

Comparative Analysis of Microwave-Assisted Extraction (MAE) and Traditional Extraction Techniques for Phytochemicals from Plants

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ABSTRACT

In recent years, using microwaves to extract substances from plants has gained a lot of attention in research. Traditional methods for extracting useful plant compounds take a long time, use a lot of solvents, and can damage heat-sensitive compounds. Also, analyzing multiple plant components is often limited by the extraction process itself. This project explains why the extraction process is important for creating reliable standards for herbal medicines around the world. Microwave-assisted extraction (MAE) is a promising new technique because it works faster, uses less solvent, and protects delicate compounds from heat damage. The review also provides a basic explanation of how microwave heating works and the main principles behind using microwave energy for extraction. It discusses key factors that affect extraction efficiency, such as the type and amount of solvent, extraction time, microwave power, plant material characteristics, and temperature. Finally, it compares the performance of this new method to traditional techniques and highlights its potential applications.

Keywords: Microwave-Assisted Extraction, Green chemistry, Phytochemicals extractions, Dielectric heating, Dipole rotation, Ionic conduction, Open Vessel MAE (OVMAE), Closed Vessel MAE (CVMAE), Thermolabile compounds, Plant matrices.

INTRODUCTION

Microwave-Assisted Extraction (MAE) is an innovative technique that utilizes microwave energy (300 MHz to 300 GHz) to extract bioactive compounds from plant matrices. Unlike traditional techniques such as Soxhlet extraction, MAE offers rapid heating, reduced solvent consumption, and improved yields of thermolabile phytochemicals. Scientists have extracted powerful phytoconstituents from plants, which have led to the creation of some highly effective drugs. For example, natural anticancer drugs like vincristine, vinblastine, and taxol come from plants[1]. This method operates through dielectric heating, involving dipole rotation and ionic conduction, which generates internal pressure, ruptures plant cell walls, and enhances mass transfer[2,3].

The historical use of microwaves in chemical processes began in the 1980s, initially for organic synthesis and later extended to sample preparation and extraction. Its adaptation to phytochemical extraction emerged in the 1990s[4]. MAE has since demonstrated effectiveness in isolating a variety of phytoconstituents including essential oils, flavonoids, alkaloids, phenolics, and polysaccharides[5,6]. It has also been used successfully in microalgae, achieving higher protein extraction yields compared to Soxhlet methods[7].

Aligned with the principles of green chemistry—particularly solvent reduction, energy efficiency, and pollution prevention—MAE supports the sustainable development of plant-based pharmaceuticals and nutraceuticals[8,9]. The integration of MAE with green solvents such as ethanol and water further enhances its environmental compatibility, particularly when compared to organic solvents like hexane or methanol[10].

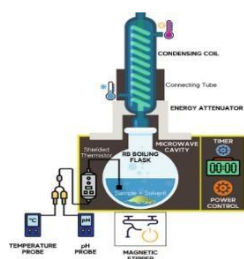


Fig. 1 Microwave Assisted Extraction of Phytochemicals

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Traditional extraction methods such as maceration, percolation, and Soxhlet extraction are often time-consuming and inefficient, especially for heat-sensitive compounds. Soxhlet, although long established since 1879, suffers from drawbacks including long durations (6–24 hours), high energy consumption, and unsuitability for thermolabile compounds[11]. In contrast, MAE can complete extractions in under 30 minutes with better preservation of pharmacological activity and reduced labor requirements[3].

MAE can be conducted in open (OVMAE) or closed (CVMAE) systems, each offering distinct operational parameters regarding temperature and pressure[2]. Its scalability and compatibility with analytical systems like HPLC and GC-MS make it a valuable tool for both laboratory and industrial applications[9].

Despite its advantages, MAE requires careful optimization of parameters such as microwave power, solvent polarity, and solid-to-solvent ratio to avoid degradation or incomplete extraction. Limited scientific literature on the application of MAE for specific phytochemicals, particularly in medicinal plants like *Grewia mollis*, highlights a need for further research[4,5].

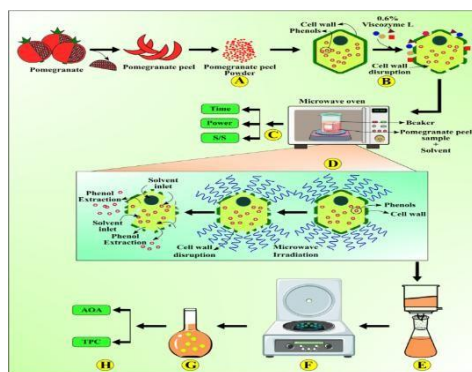
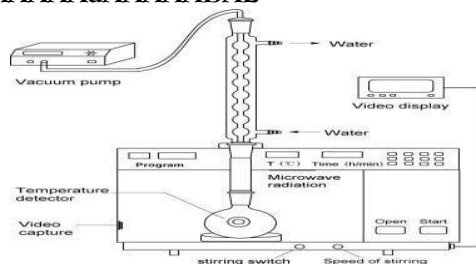


Fig. 2 Microwave -Assisted Extraction Process

https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.researchgate.net%2Ffigure%2FSchematic-diagram-for-the-cellulolytic-enzyme-assisted-microwave-extraction-EMAE-of_fig2_344366161&psig=AOvVaw2Yl0xXpO-bhrDsC_y7GICW&ust=1744955509400000&source=images&cd=vfe&opi=89978449&ved=0CBQQjRxxqFw

oTCMDpkYWv3owDFQAAAAAdAAAAABAE



2.THE DEVELOPMENT OF MAE TECHNIQUES :

Recent advancements in MAE have addressed limitations such as oxidation and thermal degradation of sensitive phytochemicals, which previously reduced extraction yields. To mitigate these issues, different MAE configurations have been developed.

➤ Closed-Vessel MAE

This method employs sealed vessels under controlled pressure and temperature, allowing solvents to exceed their boiling points and thus improving extraction efficiency, particularly for thermally stable compounds.

➤ Open-Vessel MAE

Conducted at atmospheric pressure, this technique is more suitable for thermolabile substances. Although limited to the solvent's boiling point, it offers operational simplicity and often includes a reflux condenser to minimize solvent loss[12].

➤ Nitrogen-Protected Microwave-Assisted Extraction (NPMAE)

NPMAE minimizes oxidation of sensitive compounds by using nitrogen to pressurize the extraction vessel. It has shown superior efficiency over standard MAE and Soxhlet methods in extracting ascorbic acid from peppers and guava[13].

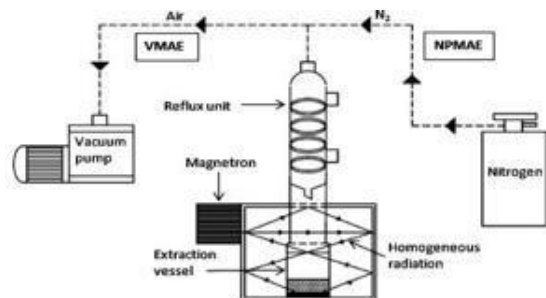


Fig. 3 Nitrogen-Protected Microwave-Assisted Extraction (NPMAE)

<https://www.sciencedirect.com/science/article/pii/S0021967311010314>

➤ Vacuum Microwave-Assisted Extraction (VMAE)

VMAE improves extraction of heat-sensitive compounds by using reduced pressure to lower solvent boiling points, minimizing oxidation and thermal degradation. It yields higher levels of compounds like vitamin C from guava and tea leaves compared to standard MAE[14] .

Fig. 4 Vacuum Microwave-Assisted Extraction (VMAE)

<https://www.sciencedirect.com/science/article/pii/S0021967308009060>

➤ **Ultrasonic Microwave-Assisted Extraction (UMAE)**

UMAE combines ultrasonic and microwave energy to enhance cell rupture and mass transfer, improving extraction efficiency. It has shown higher yields of compounds like lycopene, vegetable oil, and pectin compared to individual methods. The synergy between UAE and MAE significantly boosts pectin yield and galacturonic acid content without altering pectin structure[15].

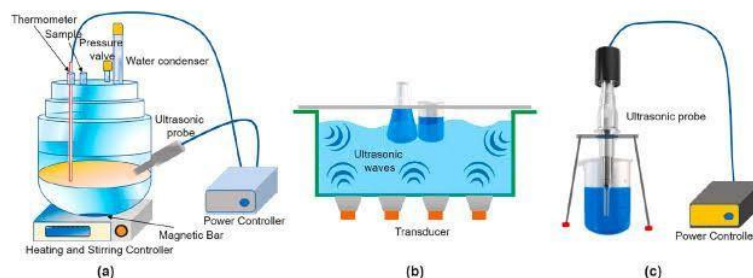


Fig. 5 Ultrasonic Microwave-Assisted Extraction (UMAE)

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➤ **Dynamic Microwave-Assisted Extraction (DMAE)**

DMAE enhances extraction efficiency by continuously introducing fresh solvent, improving solute transfer without degrading bioactive compounds. It has shown superior flavonoid yields from *Saussurea medusa* and *Herba pimedii* compared to conventional methods[16].

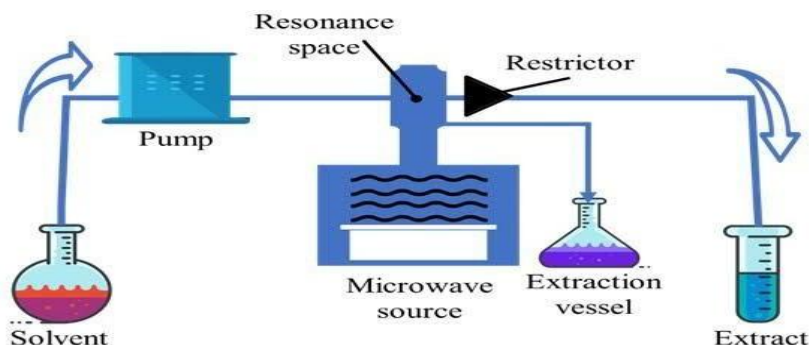
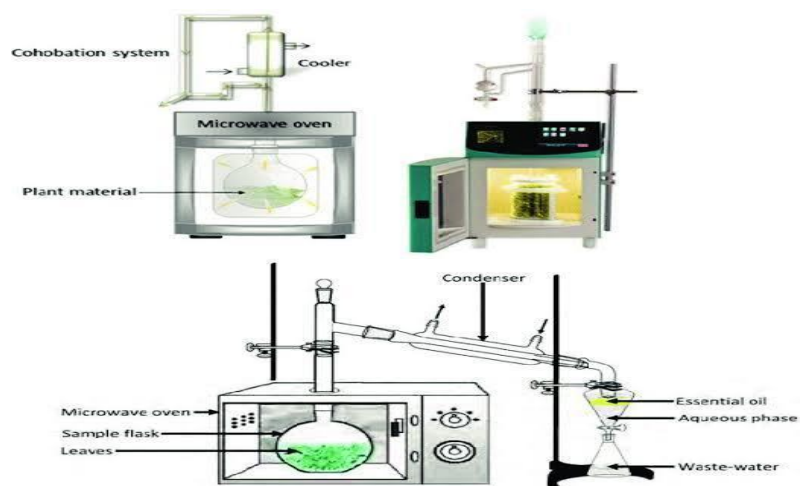


Fig. 6 Dynamic Microwave-Assisted Extraction System (DMAE)

<https://bioresources.cnr.ncsu.edu/resources/microwave-assisted-extraction-of-functional-compounds-from-plants-a-review/>

➤ **Solvent-Free Microwave-Assisted Extraction (SFMAE)**



SFMAE is primarily used for essential oil extraction, offering shorter extraction times and improved oil quality by minimizing oxidation and hydrolysis. It uses minimal or no solvent, relying on microwave heating of natural moisture in the plant matrix[17].

Fig. 7 Schematic Diagram of Solvent free Microwave-Assisted Extraction (SFMAE).

https://www.researchgate.net/figure/Solvent-free-microwave-extraction-SFME-25-30_fig1_323464573

3. Microwave-Assisted Extraction (MAE) Instrumentation:

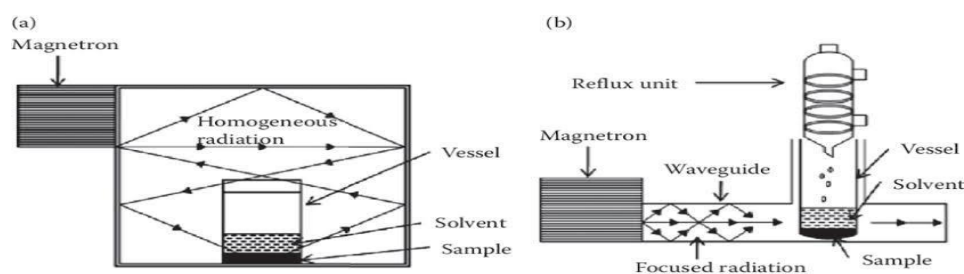


Fig. 8 Instrumentation of Microwave-Assisted extraction.

https://www.researchgate.net/figure/a-Closed-vessel-microwave-system-and-b-open-vessel-microwave-system-Adapted-from_fig4_289844027

➤ Microwave Generator (Magnetron):-

Component: Magnetron (commonly operating at 2.45 GHz).

Function: Converts electrical energy into microwave radiation.

Mechanism: When high-voltage electricity is supplied, the magnetron emits microwaves, which are directed into the cavity.

Design Note: Magnetron must be shielded to prevent radiation leakage.

➤ Waveguide :-

Component: Metallic conduit.

Function: Directs microwaves from the magnetron to the extraction cavity.

Material: Usually made of copper or aluminum.

Engineering Requirement: Properly tuned to prevent microwave losses and reflections.

➤ Extraction Vessel (Reaction Vessel) :-

Types: Open Vessel, Closed Vessel.

Open vessels: Operate at atmospheric pressure; limited to boiling point of solvent.

Closed vessels: Allow high-pressure and high-temperature conditions (also known as pressurized microwave-assisted extraction).

Material: Teflon, quartz, or borosilicate glass (microwave-transparent and chemically resistant).

Volume: Ranges from a few mL to several hundred mL depending on application.

➤ **Microwave Cavity (Chamber) :-**

Function: Acts as a resonating chamber for microwaves; holds the extraction vessel.

Design: Made from metal (usually stainless steel) to reflect microwaves internally.

Features: Uniform field distribution (via mode stirrers or rotating platforms).

Multiple ports for sensors and cooling.

➤ **Stirring and Mixing Systems :-**

Function: Ensures uniform heating and solvent/sample contact.

Types: Magnetic stirrers

Mechanical agitators.

Integration: Often linked with feedback control to adjust speed and consistency.

➤ **Temperature and Pressure Sensors :-**

Function: Real-time monitoring and control.

Temperature Sensors: Infrared sensors (non-contact).

Fiber-optic thermocouples (chemical resistant).

Pressure Sensors: Strain gauge or piezoelectric sensors.

Used in closed systems to avoid overpressure accidents.

Importance: Ensures extraction remains within optimal parameters for target compounds.

➤ **Microwave Power Control Unit :-**

Function: Modulates microwave energy (constant or pulsed mode).

Design: Can be feedback-controlled based on real-time temperature or pressure.

Variable wattage (100–1500 W typical range).

➤ **Solvent Delivery and Recovery System :-**

Solvent Delivery: Manual or automated.

Used to add solvent before or during extraction.

Solvent Recovery: Especially in systems coupled with vacuum distillation.

Reduces environmental impact and cost

➤ **Cooling System :-**

Purpose: Protects thermolabile compounds and vessel material after extraction.

Types: Air-cooling.

Water-cooling (circulated through jackets or coils).

Integration: Activated automatically at end of heating phase

➤ **Control and Data Acquisition System :-**

Interface: Often computer-based software for programming and data logging.

Functions: Set extraction parameters (time, temperature, solvent type).

Monitor real-time conditions.

Safety alarms and automatic shut-off.

Data Outputs: Graphs of temperature/pressure vs. time, power profiles, extraction yield predictions.

Safety Features:

Pressure Relief Valve: Releases pressure in case of overpressure inside the vessel.

Interlocking Doors: Prevents microwave emission if door is open.

Microwave Leakage Detectors: Ensures system compliance with safety standards.

Optional Modules :

In-line Filtration Units: For automatic separation of extract.

Coupling with Analytical Instruments: e.g., LC-MS, GC-MS for on-line analysis.

Vacuum Integration: Reduces boiling point, enabling low-temp extractions

Advanced Features in Commercial Systems :

Multi-vessel Systems: Run parallel extractions (e.g., Milestone EthosX, CEM MARS).

Green Solvent Integration: Water or ethanol-based solvents with low environmental impact.

Scaling Modules: Adaptable for lab, pilot, or industrial scale extractions[17,18].

4. Microwave Theory:

Microwaves (300 MHz–300 GHz) generate heat by interacting with polar molecules through ionic conduction and dipole rotation, with heating efficiency depending on the material's dielectric properties, particularly the dissipation factor ($\tan \delta$). Microwave heating at 2450 MHz is faster and more energy-efficient than conventional methods, especially effective for polar solvents like ethanol and methanol.

1. Ionic conduction – Ions move back and forth with the changing electric field, and this movement causes friction, which generates heat.

2. Dipole rotation – Molecules with dipoles try to keep up with the rapidly changing electric field by constantly rotating. This movement creates friction and generates heat[19].

Formula:

$$\tan \delta = \frac{\epsilon''}{\epsilon'}$$

- ϵ' = how well the material absorbs microwave energy (dielectric constant)

5. Extraction principle :

Microwave-Assisted Extraction (MAE) utilizes the rapid heating of intracellular water to generate pressure, causing cell rupture and enhancing the release of bioactive compounds. This process is more efficient when using microwave-absorbing solvents and plant matrices, leading to improved yields of compounds like pectin and essential oils. Structural disruption from MAE has been confirmed through microscopic studies on tobacco leaves and orange peels. The technique, first reported in 1975, has since evolved for diverse applications in natural product extraction[19].

6. Microwave Power :

Microwave power significantly affects extraction efficiency in MAE. Increased power (30–150 W) enhances ginsenoside recovery during short durations but may cause thermal degradation if exposure is prolonged. Higher power (e.g., 1200 W) shortens extraction time without significantly affecting flavonoid yield, though purity may decrease due to cell wall rupture and co-extraction of impurities[3,5,20,21].

7. Extraction time :

Extraction time significantly affects Microwave-Assisted Extraction (MAE) efficiency. While longer durations may enhance analyte recovery, they also risk thermal degradation of sensitive compounds. Optimal times vary by compound and plant matrix—e.g., polyphenols peak at 4 minutes[2]. Artemisinin at 12 minutes[22]. While capsaicinoid recovery from peppers showed no significant gain beyond 5 minutes[23]. Thus, careful optimization considering solvent dielectric properties is essential.

9. Mechanism of microwave heating :

Microwave heating depends on the interaction of materials with microwave radiation. Materials respond differently: some are transparent (e.g., sulfur), some reflect microwaves (e.g., copper), while others absorb them (e.g., water). Only absorbing materials are relevant in microwave-assisted extraction (MAE), where three main heating mechanisms are involved: dipolar polarization, conduction, and interfacial polarization[24,25].

➤ **Dipolar polarization** occurs in substances with a permanent dipole moment. When exposed to the alternating electric field of microwaves (typically 0.3–30 GHz), dipolar molecules like water or ethanol attempt to align with the field, generating heat through molecular friction. This mechanism is most effective when the frequency matches the natural oscillation of polar molecules, allowing for efficient energy absorption and localized heating

➤ **Conduction heating** involves ionic solutions or conductive particles. Here, the electric field induces movement of charge carriers (ions or electrons), generating resistive heat as they encounter internal resistance. This is common in polar solvents or ionic solutions, though it is limited in materials with very high conductivity, which tend to reflect microwave energy rather than absorb it

➤ **Interfacial polarization** is a combined effect seen in composite systems, such as metal powders dispersed in non-conductive media like sulfur. Though neither metal nor sulfur alone effectively absorbs microwaves, their combination forms a heterogeneous system where localized dipole-like behavior at interfaces leads to microwave absorption and heating. This mechanism is particularly useful in enhancing heating efficiency in systems with poor individual microwave response[24,25].

10. Factors Affecting MAE :

➤ **Solvent Nature**

The solvent's dielectric constant determines its ability to absorb microwave energy. Polar solvents like ethanol and methanol are highly effective due to better microwave absorption, whereas non-polar solvents require modification or co-solvents[2]. Solvent selection should also consider target compound polarity, viscosity, boiling point, safety, and cost[26].

➤ **Solid-to-Liquid Ratio**

A balanced solvent-to-solid ratio ensures adequate contact and microwave penetration. Excess solvent reduces heating efficiency, while too little impedes mass transfer[23]. Container size and solvent type also influence extraction dynamics[27].

➤ **Microwave Power**

Higher microwave power enhances extraction speed but may degrade thermolabile compounds. Thus, optimizing power and exposure time is essential for yield and compound integrity[5,12].

➤ **Extraction Temperature**

Rising temperature improves solvent diffusion and reduces viscosity, enhancing extraction. However, excessive heat can degrade sensitive compounds. Optimal temperature usually ranges between 60°C–140°C depending on target stability[28,29].

➤ **Extraction Time and Cycles**

Short extraction times (seconds to minutes) are typical in MAE. Repeated cycles using fresh solvent help maximize yield while minimizing degradation[14].

➤ **Moisture Content and Sample Characteristics**

Moisture within the plant aids microwave absorption and cell rupture. Smaller particles and higher surface area also enhance extraction efficiency[14].

➤ **Particle Size and Shape**

Smaller particles (100 µm–2 mm) increase surface area and facilitate solvent penetration. Particle shape affects

flow and solvent-layer formation, influencing extraction efficiency[30].

➤ **Agitation and Stirring**

Stirring promotes uniform temperature distribution and mass transfer, breaking stagnant solvent layers and improving yield[26].

pH of Extraction Medium

pH affects compound ionization and solubility. Adjusting pH enhances selectivity and recovery of pH-sensitive compounds like pectin[31].

➤ **Extraction Mode (Continuous vs. Intermittent)**

Continuous MAE delivers uniform heating, while intermittent modes reduce thermal degradation by allowing cooling intervals[30].

➤ **Pre-treatment of Plant Material**

Drying and grinding reduce particle size and moisture, enhancing microwave penetration and extraction efficiency[11].

➤ **Pressure**

The distribution of phytochemicals—e.g., essential oils in glands, flavonoids in vacuoles—affects extraction. MAE disrupts these compartments, improving compound release[17].

➤ **Plant Matrix Characteristics**

The distribution of phytochemicals—e.g., essential oils in glands, flavonoids in vacuoles—affects extraction. MAE disrupts these compartments, improving compound release[17].

11. Comparison Between MAE and other Conventional Extraction Techniques :

MAE has several advantages over traditional extraction methods. One of the Advantages is reduced extraction time and solvent volume savings. Better yields of Secondary metabolites are also observed. Another great advantage is that it is an automated Method, which makes it reproducible. Different works compare MAE with conventional extraction methods, reporting that MAE is a suitable and reliable Method for obtaining bioactive compounds.

Table 1: Microwave-Assisted Extraction Versus Decoction[9] :

Parameters	Microwave -Assisted Extraction	Decoction
Extraction time	Very short (5–30 minutes)	Long (30 minutes to several hours)
Temperature range	Controlled (often below 100°C)	High (boiling, ~ 100°C)
Solvent usage	Low	High
Energy Efficiency	High	Low
Equipment Cost	High	Low

Table 2: Microwave-Assisted Extraction Versus Percolation[6] :

Parameter	Microwave-Assisted Extraction (MAE)	Percolation
Extraction Method	Uses microwave energy to heat solvents and plant materials rapidly	Uses gravity to pass solvent through plant material slowly
Energy Source	Microwave radiation	No external energy, uses gravity
Time Required	Short (minutes to a few hours)	Long (several hours to days)
Solvent Consumption	Low	High
Suitability for Thermolabile Compounds	Less suitable (can degrade compounds at high temperature)	More suitable (gentler process)
Cost	Higher initial setup cost	Low setup cost

Table 3: Microwave-Assisted Extraction Versus Soxhlation[33]:

Parameter	Microwave-Assisted Extraction (MAE)	Soxhlation
Principle	Uses microwave energy to heat solvents and samples	Continuous solvent reflux over sample
Solvent Consumption	Low	High
Temperature Control	Precise and programmable	Limited
Energy Efficiency	High (rapid heating)	Low (prolonged heating)
Extraction Efficiency	High	Moderate
Instrumentation Cost	Higher	Lower
Suitability for Heat-Sensitive Compounds	Good	Poor

Table 4: Comparative study of MAE with other Extraction Techniques[34] :

	Solvent extraction	Microwave assisted extraction	Supercritical fluid Extraction	Ultrasound-Assisted extraction	Pulsed electric Field	Pressurized Solvent extraction	High Hydrostatic Pressure Extraction
Brief description	Solvent is heated By a conventional	Immersion of the sample in solvent and microwave energy is submitted	A high pressure vessel is filled with	Immersion of the sample in solvent	Pulses of high electric voltages are applied to the	Heat of the sample by a conventional	Sample is pressurized (100 -1000 MPa) through a pressure

	Oven And passed by the Sample		sample and crossed continuously by the supercritical fluid	and submission to ultrasound using a US probe or US bath	sample placed in between two electrodes	1 oven and crossed by the extraction solvent under pressure	transmitter liquid
Extraction time	6-8 hours	3-30 min	10-60 min	10-60 min	-	10-20 min	1 - 30 min
Sample size	-	1-10 g	1-5 g	1-30 g	-	1-30 g	-
Solvent volume	-	10-40 ml 2-5 ml (solid trap)	30-60 ml (liquid trap)	50-200 ml	-	15-60 ml	-
Cost		Moderate	High	Low	High	High	High
Advantages	Rapid and easy to handle	Rapid Easy to handle Moderate solvent consumption	Rapid Low solvent consumption Concentration of the extract No filtration necessary Possible high selectivity	Easy to use	Rapid and non-thermal process	Rapid No filtration necessary Low solvent consumption	Rapid Green technology High selectivity High extraction Yield No degradation of target molecules
Disadvantages	High solvent consumption, long treatment time and thermal degradation	Extraction solvent Must absorb microwave energy Filtration step required	Many parameters to optimize	Large amount of solvent consumption Filtration step required	Mechanism not well known and process intensification is difficult	Possible degradation of thermolabile analytes	High cost equipment

Microwave-Assisted Extraction (MAE) has significantly evolved over the past decade due to advancements in technology, green chemistry, and analytical science. Recent developments aim to enhance efficiency, sustainability, and scalability of the process.

12. RECENT ADVANCES AND DEVELOPMENTS IN MICROWAVE-ASSISTED EXTRACTION (MAE):

Microwave-Assisted Extraction (MAE) has significantly evolved over the past decade due to advancements in technology, green chemistry, and analytical science. Recent developments aim to enhance efficiency, sustainability, and scalability of the process.

➤ **Green Solvents and Eco-Friendly Extraction**

A key advancement in MAE is the use of green solvents like natural deep eutectic solvents (NADES) and ionic liquids, which enhance extraction efficiency and environmental safety. For example, NADES significantly increased both yield and antioxidant capacity of turmeric extracts, promoting sustainability in MAE[35].

➤ **Hybrid Extraction Techniques**

Researchers have combined MAE with other technologies such as ultrasound-assisted extraction (UAE) and enzyme-assisted extraction (EAE) to enhance yields and selectivity. Employed a microwave-ultrasound sequential method that improved the extraction of flavonoids from red onion peels by over 30%[36].

➤ **Process Optimization Using Statistical Tools**

Statistical optimization techniques like Response Surface Methodology (RSM) and Taguchi design are now widely used to fine-tune parameters such as microwave power, time, solvent-to-solid ratio, and temperature. successfully applied RSM to maximize phenolic extraction from date seeds using MAE[37].

➤ **Improved Instrumentation and Automation**

Modern MAE systems are now equipped with features like infrared temperature sensors, real-time pressure control, and programmable extraction cycles, ensuring better reproducibility and safety. Such advancements have minimized thermal degradation of sensitive compounds[38].

➤ **Industrial-Scale Applications**

MAE is being scaled for industrial use, particularly in the food, pharmaceutical, and cosmetics sectors. In recent review discussed the successful implementation of pilot-scale MAE systems for essential oil extraction, highlighting time and cost efficiency[39].

CONCLUSION

The increasing global interest in plant-based medicines and natural compounds has emphasized the need for more efficient, reliable, and environmentally sustainable extraction techniques. This thesis highlights the growing importance of Microwave-Assisted Extraction (MAE) as an advanced method for extracting bioactive compounds from plant materials. It allows faster extraction, uses less solvent, and protects heat-sensitive compounds better. These advantages make MAE a useful method for preparing high-quality herbal medicines. This technique supports the creation of reliable, standardized plant-based products, which is important for both research and commercial use. Overall, MAE is an effective, time-saving, and environmentally friendly method that can improve how natural compounds are extracted from plants.

Future Scope :- Microwave-Assisted Extraction (MAE) offers great potential for future research and industrial applications. Further optimization of extraction parameters for different plant materials can improve yield and efficiency. Scaling up MAE for commercial production is a key next step. Using eco-friendly solvents and combining MAE with other methods like ultrasound or enzyme-assisted extraction can enhance sustainability and effectiveness. Integration with advanced analytical tools can improve compound identification. MAE can also be applied to other natural sources such as fungi, algae, and agricultural waste. With proper standardization, MAE could become a widely accepted method for producing high-quality herbal and natural products.

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