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GREEN EXTRACTION OF BIOACTIVE COMPOUNDS FROM MEDICINAL PLANTS: SUSTAINABLE TECHNIQUES AND PHARMACEUTICAL APPLICATIONS

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ABSTRACT

Medicinal plants are a rich source of biologically active compounds with diverse structures and beneficial properties. The major classes of these compounds are phenolic acids, flavonoids, alkaloids, terpenoids, tannins and glycosides. These metabolites are regarded as potential active ingredients, drug leads and formulation components. Conventional extraction approaches are associated with long processing times, high solvent consumption and high energy costs, and unstable physicochemical conditions that may damage sensitive molecules. Green extraction technologies offer the possibility of obtaining desired compounds with reduced environmental impact. This study aimed to discuss ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), enzyme-assisted extraction (EAE) and pressurized liquid extraction (PLE) in the context of water, ethanol, water–ethanol mixtures and natural deep eutectic solvents as alternative approaches. These processes differ in their mechanisms of action, such as cavitation, rapid dielectric heating, variable solvent properties, enzymatic disruption of cell walls and increased solubilization due to pressure. The choice of an appropriate method depends on a variety of factors, including the type of plant material, the specific target molecule, the choice of solvent, operating conditions and the degree of purification. In pharmaceutical applications, green extractions were used for natural-product screening, antioxidant and antimicrobial investigations, herbal-extract standardization and drug-delivery research. However, a potentially valuable extract alone cannot guarantee therapeutic efficacy or overall sustainability. The importance of product safety, reproducibility, solvent removal, lifecycle analysis, scalability and regulatory compliance should not be overlooked. Green extraction methods can help to achieve higher sustainability if supported by appropriate analytical validation and justified conclusions.

Keywords: Green Extraction; Medicinal Plants; Bioactive Compounds; Sustainable Extraction; Ultrasound-Assisted Extraction; Microwave-Assisted Extraction; Supercritical Fluid Extraction.

1 INTRODUCTION

Medicinal plants have permeated through the traditional healthcare systems of diverse cultures and continue to play a significant role in contemporary ethnopharmacological research. Hundreds of secondary plant metabolites with physiological activity in humans have been identified. For example, curcumin in turmeric (Curcuma longa), eugenol in clove (Syzygium aromaticum), catechins in green tea (Camellia sinensis), glycyrrhizin in liquorice (Glycyrrhiza glabra) and various alkaloids in numerous medicinal species. The chemical composition of any given plant species is not fixed, but may vary considerably depending on the genetic make-up, climatic conditions, soil composition, period of harvesting, drying, storage and other factors.

Extraction processes aim at isolating specific active ingredients from plant matrices and the choice of an appropriate technique depends on the nature of the matrix and the targeted compounds. The yield is determined by such variables as plant parts used, particle size, solvent polarity, solid-to-solvent ratio, pH, temperature, time of extraction and mixing efficiency. Traditional methods are relatively simple and comprise maceration, infusion, decoction, percolation and Soxhlet extraction. However, they often require extended periods of time, large volumes of solvents and/or elevated temperatures. In addition, organic solvents widely used in these processes may vary drastically in their toxicological and flammability hazard potential, require different recovery procedures and impose different environmental burdens. A combination of elevated temperature, oxygen exposure, light irradiation and extreme pH may accelerate undesirable side-reactions and alter the targeted extract properties.

Green extraction processes have emerged as a sustainable alternative to the conventional methodologies. They are focused on the minimisation of the environmental impact while ensuring the quality of the extract and active principles. It is noteworthy that green extraction is not confined to the use of one specific solvent or technique, but comprises a range of unit operations, where attention is paid to the selection of an optimal solvent, energy consumption, time, waste production, extraction yield, equipment, solvent recovery, operator safety and residue incineration. The concept and principles of green extraction were introduced by Chemat, Vian and Cravotto, who also discussed the sustainability of various methods [1-4]. The review provides an overview of the relevant techniques, elucidates their mechanisms, discusses the choice of solvents and presents applications in pharmaceutical studies, highlighting the potential limitations and the need for standardised protocols as well as toxicological and evidence-based evaluations.

Aim

To review sustainable techniques for extraction of bioactive compounds from medicinal plants and discussing their pharmaceutical application and development.

Objectives

- To describe the types of bioactive compounds that can be extracted from medicinal plants;
- To describe the principles of action and working concepts of the main green extraction approaches;
- To characterize safer solvents applicable in the extraction process and factors that influence the efficiency of extraction;
- To sum up the possible pharmaceutical application of the extracted compounds;
- To identify the advantages and disadvantages of the methods, their possibilities for scale-up and further research needs.

2 BIOACTIVE COMPOUNDS IN MEDICINAL PLANTS

Bioactive compounds are chemical constituents of biological origin that can interact with biological systems. They are often classified according to their chemical structure: thus, phenolic compounds (phenolic acids, flavonoids), which are widely studied for their antioxidant properties and other biological activity, alkaloids, which are nitrogen-containing derivatives with varied pharmacological effects, but significantly different toxicological properties. Other groups of bioactive substances are terpenoids (found in essential oils and other plant fractions), tannins (able to precipitate proteins and other macromolecules), glycosides (a combination of a carbohydrate and another molecule), saponins, coumarins, lignans, and others.

The choice of an appropriate method depends on the physicochemical properties of the desired compound. Thus, polar molecules can be extracted with water or aqueous ethanol, while less-polar substances can be extracted with more hydrophobic solvents or supercritical CO_2. In addition, temperature, oxidation-reduction potential, pH, and other parameters should also be taken into account, as some bioactive compounds are unstable to various environmental

influences. It is also important to note that high total extract yield does not necessarily mean that the desired group of substances has been extracted in sufficient quantities. Therefore, when researching extracts, it is necessary to determine not only the total content but also the qualitative and quantitative composition of individual fractions using appropriate methods.

3 CONCEPT AND PRINCIPLES OF GREEN EXTRACTION

The overall objective of green extraction is to maximize the amount of valuable products, while minimizing consumption of resources and the impact on environment. Therefore, the following principles should be prioritized:

- Use inherent solvents and auxiliaries when technically feasible.
- Minimize solvent and, where applicable, recover or recycle spent solvent.
- Avoid unnecessary heating and operate at optimal temperature, to save energy.
- Avoid waste generation, by utilizing appropriate biomass or process residues.
- Maximize selectivity to minimize impurities and the need for downstream purification.
- Maximize yields of target molecules, while avoiding degradation of active compounds.
- Evaluate the entire process, including equipment, cleaning, recovery of solvents, waste treatment and scale-up potential.

A process should not be considered sustainable simply because it employs a water or state-of-the-art technology. A water-intensive process might involve high-energy consuming operations, such as evaporation and difficult solvent recovery. Or it might have poor selectivity and create more waste than a conventional process [1,3,4].

4 MAJOR GREEN EXTRACTION TECHNIQUES

UAE uses high-frequency sound waves in a liquid containing plant material which cause acoustic cavitation. Bubbles are formed, grow and collapse which create local mechanical effects that can break up tissue and improve wetting and movement of solutes from the matrix. UAE can be applied to a wide range of plant constituents including phenolics and flavonoids and can often work at relatively low bulk temperatures.

It has the advantage of relatively short processing times and can potentially reduce solvent usage and be simpler than high-pressure systems. Performance depends upon frequency, amplitude, duration, temperature, solvent, particle size and the design of the probe or bath. Over-sonication can lead to heating or oxidation and scale-up can be problematic due to uneven distribution of acoustic energy and therefore optimized conditions and appropriate controls are crucial [5].

4.1 Ultrasound-Assisted Extraction (UAE)

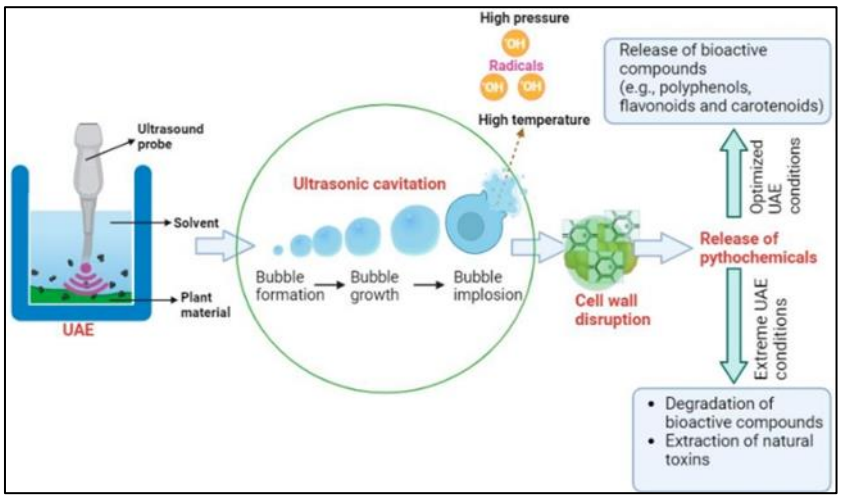


Figure 5.1: Ultrasound-Assisted Extraction (UAE)

4.2 Microwave-Assisted Extraction (MAE)

MAE employs microwave energy to heat the solvent and plant matrix. Polar molecules and dissolved ions respond to the electromagnetic field, undergoing volumetric heating. Heating and pressure within moist plant cells can help release

intracellular compounds. MAE offers potential for reducing extraction time and solvent consumption as compared with some conventional methods.

The technique is suitable for certain phenolic compounds, flavonoids and other constituents if the solvent and matrix demonstrate appropriate response to microwave energy. Temperature, power, moisture content and exposure time must be controlled. Heat-sensitive molecules may degrade under excessive treatment, not all solvents or samples are suitable for a microwave system and closed-vessel systems necessitate appropriate pressure and safety controls.

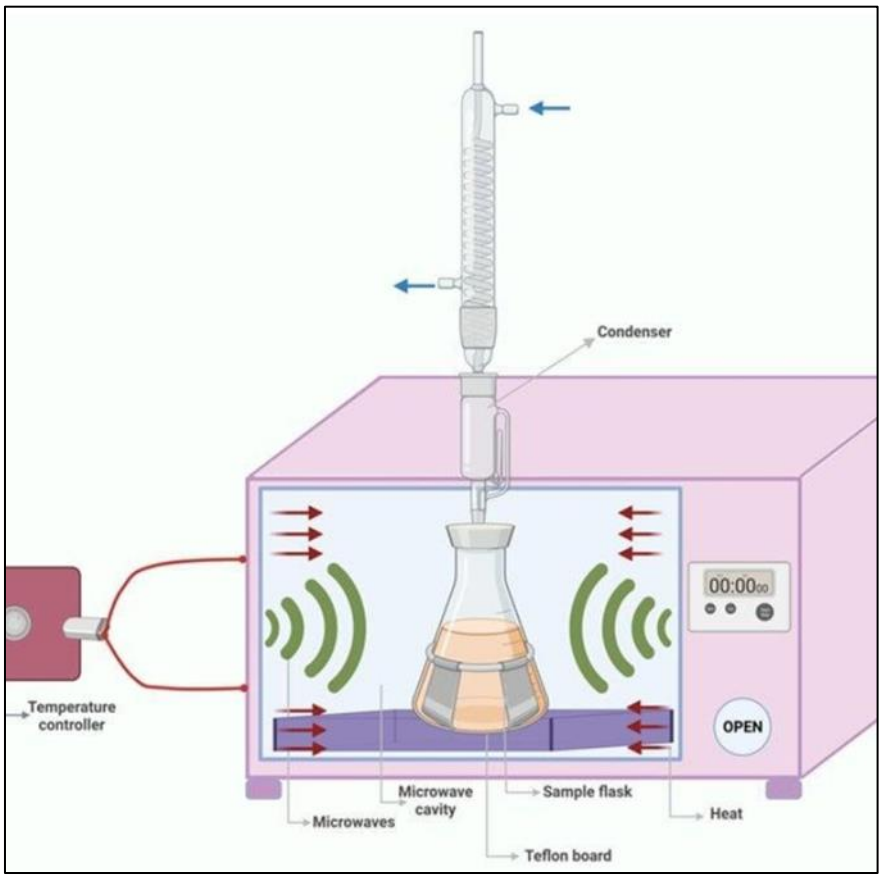


Figure 5.2: Microwave-Assisted Extraction (MAE)

4.3 Supercritical Fluid Extraction (SFE)

A supercritical fluid is held above its critical temperature and pressure, where it combines useful gas-like transport properties with liquid-like solvating ability. Carbon dioxide is commonly used because it is relatively accessible, non-flammable under typical extraction conditions and can be removed by depressurization. Changes in pressure and temperature alter its density and solvent strength. A small quantity of a suitable co-solvent, often ethanol, may be used to improve extraction of more polar constituents.

SFE is particularly useful for essential oils, aromas, terpenes and other relatively non-polar substances. It can produce extracts with low residual carbon dioxide and may reduce the need for conventional organic solvents. Limitations include the capital cost of high-pressure equipment, energy needs, operational complexity and weaker performance for highly polar compounds without a modifier. The method is most useful when its selectivity and product quality justify the investment.

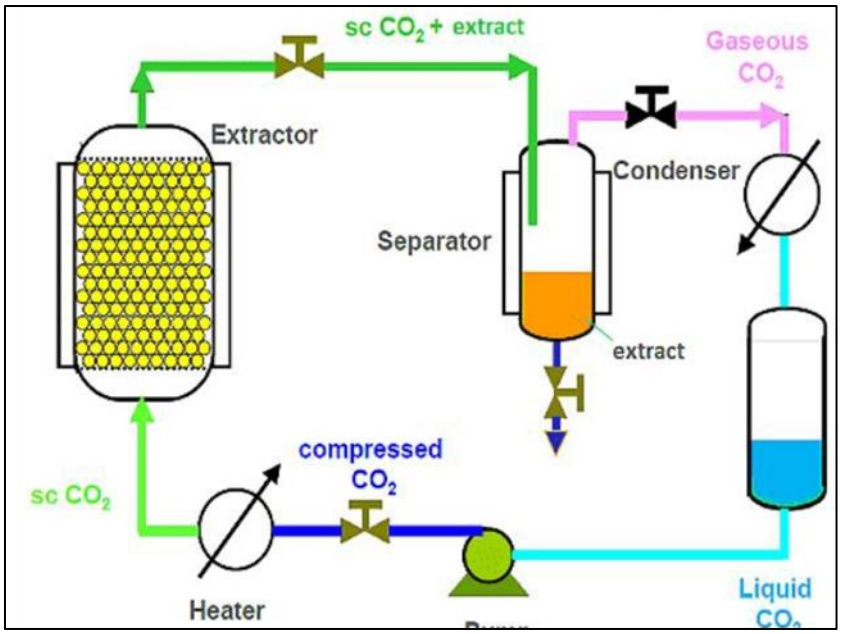


Figure 5.3: Supercritical Fluid Extraction (SFE)

5 ENZYME-ASSISTED EXTRACTION (EAE)

EAE (Enzymatic assisted extraction) employs enzymes like cellulases, pectinases or hemicellulases which breakdown structural elements of plant cell walls. This process can increase cell-wall permeability, facilitating the removal of intracellular elements. The enzymes can operate under relatively mild conditions thereby reducing the energy and resources required. Such a treatment reduces the need for aggressive physical and chemical treatment.

The type and amount of enzyme, pH, temperature, time of treatment and the plant matrix are determining factors in EAE. The cost of enzyme, stability during storage, reaction time, and requirement for inactivation or removal prior to downstream processing will be decisive for the commercial implementation. EAE can be combined with other techniques but the combined process should be evaluated for yield, product stability, cost and environmental impact.

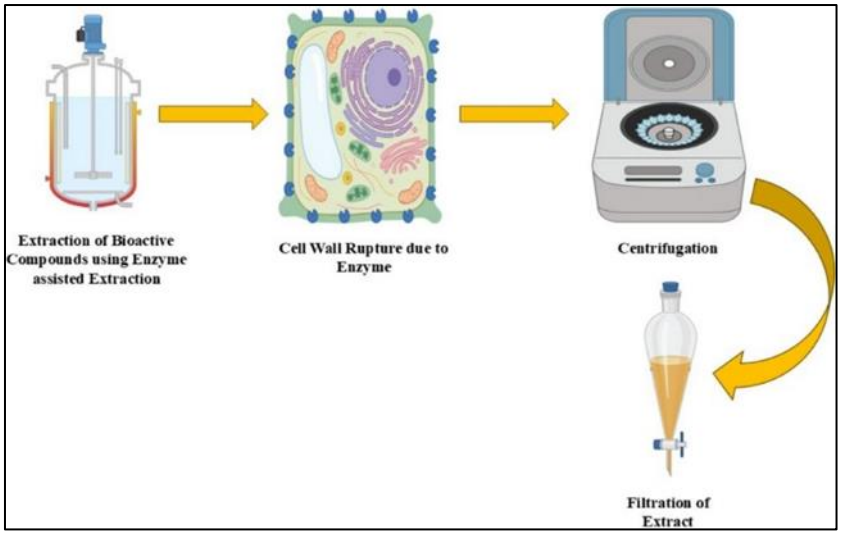


Figure 5.4: Enzyme-Assisted Extraction (EAE)

5.1 Pressurized Liquid Extraction (PLE)

PLE is based on the principle of using the liquid solvent. The solvent is placed at high temperatures and pressures to maintain its liquid state. High temperatures ensure sufficient solubility and diffusion of substances in solution while also reducing the viscosity of the solvent. Meanwhile, pressure prevents vaporization. Thus, PLE allows for a relatively short time of soaking the material under study in a solvent.

The method is used to extract such useful substances as phenolic compounds, but it requires specific devices, and the temperature is difficult to control. Besides, not all bioactive compounds are resistant to high temperatures. Therefore, it is essential to compare different methods of extraction taking into account the amount of the target substance, the number of solvents, their consumption, energy input, and the need for subsequent purification steps.

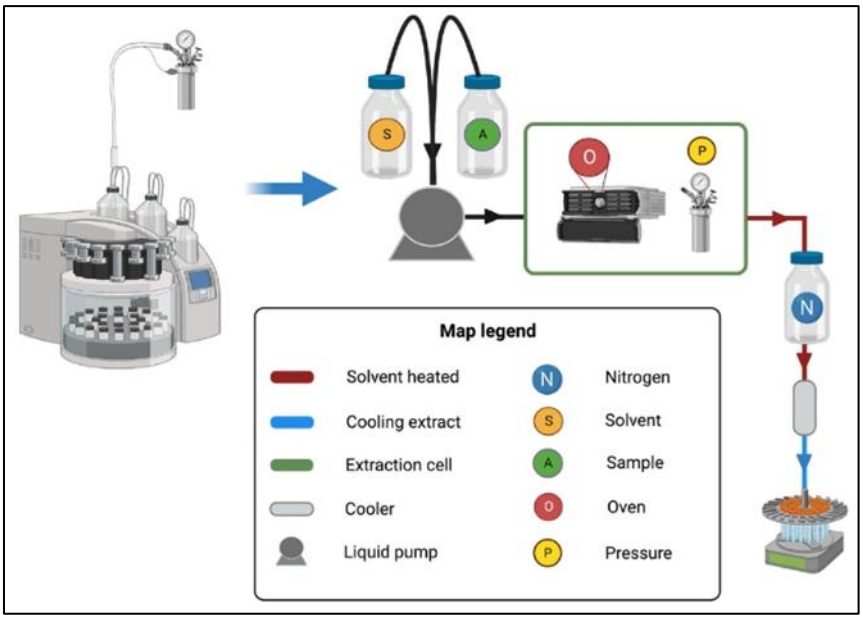


Figure 5.5: Pressurized Liquid Extraction (PLE)

5.2 Conventional Methods in a Green-Extraction Context

Maceration, percolation, infusion and decoction may still be of use in the case of certain plant materials and for small scale preparations. Their impact on the environment will depend on the particular solvent, time, heating and waste treatment involved. Thus, green extraction is not suggesting that these other methods are inherently unsustainable but that choices should be made on the basis of overall impact on the environment taking into account effectiveness and safety of products.

6 GENERAL PRINCIPLE DIAGRAM

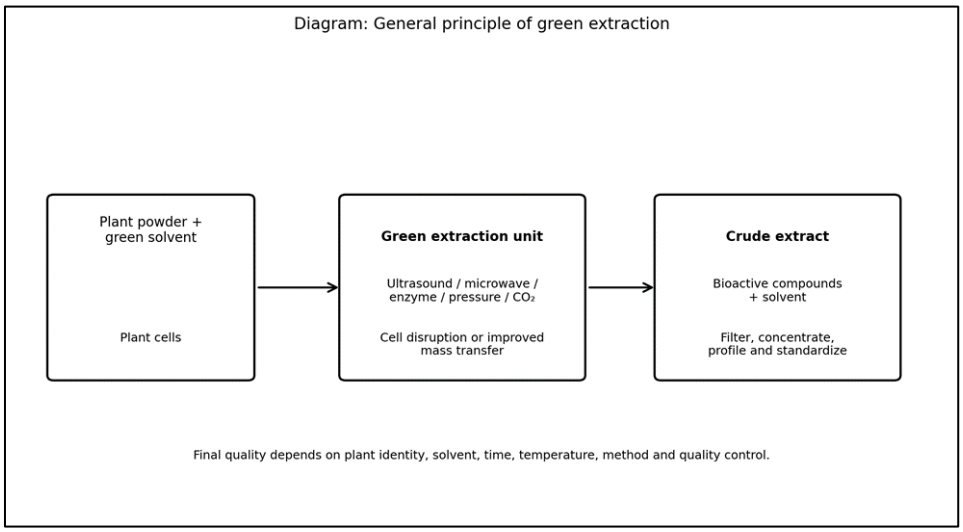


Figure 1: General principle of green extraction of plant bioactive compounds.

Generally, the plant material that has been prepared is contacted with a selected solvent and extracted by a suitable approach. The crude extract that is obtained comprises of the solvent as well as the constituents that have been extracted. It may then require filtration, concentration, purification and profiling. The precise steps that are involved depend on the type of process and also the use that the extract will be put to.

7 FLOW CHART OF THE GREEN EXTRACTION PROCESS

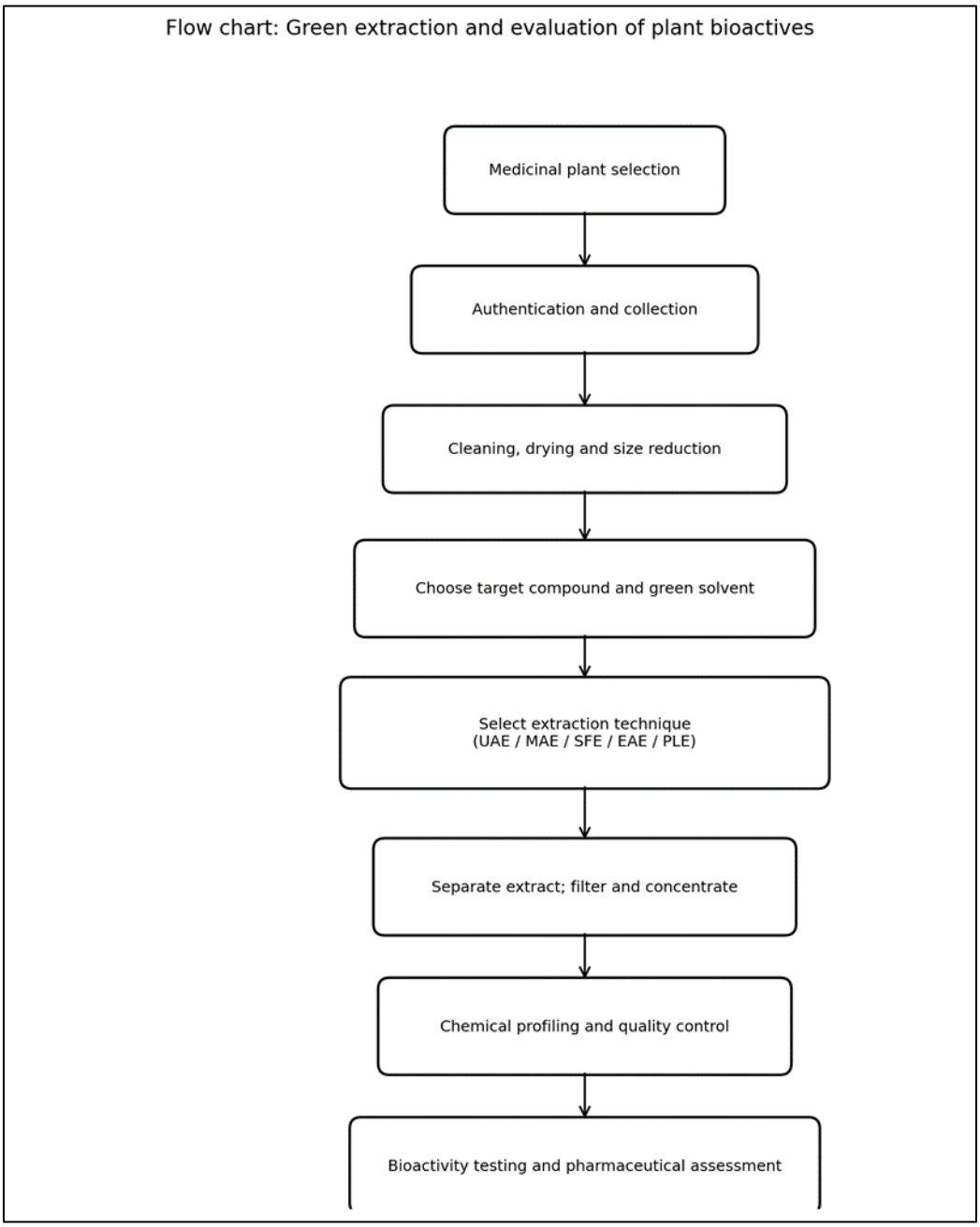


Figure 2: Workflow from plant selection to pharmaceutical assessment.

The flow chart shows that the first step is to identify the plant material to be extracted; second, to determine the conditions of extraction, depending on the target compound isolated. The last step is the evaluation of the resultant extract. The extract must be profiled and pass certain quality control tests. A biological screen should be done using proper controls and methods.

8 GREEN SOLVENTS

The choice of solvent strongly influences the selectivity, safety, cost, and environmental impact of an extraction process. Water is cheap, non-flammable, and suitable for many polar compounds, but may be less effective for some poorly water-soluble constituents, and can complicate drying or microbial control. Ethanol is capable of dissolving a large variety of plant constituents and is acceptable for food and pharmaceutical use when the grade and allowable limits are complied with. Water–ethanol mixtures allow the solvent polarity to be adjusted.

Natural deep eutectic solvents are mixtures made from selected hydrogen-bond donors and acceptors. Some have proven to be promising for phytochemical extraction. However, the high viscosity of these mixtures may impair mass transfer, and the solvent may be difficult to remove from the extract. Toxicity, biodegradability, impurities, stability, and suitability for the intended route of administration must be evaluated rather than assumed.

Supercritical carbon dioxide is a valuable solvent for relatively non-polar constituents and can be removed after extraction by reducing the pressure. In all cases, the solvent should be chosen on the basis of the target compounds and the downstream pharmaceutical use. A solvent that is acceptable for analytical research is not necessarily acceptable in a medicine.

9 FACTORS AFFECTING EXTRACTION EFFICIENCY AND QUALITY

- Plant identity and the used part: leaves, roots, bark, flowers and seeds vary in their chemical composition.
- Particle size: larger surface area, but potentially harder to filter.
- Solvent polarity: determines the range of compounds that can be extracted and the selectivity of the extraction.
- Solid-to-liquid ratio: essential for concentration gradients, solvent consumption and overall cost of the process.
- Temperature and time: can enhance extraction by increasing molecular motion, but may also degrade heat-labile compounds.
- pH: can affect ionization and solubility of certain metabolites.
- Settings of the applied method: adequate adjustment of parameters such as ultrasound amplitude, microwave power supply, pressure differences or enzymatic activity is required for optimal cell disruption.
- Storage conditions and light exposure: can affect the composition of the extract post-extraction.

If possible, the optimization of an extraction process should be done using a defined analytical endpoint (e.g. the content of a certain compound), rather than the total amount of extractives. Clearly stating the parameters used in an experiment enhances the possibility of its successful reproduction and comparison with other studies.

10 NATURAL-PRODUCT RESEARCH AND DRUG DISCOVERY

Plant extracts can be screened for bioactive compounds. The green extraction process can isolate compounds suitable for preparative chromatography, spectroscopy characterization, structure determination, and biological evaluation. Lead compounds can be isolated during preparative chromatography. Compounds isolated from extracts need to undergo further studies before they can be considered for drug development.

10.1 Antioxidant and Anti-inflammatory Research

Phenolic compounds and flavonoids are often studied for their antioxidant properties and potential effects on inflammatory pathways. Turmeric-derived curcumin and tea catechins are common examples of compounds that have been studied for their activity in natural products. UAE or MAE could be used to recover them if the conditions are suitable. However, results from chemical antioxidant assays do not necessarily prove that they are good for human health.

10.2 Antimicrobial Research

Some constituents of plants are investigated for their activity against bacteria, fungi or other microorganisms. Green extraction could help produce samples for laboratory testing, and minimize the use of less desirable solvents. Research should involve standardized extracts, appropriate positive and negative controls, and validated microbiological assays. Activity in a laboratory assay does not equate to safe and effective treatment in patients.

10.3 Herbal Products and Extract Standardization

Plant-derived extracts may be used in herbal products or in pharmaceutical research. To ensure consistency, botanical authentication of the source material must be carried out, as well as control of the raw material, testing for microbial contaminants, pesticides, heavy metals and adulterants where applicable, and chemical fingerprinting or marker-compound analysis. The extraction conditions should be documented to compare batches. On the other hand, standardization helps to ensure quality but does not in itself constitute proof of clinical efficacy.

10.4 Formulation and Drug Delivery Research

Certain plant-derived compounds are being investigated in terms of nanoparticles, liposomes, and other formulations as potential solutions to the issue of solubility in water, stability, or delivery mechanisms. It is necessary to test their

compatibility, release mechanism, stability, safety, and effectiveness. Although green extraction might contribute to the creation of the substance, its formulation's advantages must be proven.

Table 1: Examples of Compounds and Research Relevance

Compound/group	Example source	Research relevance
Curcumin	Turmeric (Curcuma longa)	Investigated for anti-inflammatory and antioxidant properties.
Eugenol	Clove (Syzygium aromaticum)	Studied for antimicrobial and local analgesic applications.
Catechins	Green tea (Camellia sinensis)	Investigated for antioxidant and other biological activities.
Glycyrrhizin	Liquorice (Glycyrrhiza glabra)	Studied for a range of pharmacological effects.
Alkaloids	Various medicinal plants	Some provide established medicines; others are research leads.
Terpenoids	Various aromatic and medicinal plants	Studied for diverse biological and pharmaceutical applications.

These examples illustrate relevance of the research and should not be taken as indicating that any crude extract is a proven medicine. The clinical utility of any preparation depends on the individual compounds or products, their doses, formulation, safety data and regulatory status.

Advantages of Green Extraction

- Less harmful when used as replacements for solvents.
- May cut the time of extraction processes and the amount of solvent used.
- Recover more or a better grade of a substance when conditions are right.
- May help prevent loss of valuable, heat-sensitive substances.
- Produce less waste and recover more of the solvent.
- Use the by-products of extracting plants as sources of valuable substances.
- Speed up pharmaceutical research that uses less material and is cleaner.

These are possible advantages, but they are sometimes only advantages if one method is compared against another. For instance, high-pressure extraction may need a lot of energy to create the pressure, while solvents that replace some solvents are hard to remove completely. A thorough comparison would have to look at the whole process and not just the part that extracts.

Limitations and Challenges

- Equipment cost: advanced systems may require a high initial investment and trained operators.
- Method optimization: each plant matrix and target compound may require different conditions.
- Chemical degradation: heat, oxygen, light or pH changes can damage sensitive compounds.
- Natural variability: growing and storage conditions can change the composition of plant material.
- Solvent issues: some alternative solvents have high viscosity or difficult removal requirements.
- Scale-up: heat, mixing, ultrasound distribution and pressure behaviour may change at industrial scale.
- Quality and regulation: pharmaceutical applications require validated analytical methods, safety evaluation and suitable manufacturing controls.
- Environmental trade-offs: energy use, water use, cleaning, solvent recovery and waste treatment must be considered.
- A green method should be compared with a relevant baseline using consistent metrics, including yield of the target compound, solvent intensity, energy demand, waste, process time, purity and cost. Life-cycle assessment can help identify hidden environmental burdens.

Future Prospects

Future work may seek to combine different approaches to extraction, such as ultrasound-assisted with enzymes or microwave-assisted with an aqueous ethanol solvent, if such combinations are found to improve the overall process. Automated monitoring and design-of-experiments-based approaches can optimize extraction parameters with fewer

trials. Improved analytical methods may enable real-time or rapid assessment of marker compounds and batch consistency.

Researchers may also look to agricultural by-products and residues as potential sources of valuable phytochemicals, facilitating the development of circular-economy strategies. For industrial applications, studies should assess energy and solvent consumption, solvent recovery, scale-up feasibility, and waste management, while alternative solvents require rigorous safety and environmental impact evaluations, particularly in view of possible human exposure. Lastly, linking extraction research to validated quality-control methods and appropriate biological or clinical evidence may help to distinguish between promising laboratory findings and products with demonstrated therapeutic value.

11 CONCLUSION

Green extraction is an appropriate strategy to obtain valuable bioactive compounds from medicinal plants while minimizing the solvents' adverse effects, energy consumption, and waste. UAE, MAE, SFE, EAE, and PLE technologies are effective but differ in working principles and are more or less perspective for different plants and active ingredients. Thus, water, ethanol, water-ethanol mixture, and selected NADES have the potential to be applied for less sustainable methods due to their unique properties and safety.

The quality of the extracts and consequently the pharmaceutical value depend not only on the high-yield production of the target compounds using the selected protocols, but on the extract's physicochemical properties, its content, stability, and the possibility of application. Therefore, the development and validation of standardized analytical profiles, testing of extracts on toxins, and biological evaluation of the active principles are critical steps in the study of such materials. These factors ensure the quality and safety of the extracts of natural origin and enable the implementation of green extraction methods into the sustainable research process of pharmaceutical compounds.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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REFERENCES

[1] Chemat F, Vian MA, Cravotto G. Green extraction of natural products: concept and principles. International Journal of Molecular Sciences. 2012;13:8615–8627. https://doi.org/10.3390/ijms13078615

[2] Herrero M. Towards green extraction of bioactive natural compounds. Analytical and Bioanalytical Chemistry. 2024;416:2039–2047. https://doi.org/10.1007/s00216-023-04969-0

[3] Martins R, Barbosa A, Advinha B, Sales H, Pontes R, Nunes J. Green Extraction Techniques of Bioactive Compounds: A State-of-the-Art Review. Processes. 2023;11(8):2255. https://doi.org/10.3390/pr11082255

[4] Bitwell C, Singh IS, Chimuka L, Maseka KK. A review of modern and conventional extraction techniques and their applications for extracting phytochemicals from plants. Scientific African. 2023;19:e01585. https://doi.org/10.1016/j.sciaf.2023.e01585

[5] Cannavacciuolo C, Pagliari S, Celano R, Campone L, Rastrelli L. Critical analysis of green extraction techniques used for botanicals: Trends, priorities, and optimization strategies—A review. TrAC Trends in Analytical Chemistry. 2024. https://doi.org/10.1016/j.trac.2024.117627

[6] Islam M, Malakar S, Rao MV, Kumar N, Sahu JK. Recent advancement in ultrasound-assisted novel technologies for the extraction of bioactive compounds from herbal plants: a review. Food Science and Biotechnology. 2023;32:1763–1782. https://doi.org/10.1007/s10068-023-01346-6

[7] Pogorzelska-Nowicka E, Hanula M, Pogorzelski G. Extraction of polyphenols and essential oils from herbs with green extraction methods—An insightful review. Food Chemistry. 2024;460(Pt 1):140456. https://doi.org/10.1016/j.foodchem.2024.140456

[8] Mungwari CP, King'ondu CK, Sigauke P, Obadele BA. Conventional and modern techniques for bioactive compounds recovery from plants: Review. Scientific African. 2025;27:e02509. https://doi.org/10.1016/j.sciaf.2024.e02509