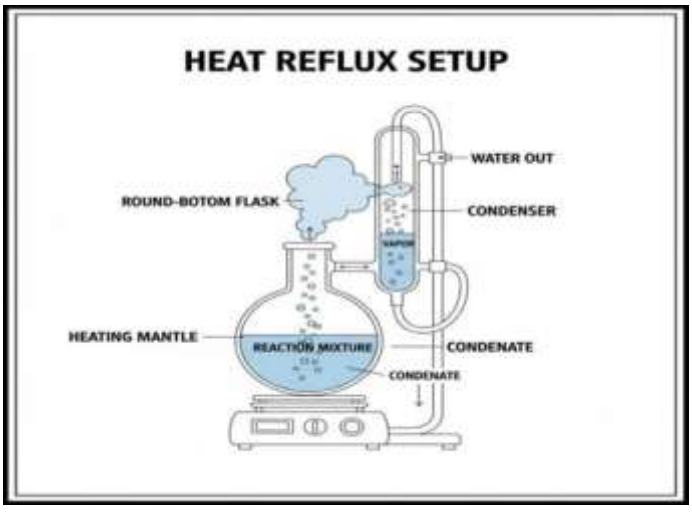

Fig. 5 Heat reflux setup

Principle:-

The sample is directly boiled in the solvent, with a condenser preventing solvent loss. Unlike Soxhlet, the entire solvent volume remains in contact with the sample, maximizing the surface area of interaction. Extraction under reflux condenser prevents solvent loss while boiling.

Stepwise Working:-

1. Drug + solvent boiled in flask.
2. Vapours condensed in reflux condenser.
3. Continuous contact of solvent and drug → extraction

Instrumentation:- Round-bottom flask, Reflux condenser, Heating mantle.

Applications:-

- Extraction of phenolic compound, caffeine, essential oils.
- E.g. Caffeine, polyphenols, rosmarinic acid.

Advantages:-

- Simplicity, high capacity, and faster equilibrium than maceration. It remains a cost-effective, high-throughput method for thermo-stable compounds.
- Shorter duration than maceration.
- Less solvent needed compared to Soxhlet.

Disadvantages:-

- Thermal degradation possible.
- Solvent must be stable at high temperature.

Limitations:- Solvent-intensive, high heat may destroy fragile.

4. Advanced Extraction Technologies:-

1. Microwave-Assisted Extraction (MAE)

MAE uses electromagnetic radiation to heat the solvent and moisture within the sample matrix.

Mechanism:-

Microwave energy causes two primary effects: dipolar rotation (polar molecules like water and ethanol align with the oscillating electric field) and ionic conduction (ions oscillate due to the electric field). Both result in rapid, volumetric heating. Microwaves cause dipolar rotation and ionic conduction → rapid heating → improved solvent penetration.

Closed-vessel MAE allows higher pressures, improving efficiency. Open-vessel MAE is less efficient but safer for lab use.

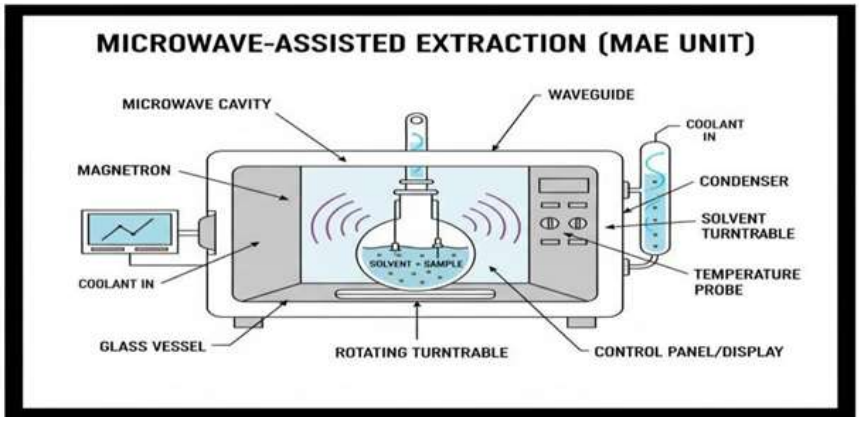

Fig. 6 Microwave assisted extraction

Advantage:-

Because the solvent and moisture are heated internally and simultaneously, high temperatures can be achieved much faster and more uniformly than conventional heating, often leading to better extraction yields in shorter times (minutes vs. Hours). The buildup of internal pressure within the cell enhances the rupture process.

Faster, uses less solvent, higher efficiency.

Limitation:- It is best suited for solvents with a high dielectric constant (polar solvents), and it shares a similar risk of thermal degradation as Soxhlet if not carefully controlled.

Applications:- It is used to extract compounds such as Polyphenols, triterpenes, flavonoids.

Stepwise Working:-

1. The plant sample is mixed with a suitable solvent (polar solvents like ethanol, methanol, or water).
2. The mixture is placed inside a microwave reactor chamber.
3. Microwaves (at 2450 MHz frequency) penetrate the sample, causing dipole rotation of polar molecules and ionic conduction.
4. Rapid heating disrupts plant cell walls, releasing bioactive compounds into the solvent.
5. The extract is filtered and concentrated for further use.

2. Ultrasound-Assisted Extraction (UAE) Cavitation-Induced Disruption

UAE is a mechanical extraction method that exploits the phenomenon of acoustic cavitation

Mechanism:-

Ultrasonic waves (typically 20-100~\text{kHz}) create, grow, and violently collapse micro-bubbles within the solvent. This collapse generates localized micro-jets, shockwaves, and intense pressure/temperature spikes (up to 5000~\text{K} and 1000~\text{atm}) at the solid-liquid boundary. Acoustic cavitation ruptures plant cell walls, facilitating release of phytochemicals.

Low temperature makes UAE suitable for heat-sensitive compounds.

Probe-type UAE gives stronger cavitation than bath-type

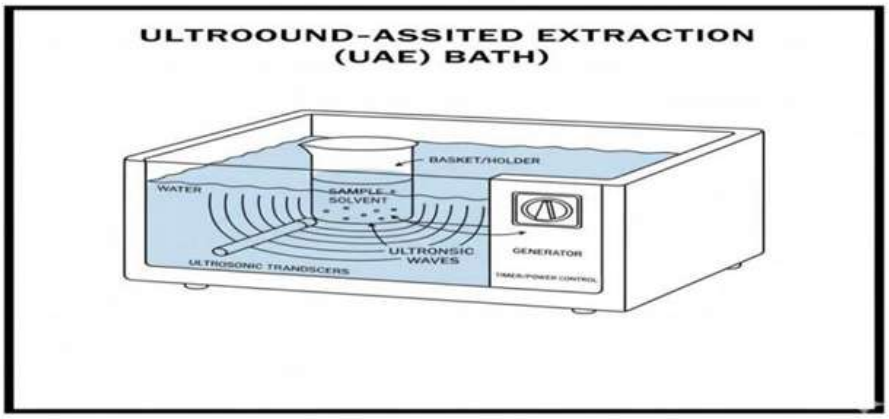

Fig. 7 Ultrasound assisted extraction

Impact:- This mechanical force effectively ruptures the plant cell walls and breaks down the solid matrix, dramatically increasing solvent penetration and mass transfer rate.

Optimization Challenge:- While low temperature is a strength, high ultrasonic power (intensity) can generate free radicals (sonochemistry) that may chemically alter or destroy the target compounds. Optimal extraction requires balancing mechanical force with chemical preservation.

Applications:- It is used to extract compounds such a Anthocyanins, essential oils, propolis.

Advantages:-Low-cost, eco-friendly, reduced extraction time.

Disadvantages:- Excess ultrasound may generate free radicals.

Stepwise Working:-

1. Sample is immersed in solvent inside an ultrasonic bath or probe system.
2. Ultrasound waves (20–100 kHz) are applied.
3. These waves generate acoustic cavitation → microbubbles form and collapse
4. Bubble collapse creates localized high pressure and temperature, breaking plant cell walls.
5. Phytochemicals diffuse into solvent more quickly.
6. Extract is separated by filtration or centrifugations

3. Enzyme-Assisted Extraction (EAE)/ Biological Deconstruction

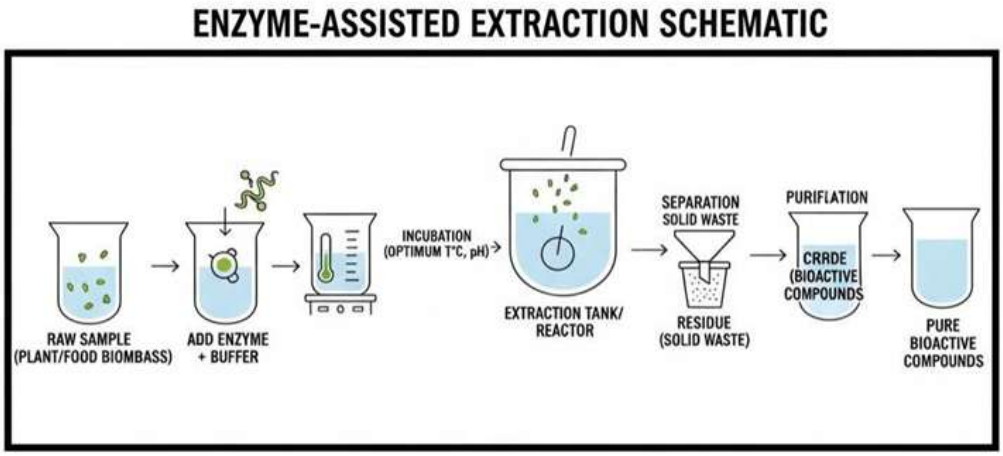

Fig. 8 Enzyme assisted extraction

Mechanism:-

Enzymes like cellulases, pectinases, and hemi-cellulases hydrolyze the structural polysaccharide components of the plant cell wall. This weakens the matrix, allowing the solvent to access and diffuse into the intracellular spaces more readily.

EAE is selective and eco-friendly.

Requires optimization of pH, temperature, enzyme concentration, and time.

EAE uses specific enzymes to break down the physical barriers of the plant matrix.

Strength:- It operates under mild conditions (near-neutral \text{pH} and moderate temperature), preserving the integrity of sensitive

compounds. It is particularly effective for compounds tightly bound within the cell wall.

Limitation:- Cost of the enzyme preparation and the requirement for precise \text{pH} and temperature control to ensure optimal enzyme activity

Enzymes such as cellulase, pectinase break down cell walls.

Applications: it is used in Extraction of polysaccharides, polyphenols.

Stepwise Working:-

1. Plant material is treated with enzyme solution (cellulase, hemicellulase, pectinase).
2. Enzymes degrade plant cell wall components (cellulose, lignin, pectin).
3. Bioactive compounds are released into solvent.
4. Enzymes are inactivated by heating or pH adjustment.
5. Extract is separated by filtration

4. Accelerated Solvent Extraction (ASE)/ Pressurized Liquid Extraction (PLE)

Mechanisms:-

ASE uses liquid solvents at elevated temperatures (up to 200^\circ\text{C}) and high pressures (up to 1500~\text{psi}). The high pressure maintains the solvent in a liquid state even above its atmospheric boiling point. High pressure & temperature enhance solubility and extraction efficiency

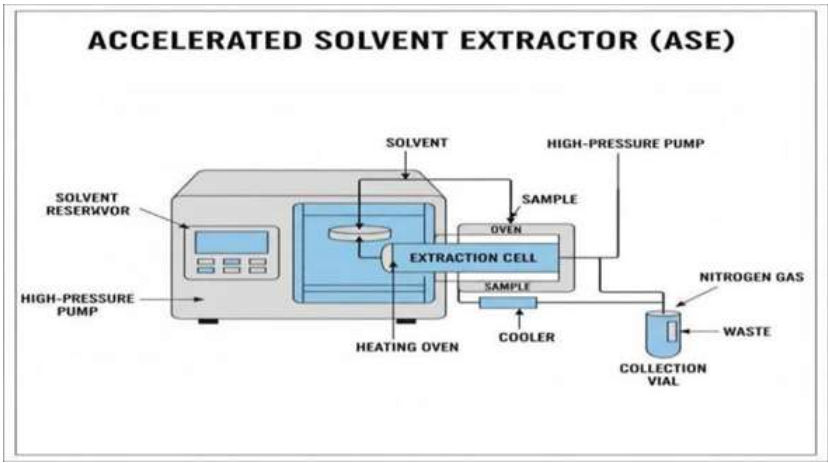

Fig. 9 Accelerated solvent extractor

Kinetics Enhancement: The combination of high temperature (which increases the analyte's solubility and the solvent's penetrability) and high pressure (which forces the solvent into the matrix pores) drastically accelerates the kinetics of dissolution and desorption.

Advantage:- Extremely fast extraction (typically 10-15 minutes per sample) and low solvent consumption, Automated, quick, less solvent.

Disadvantage:- Expensive equipment

Applications: Quality control of flavonoids, pigments.

Stepwise Working:-

1. Sample is loaded into a stainless steel extraction cell.

2. Solvent is pumped in under high pressure (100–200 bar).
3. Temperature is raised (50–200 °C), increasing solubility and diffusion rate.
4. Extraction occurs rapidly inside the closed vessel.
5. Extract is flushed out with fresh solvent and collected

5. Supercritical Fluid Extraction (SFE)/ The Tunable Solvent

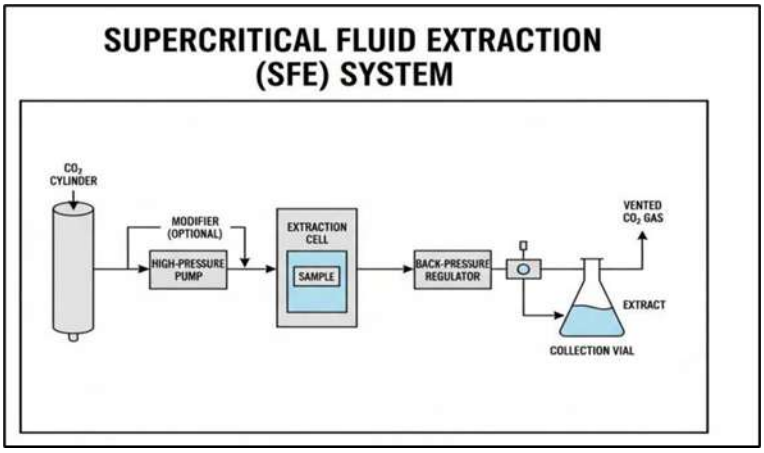

Fig. 10 Supercritical fluid extraction

A supercritical fluid (SF) is any substance maintained above its critical temperature (\text{Tc}) and pressure (\text{Pc}). In this state, the fluid exhibits unique properties of both liquids and gases:

Gas-like:- It can diffuse through solids like a gas, enabling rapid penetration into the matrix.

Liquid-like:- It possesses the ability to dissolve substances like a liquid (high solvation capacity).

Tunability:- The single most powerful aspect of SFE is the ability to adjust its density and, thus, its solvency power, by changing the pressure and temperature. This allows for highly selective fractionation of compounds, where, for instance, non-polar lipids can be extracted first, followed by more polar compounds by adding a small percentage of a co-solvent (modifier) like ethanol.

SFE Mechanism:-

The SFE mechanism involves three primary steps:

Resolving:- High-pressure liquid \text{CO}_2 is introduced into the extraction chamber, where it reaches its supercritical state. It diffuses and dissolves through the sample matrix, selectively extracting target analytes (predominantly non-polar).

Expanding:- The resulting mixture of \text{SC-}\text{CO}_2 and extracted analytes moves out of the chamber.

Capturing:- The pressure is reduced, causing the \text{CO}_2 to rapidly evaporate, allowing the pure, solvent-free extract to be captured.

Advantages:-

SFE is widely studied for phytochemical extraction and offers:

Minimal Solvent Use:- It significantly reduces or eliminates the need for organic solvents. Short Extraction Times and Higher Efficiency.

Recovery and Automation:- Faster restoration rates and automation properties. Non-toxic, selective, solvent-free product.

Applications:-

Fruit Waste Valorization: SFE can be used to extract a diversity of components—polysaccharides, proteins, lipids, polyphenols, and vitamins—from fruit waste for conversion into value-added products, including bio-diesel Caffeine decaffeination, volatile oils, nutraceuticals'.

Supercritical CO_2 acts as solvent; modifiers (ethanol, methanol) allow extraction of polar compounds.

Used in caffeine removal, essential oils, omega-3 extraction.

Disadvantage:- this method have Very high capital investment.

Stepwise Working:-

1. CO_2 gas is compressed above its critical pressure (73.8 bar) and heated above critical temperature (31.1 °C).
2. Supercritical CO_2 is passed through the sample in an extraction vessel.
3. Due to its dual nature (like a liquid & gas), it dissolves both non-polar and moderately polar compounds.
4. Extract-laden CO_2 flows into a separator vessel.
5. Pressure is reduced → CO_2 becomes gas again and escapes, leaving behind pure extract.

6. Solid Phase Extraction (SPE)/ The Analytical Workhorse

SPE is a sophisticated technique for isolating and quantifying target analytes from a liquid stream by trapping them onto a solid sorbent material.

SPE is an indispensable technique for both sample clean-up and pre-concentration.

Mechanism:-

It involves the selective adsorption of target analytes from the liquid matrix onto solid sorbent (e.g., silica, C18, ion-exchange resins), followed by selective elution using a series of solvents. Enhanced Selectivity: Modern SPE utilizes highly specialized sorbents like Molecularly Imprinted Polymers (MIPs), which possess tailor-made cavities that selectively bind a single target molecule, offering purity that rivals expensive chromatography techniques.

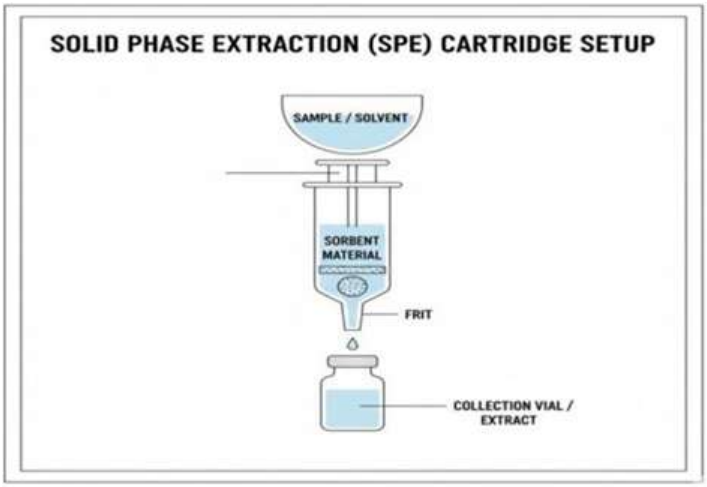

Fig. 11 Solid phase extraction

Advantages:-

High selectivity, reusable sorbent, portable

Available in cartridge, disk, and 96-well plate formats.

Disadvantage:- Limited to specific analytes, cost of cartridges.

Application:- it is used to drug residue analysis and water testing, bioanalytical sample preparation

Stepwise Working:-

1. A sample (liquid or dissolved solid) is passed through a cartridge containing solid sorbent (silica, polymer, C18).
2. Analytes of interest are adsorbed onto the stationary phase.
3. Unwanted components are washed away with weak solvent.
4. Target compounds are eluted with a strong solvent.

7. Solid Phase Micro-Extraction (SPME)

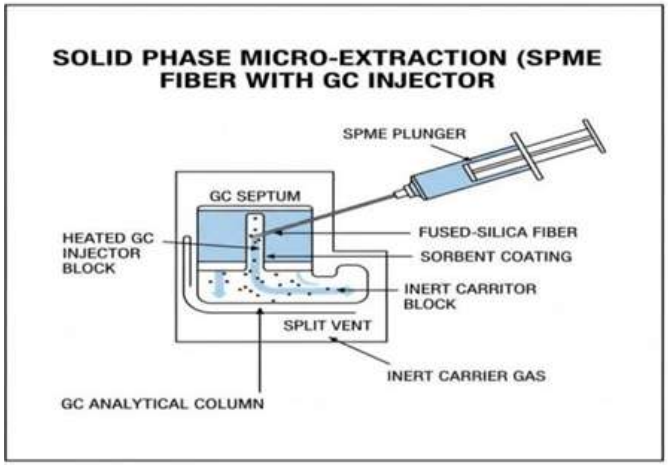

Fig. 12 Solid phase micro-extraction

Mechanism:- Coated fiber adsorbs volatile/semi-volatile compounds; desorption into analytical instrument.

Completely solvent-free.

Applications:- used to detect fragrance profiling, essential oils, volatile impurities, pesticides detection.

Advantage:- Solvent-free, sensitive, integrates with GC/MS, HPLC.

Disadvantage:-Few fiber coatings available, fragile fiber

Stepwise Working:-

1. A fused-silica fiber coated with polymer (e.g., PDMS) is exposed to a liquid or gaseous sample.
2. Volatile/semi-volatile compounds adsorb onto the fiber coating.
3. Fiber is inserted into the injector of GC or HPLCsystem.
4. Analytes are thermally desorbed and analyzed.

5. Comparative Evaluation:-

A comparative table can be included showing yield, time, solvent use, cost

Parameters	Conventional methods	Modern methods
Solvent requirement	Very high	Low to moderate
Extraction time	Long(hours to days)	Very short (minutes to hours)
Energy use	High (heating required)	Optimized, less energy
Temperature control	Poor	Precise
Selectivity	Non- selective	High selectivity
Scalability	Limited	Industrial scalable
Cost	Low setup cost	High cost equipment
Suitability for heat- sensitive compound	Poor	Better with UAE, EAE, SFE

6. Applications:-

1. **Pharma & Drug Discovery — getting chemicals ready for testing and development**

To isolate pure bioactive compounds, standardize extracts, and provide material for pharmacological tests.

E.g.Isolating alkaloids for structure-activity studies.

2. **Nutraceuticals & Functional Foods — concentrated, safe, marketable extract**

To obtain extracts that are safe to ingest, rich in desired actives, and cost-effective

E.g.Concentrated antioxidant extracts from berries or green tea for capsules.

3. **Cosmetics & Personal Care — clean, fragrant, and bioactive extracts**

To integrate natural fragrances, essential oils, and active botanicals into creams, serums, and perfumes.

Eg. Extracting lavender oil with SFE for perfume blends.

4. **Food Industry & Flavouring — efficient, safe flavor extraction**

To recover flavors, aromas, and natural preservatives while maintaining safety

E.g. Removing impurities or toxins from raw extracts before food use.

5. **Environmental Monitoring & Forensics — trace-level sensitivity**

To detect pollutants, residues, or trace compounds in complex environmental or forensic samples.

E.g.Detecting volatile organic compounds (VOCs) from contamination sites.

6. **Analytical Chemistry & Quality Control — rapid, reproducible prep.**

To prepare clean samples for HPLC, GC, LC-MS with minimal interference.

E.g. Stability-testing sample prep for degradation studies.

Trace impurity profiling before batch release.

7. **Industrial Scale Production — process design and cost-efficiency**

To scale lab methods into reliable, safe manufacturing processes.

E.g. Mass production of plant extracts for pharmaceuticals, Cosmetic.

8. **Research & Innovation — combining techniques for novel outcomes**

To push boundaries (new solvents, nano-sorbents, AI optimization).

E.g. Developing green processes for high-value actives.

Creating targeted extraction protocols for single-compound isolation.

Food Industry: Extraction of natural flavors, antioxidants, colorants

Cosmetics: Essential oils, natural fragrances.

7. Summary of Advantages & Disadvantages:-

A consolidated table format will compare each method's strengths and limitations

Method	Advantages	Disadvantages
Maceration	Simple, inexpensive, widely used	Long duration, poor efficiency
Decoction	Good for hard plant part easy method	Heat can degrade active compounds
Percolation	Continuous process, efficient	Risk of channeling, time consuming
Soxhlet extraction	Solvent recycling, large sample used	Not suitable for thermolabile compounds
Reflux	Faster than maceration, less solvent used	Risk of degradation due to high temperature
Microwave assisted extraction	Very fast, less solvent used, eco friendly	Expensive setup, thermal degradation
Ultrasound assisted extraction	Low energy, short time, eco- friendly.	Risk of Free radicals, thermal degradation.
Enzyme assisted extraction	Selective, mild, eco-friendly	Costly enzyme complex optimization
ASE	Automated, very efficient	Very costly equipments
SFE	Solvent Free, highly selective	High setup cost
SPE	Portable, reusable	Limited to certain analysts
SPME	Solvent Free, sensitive	Fragile fibers limited coating

8. Recent Developments:-

Extraction science has moved fast in the last decade. The big themes are efficiency, selectivity, sustainability, and automation. Researchers and industry aren't just trying to get more material out of plants — they want higher-quality extracts, less solvent and energy use, easier scale-up, and processes that are safe for people and the planet. Below I summarize the major advances, how they work, why they matter, and any practical limits.

1. **Green solvents: Deep eutectic solvents (DES) and safer alternatives**

What changed: People are replacing hazardous organic solvents (like hexane, chloroform) with greener alternatives — especially deep eutectic solvents (DES), some ionic liquids, and bio-based solvents (e.g., limonene).

How they work: DES are mixtures (often of a hydrogen-bond donor and acceptor) that liquefy at room temperature and can dissolve many plant compounds. They can be tuned (by changing components) to favor polar or non-polar targets.

Why it matters: DES are often cheaper than ionic liquids, biodegradable in many cases, and reduce VOC emissions and disposal costs. They also allow extraction at lower temperatures, protecting fragile compounds.

Limitations: Not all DES are fully biodegradable; some are viscous (makes mass transfer slower) and require careful removal or downstream cleanup. Regulatory acceptance in pharma still needs case-by-case demonstriations.

2. **Hybrid / combined methods (stacking the strengths)**

What changed: Single-technique extractions (just Soxhlet or just MAE) are being replaced by hybrid approaches — for example, ultrasound + supercritical CO_2, enzyme pre-treatments + microwave, or MAE followed by SFE.

How they work: Each technique addresses a weakness of the other. Enzyme pre-treatment loosens cell walls; microwaves rapidly heat and liberate solutes; SFE then selectively picks up non-polar molecules with CO_2.

Why it matters: Hybrids often give higher yields, better selectivity, and shorter total processing time than either method alone.

Limitations: More complex equipment and process optimization; scale-up requires careful design to preserve synergy seen at lab scale.

3. **Nano-enabled and sorbent innovations**

What changed: Novel sorbent materials — metal-organic frameworks (MOFs), Molecularly imprinted polymers (MIPs), functionalized magnetic Nanoparticles and graphene-based sorbents — are being used for highly selective extraction and cleanup.

How they work: These materials either adsorb target molecules selectively (MIPs, MOFs) or can be manipulated magnetically to speed separation (magnetic nanoparticles). They are often used in SPE, dispersive SPE (dSPE), or in hybrid extraction workflows.

Why it matters: They allow very selective cleanup, reduce sample prep time before HPLC/GC, and enable low-volume, solvent-free approaches for trace analysis.

Limitations: Cost of advanced sorbents, potential leaching of sorbent components, and the need to validate reusability and stability.

4. **Enzyme engineering and tailored biocatalysis**

What changed: Enzymes used in EAE are being engineered or formulated (immobilized enzymes, enzyme cocktails) to be more robust, reusable, and specific.

How they work: Tailored enzyme blends degrade specific cell wall components while leaving targets intact; immobilized enzymes can be reused, lowering cost.

Why it matters: Greater selectivity, milder conditions, reduced solvent and energy needs.

Limitations: Enzyme procurement and formulation can be costly; optimization is matrix-dependent.

5. **Automation, AI-assisted optimization and digitalization**

What changed: Extraction optimization is increasingly automated and assisted by data-driven tools (design of experiments, machine learning) that find ideal temperature, solvent mix, and time far faster than manual tuning.

How they work: Automated platforms run many parameter combinations; AI models predict best settings based on previous data and chemical properties.

Why it matters: Faster R&D, lower development costs, more reproducible processes.

Limitations: Requires quality data and initial investment in automation/software.

6. **Regulatory and sustainability integration**

What changed: Regulatory pressure and consumer demand push the industry toward solvent reduction, solvent replacement, and transparent supply chains. Life-cycle assessments (LCA) of extraction processes are now routine in larger companies.

Why it matters: Choosing extraction methods now includes environmental impact and regulatory acceptance, not just yield.

Green solvents: Ionic liquids, deep eutectic solvents (biodegradable, recyclable). Hybrid techniques: Combining UAE + SFE, or MAE + enzyme pre-treatment.

Nano-extraction: Nanoparticle-assisted methods for higher selectivity. Automation: Robotic sample handling in ASE and SP.

9. Future Scope:-

The future of extraction science is being shaped by three major pillars: sustainability, technology integration, and pharmaceutical relevance.

1. Sustainability and Green Chemistry

Increasing demand for eco-friendly solvents such as ionic liquids and deep eutectic solvents (DES).

Greater emphasis on solvent-free techniques (SPME , SFE) to minimize environmental hazards.

Adoption of renewable bio-based solvents (like limonene from citrus waste).

2. Integration of Technology

Automation and robotics are making ASE and SPE systems more precise and high- throughput.

AI and machine learning are being integrated into extraction optimization, predicting ideal solvent systems and parameters.

Miniaturization & Lab-on-Chip devices are gaining traction for microscale extractions, reducing time and cost in drug screening.

3. Pharmaceutical Industry Relevance

Extraction techniques are key to drug discovery pipelines, as ~50% of current drugs originate from natural sources.

Growing global demand for standardized herbal medicines will push industries to adopt advanced extraction.

In clinical research, efficient extraction ensures reproducible bioavailability and pharmacokinetic studies.

CONCLUSION

Extraction techniques continue to play a central role in natural product research, drug discovery, and the development of new pharmaceutical products. Traditional methods like maceration, infusion, decoction, percolation, Soxhlet extraction, and heat-reflux extraction are still widely used because they are simple, affordable, and easy to perform, even in basic laboratory environments. These classical approaches help researchers obtain crude extracts, identify potential bioactive compounds, and study the overall chemical profile of medicinal plants. However, they often require long extraction times, large amounts of solvent, and can sometimes damage heat-sensitive molecules. In comparison, modern extraction techniques—such as microwave-assisted extraction, ultrasound-assisted extraction, enzyme-assisted extraction, accelerated solvent extraction, supercritical fluid extraction, solid-phase extraction, and solid-phase micro-extraction—offer major improvements. They are designed to increase extraction efficiency, target specific compounds more effectively, reduce solvent and energy use, and better protect delicate plant constituents. These advanced methods also support industrial needs by providing faster, more reliable, and scalable processes. Overall, the shift from conventional to modern extraction technologies highlights the growing demand for cleaner, more efficient, and standardized natural products. As technology continues to advance, future extraction methods are expected to incorporate green solvents, hybrid techniques, continuous processing, and AI-based optimization, making natural product research quicker, more sustainable, and scientifically more powerful.

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HOW TO CITE: Shaikh Neha Hamid, Kiran Rodage, Rutuja Mashalkar, Prerna Bhusne, Tejas Wagmare, Extraction Techniques, Int. J. of Pharm. Sci., 2026, Vol 4, Issue 4, 3212-3234. https://doi.org/10.5281/zenodo.19673531