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Review Article

Extraction Techniques in Modern Research: Conventional Methods, Emerging Technologies, and their Benefits and Challenges

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ABSTRACT

Extraction techniques play a vital role in modern scientific research by enabling the isolation of valuable bioactive compounds from natural and synthetic sources. Over the years, extraction methods have evolved from traditional approaches to advanced technologies aimed at improving efficiency, selectivity, and environmental sustainability. Conventional extraction methods such as maceration, percolation, Soxhlet extraction, and distillation remain widely used because of their simplicity, affordability, and ease of operation. However, these methods often require large volumes of solvents, longer extraction times, and high energy consumption, which may reduce the quality of heat-sensitive compounds. To overcome these limitations, emerging extraction technologies including microwave-assisted extraction, ultrasound-assisted extraction, supercritical fluid extraction, enzyme-assisted extraction, and pressurized liquid extraction have gained significant attention. These modern approaches offer advantages such as reduced extraction time, lower solvent usage, improved extraction yield, and enhanced preservation of bioactive constituents. Despite these benefits, advanced techniques may involve high operational costs, sophisticated instrumentation, and technical expertise, limiting their large-scale application in some settings.

INTRODUCTION

Medicinal plants nowadays are regarded with great attention as an important source of medicinal phytochemicals which have a potential role in the development of new drugs [1,2]. This can be attributed to its natural origin, accessibility within aboriginal communities, low-cost, ease of administration and potentially even more tolerable [3], lower drug resistance and minimal side as well as negative effects. A medicinal plant is an element of a plant that contains the active

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ingredient or bioactive compounds (metabolites), otherwise known as secondary metabolites [4]. The term primary plant constituents relates to the different nutritional compounds of common sugars, proteins, amino acids and chlorophyll that are constituent parts of such a medicinal plant. These are phytochemical residues derived from the plant known for their biological activities. Our secondary metabolites or the secondary plant constituents includes of alkaloids, saponins, terpenoids, flavonoids, phenolic compounds and tannins [4.

Research in this natural medicinal herb begins with process for extraction of key bioactive phyto-nutrients, which represents a significant step in the manufacture of herbal compounds. Extraction: This is the fundamental step in isolating, identifying and utilizing primary metabolites from various plant extracts. [6]. The present techniques for extracting essentialoils, fat and oils are Soxhlet [6], hydrodistillation[5] and maceration with alcohol and others [7]. The compounds derived in this way from the plants are largely impure, unrefined powders, semisolids, or liquids to be used exclusively topically/orally. such as infusions, decoctions, fluid extracts, powdered extracts and tinctures. [8].

Parameters to be Considered before Extraction:

1. The plant material must be verified and authenticated prior to the extraction, with all foreign material (soil, sand, stones, glass,dust, metal and plastic) being removed.

2. Geographic location, age of plant, time of collection, season, locus of collection and part of plant: Quality control.

3. It is necessary to use the exact plant organ.

4. The drying process mainly relies on the specific chemical constituents of plant material. Generally speaking, the blow fans with cold or hot air blasting approaches are the superior choice.

5. Cutoff processes which generate heat need to be avoided as much as operationally possible for the grinding procedure.

6. The appropriate sieves are employed to obtain the obligatory uniform-sized particles of the powder plant material by passing through it [8,9,10]

Methods:

Pre-extraction preparation of plant samples:

Preparation of plant sample :The very first step of the study of herbal medicinal plants. It is done to conserve the biomolecules in plants. Plant samples (leaves, bark, roots, fruits and flowers) may be obtained from dried or fresh plants. Preservation of phytochemicals in the plants are affected not only by drying but also by grinding and drying [11].

Fresh vs. dried samples:

In the research of medicinal plants, either fresh or dried sample is utilized. Dried sample is preferred for most of studies as compared to fresh sample because of time involvement in designing the experiment. In addition to time limitation, all fresh samples are delicate and deteriorate faster than dried ones[12]

Grinded vs. powdered samples:

We further increase the contact surface between samples and solvent by reducing particle size. Grinding and powdered samples made small size but powdered samples have their own advantage

because they are more homogenized and his size is smaller. This is particularly important, since for basic extraction to occur the solvent needs to be touching the analytes in a sample smaller than 0.5 mm[key] [13].

Drying of plant samples by air, microwave, oven and freeze-drying (lyophilisation):

Table no 1: Drying of plant samples by air, microwave, oven and freeze-drying (lyophilisation): [14,15,16]

Drying Method	Principle	Typical Conditions	Time Required	Effect on Phytochemicals	Limitations
Air-drying	Natural moisture removal under ambient temperature	The plant parts are bound, then hanged for drying air	in 3 to 7 days up to several months	Without the use of high heat, heat-labile compounds are preserved	Best for the preservation of phenolics and other heat-sensitive phytochemicals
Microwave	Electromagnetic fields induce dipolar gyration → quick internal heating	microwave fields in short bursts	Minutes to hours	Damages the sensitive phytochemicals due to quick heating	Potential for overheating and compound declination
Oven	Thermal energy use for evaporation due to loss of moistness	Controlled temperature of hot air at around 40–45 °C for a few hours	Hours	antioxidants may get degrade due to heat	temperature needs to be optimized
Freeze-drying	Sublimates the frozen water contained in the tissue under vacuum	Pre-freeze at −20 to −80 °C; vacuum drying	24–48 hours	Sustain the highest level of phenolic compounds and thermally sensitive phytochemicals	Expensive equipment is required; process is complicated; sample loss

Types of Extraction: There are generally two types of Extraction method, that are:

1. Conventional Method
    - Maceration
    - Percolation
    - Decoction
    - Soxhlet
    - Infusion
    - Steam distillation
2. Modern Method
    - Microwave assisted Extraction
    - Supercritical fluid extraction

- Ultrasound assisted extraction/ Sonication extraction
- Accelerated Soxhlet extraction
- Vibrocavitation extraction

1. Conventional Method:

- **Maceration:** This is a traditional extraction method in which the powdered solid material is put in a closed vessel and solvent is added. The test can stand for long time (From hours to days) and shake it up from time to time. It is granted absolute time for the solvent to penetrate through the cell wall to solubilize the constituent available in plant. It only takes place via molecular diffusion. The liquid is then removed after the desired time, and the solid by-product is pressed to obtain as much solvent as possible. In cases where the solvent is water and maceration lengthy, a small proportion of alcohol may be used to inhibit microbial activity 17.

Merit	Demerit
It is simple and non-complex method.	Solvent requirement is more.
Energy saving process.	Slow process and time consuming.
Skilled operators are not required.	Not exhaustively extract the drug.

- **Percolation:** Percolation is performed in an apparatus called percolator, the solid substance is filled up with a prescribed solvent for hours in a closed container after which the mass fitted and a lid placed on the top of percolator. The extract is pressed and the liquid ends up in percolate [17]. The mixed liquid is filtered or centrifuged to remove solids and then diluted with a sufficient amount of solvent to get the desired volume. This continues until a drop from the percolator when evaporated leaves no residue [18].

Merit	Demerit
Requires less time than maceration.	More solvent needed
Suitable method for potent and costly drugs.	Skilled person is required.
Extraction of thermolabile constituents can be possible.	Requires more time than soxhlation.

- **Decoction:** Using water, boiled the plant material for formation of liquid preparation. This is with the work of fibrous plants and barks. It means a method of constant heat [19].

Merit	Demerit
Easy to perform	Not for heat sensitive compound
No trained operator	-
Suitable for heat stable compound	-

- **Soxhlet extraction:** Soxhlet extraction: Used when active ingredients are hard to extract from plant cell, Soxhlet extraction can be performed [20] · Decoction: obtained not only by heat stable compound and also hard plant material. So it is Called Hot Percolation method as well. The drug to be extracted is placed and packed in the body of Soxhlet apparatus. The setup is attached to a round bottom flask which already contains the solvent, and attached it with a reflux condenser. Solvent in the round bottomed flask is boiled gently; vapour goes up through the side tube, condensed by condenser and be deposited into thimble containing the material and fills up gradually Soxhlet. The solvent siphons over once it reaches the top of the attached tube to the flask, removing a portion of extracted compound. The flasks will contain the active soluble constituent while solvent will be volatized. This process continues until drug is completely depleted 20.

Merit	Demerit
Smaller quantity of solvents compared to maceration	The process allows manipulation of limited variables.
Repeatedly can use solvent	The extraction time is lengthy and the process is labor intensive.
Does not require filtration after extraction	Exposure to hazardous flammable liquid organic solvents, with potential toxic emissions during extraction.

- **Steam distillation:** This is to extractoil from the plant material consisting of particles as it penetrates into the heat and releases oil globules. The essential oil vapor and the steam pass out the top of the still into a water-cooled pipe, where they are condensed back to liquids. At this stage, the essential oil floats to the upper part of the water 21.

Merit	Demerit
Higher oil yield.	Complete extraction is not possible.
Oil quality is more reproducible.	Heat control is different
Cheap and environment friendly.	The process is uneconomical.

- **Infusion:** In this process active drug components are dipped in appropriate solvent. The solids are then macerated for a few minutes with either cold or boiling water to make fresh infusions 22.

Merit	Demerit
Easiest and simple method.	Time taking process
No trained operator required	Not suitable for heat sensitive compounds

- **Modern Method:**
  Microwave assisted Extraction: This method uses microwave energy to partition analytes from sample matrix in solvent. Microwave radiation interact with polar material interface/near surface of the material and conduction heat transfer. Microwave Assisted Extraction (MAE) is an extraction method that use microwave energy to help transfer the phytochemicals from the sample phase into the reaction solvent. This dipoles is the reason polar solvent and the polar compounds of sample are heated through microwaves. Consequently, these compounds get heated up quickly at the surface before the heat is transferred. The hydrogen bonds break due to the microwave rotating the molecules. This allows for the movement of ions made free by the dissolution as well as solvent which has also penetrated into the matrix. Its because non-polar solvents are low absorbers of microwave energy and thus do not heat well under microwaves. Since MAE is a selective method for polar compounds, polar solvents with high dielectric constants are suitable 23.

Merit	Demerit
Reduced extraction time	Risk of thermal degradation
Lower solvent consumption	Not suitable for heat-sensitive compounds
Effective for phenolic compounds	More suitable for low-molecular-weight phenolics than complex polyphenols

- **Supercritical fluid extraction:** Supercritical fluid (SF) or dense gas is defined as the state of a substance that has properties of both liquids and gases when it is held above its critical temperature, as well as critical pressure. The most common supercritical fluid used, carbon dioxide (CO_2), enters the supercritical state at temperatures of 31.1 °C or higher and pressures above 7.38 MPa.[2] Supercritical carbon dioxide (SC-CO_2), or simply SC CO_2, is the most commonly used non-polar extractant, because of its high capacity, lower cost and easy availability as well as the fact that it's ultimately a non-toxic natural solvent. Even a solution polar solvent, the addition of polar modifiers such as ethanol, methanol etc., will help to determine effective solvation of polar compounds. The extracts that we manage to extract with the help of supercritical fluids are typically offered in a

concentrated form because the critical home property of that superconducting fluid (carbon dioxide) vaporizes very quickly at area temperature. Additionally, the supercritical fluids quantity can also be changed in order to reduce time taken. The best yield from the SC-CO2 (Super-Critical Carbon Dioxide) leaves extract of Wadeliacalendulacea 25[27] was obtained with extraction conditions at 25 MPa, 25 ºC temperature, concentration modifier of 10%, and time of extraction for 90 minutes.

Merit	Demerit
Solvent free extract	Requires high-pressure pumps, vessels.
Fast extraction rate	High pressure requirements -Typically 100–400 bar
Highly pure extract	Not ideal for very polar compounds

- **Ultrasound assisted extraction:** UAE is a promising technology which is simple, cost-effective and more affordable not needing complex instruments. It is applicable on both large and small scale. Ultrasonic frequency range :- 20 kHz upto 2000 kHz will be used by UAE. Ultrasonic sound waves have been help in increasing the mechanical effect of the acoustic cavitation allowing...solvents to closer contact between and improve cell wall permeability. Ultrasonic treatment changes the phyco - chemical characters of materials. Also, the ultrasonic treatment ruptures the cell wall of plants to facilitate both the release of chemical constituents and also the mass transfer of solvents into plant cells. This is a straightforward and inexpensive procedure. It is suitable for small-scale as well as large-scale phytochemical extraction [28][17][29][30][24][33].

Merit	Demerit
Less extraction time	Use of ultrasound energy more than 20 kHz may influence the active phytochemicals
Less solvent consumption	Possible degradation of sensitive compounds

- **Accelerated Soxhlet extraction:** The rapid form of liquid-solvent extraction is the accelerated solvent extraction (ASE), which leads to an effective and economic process to extract bioactive compounds in comparison with maceration or conventional Soxhlet method due to use a smaller volume of solvent. When performing ASE, the sample is filled with sand particles into a stainless-steel ASE extraction cell to prevent AS from aggregating in the sample. This is typically achieved via the layered distribution of a sand-sample mixture by inclusion of cellulose filter papers as spacing. ASE is an automated system that performs extraction

at different pressures and set temperatures, finishing extract of plant material in under one (1) hour. The ASE efficiency, as with all solvent extraction methods, is primarily a function of the type of solvent used: for example, the maximum bixin yield was obtained from the ASE of Bixa orellana (obtained after heating at 50 °C for 5 min) using cyclohexane–acetone in a proportion of 6:4 v/v (68.16% purity). For the quality control experiments, 80% aqueous methanol was used to obtain high flavonoids (~94%) of Rheum palmatum by ASE 31.

Merit	Demerit
Much faster than conventional Soxhlet	High equipment cost
Uses less solvent	Not suitable for very heat-sensitive compounds
Better penetration	Limited sample size

- **Vibrocavitation extraction:** Using intense agitation, the interfacial area of mixed ingredients is significantly increased and high energy. Currently, small volumes and the potential to process media with different viscosities on the same equipment are major drives for developing existing extraction technologies. Within the context of this trend, an effective method for extraction of liquid components (dispersion) in a large viscosity range was developed using vibrocavitation. This method processes materials via segments: from simple blending up to dispersion and homogenization until disperse- stage particle size with sizes reach around 5 m. Inputs are for the primary processingstuff that is combined are put into a pre-mixer. Vibrocavitational extraction consists of short-time treatment of raw material (even less than 1 min) which must produce a highly disperse emulsion [34].

Merit	Demerit
Very fast extraction	Possible degradation of sensitive compounds
High yield	Equipment cost
Short processing time	Noise and vibration

CONCLUSION:

Extraction techniques continue to evolve alongside the growing demands of scientific research and industrial applications. While conventional methods remain important because of their simplicity, accessibility, and cost-effectiveness, modern extraction technologies provide improved efficiency, faster processing, and better preservation of valuable compounds. Each method has its own strengths and limitations, making the choice of technique highly dependent on the nature of the sample, desired yield, available resources, and research objectives.

In recent years, there has been a strong shift toward greener and more sustainable extraction approaches that minimize solvent use, reduce energy consumption, and improve environmental safety. Although advanced technologies may

require higher investment and technical expertise, their long-term benefits in terms of quality, productivity, and sustainability make them increasingly valuable in modern research.

Rather than replacing conventional methods entirely, emerging extraction techniques should be viewed as complementary tools that expand the possibilities of scientific investigation. A balanced understanding of both traditional and advanced approaches can help researchers select the most suitable method for specific applications. Continued innovation and optimization in extraction science are expected to support future developments in pharmaceuticals, food technology, biotechnology, and natural product research

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