

Evolution of Microwave-Assisted Extraction Techniques for Natural Products: Emphasis on Sustainable and High-Efficiency Solvent System

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Abstract

Microwave-assisted extraction (MAE) has become a viable and sustainable method of extracting bioactive phytochemicals of plant matrices. This application uses micro-wave irradiation to create high-volumetric heating by rotating the dipoles and ionic conduction in polar solvents which results in faster disruption of cell walls, increased solvent uptake, and increase in mass transfer. MAE is normally run at frequencies of about 2.45 GHz and consumes less extraction time and solvent than traditional thermal extraction processes. There are various operation parameters such as the physicochemical character of solvent, Microwave power density, extraction temperature, solvent to solid ratio, particle size and the intensity of the agitation that affects extraction performance. In order to overcome some of the process drawbacks, and enhance selectivity, some more advanced MAE configurations have been created, including nitrogen-protected MAE to reduce oxidative degradation, vacuum MAE to work with thermolabile compounds, ultrasonic-assisted MAE to enhance cell rupture synergy, and dynamic MAE to enhance diffusivity. Similar improvements of solvent systems especially ionic liquids (ILs), natural deep eutectic solvents (NADES), surfactant-based mediums, alkaline solvents, supercritical CO₂, and specialized binary or ternary mixtures have significantly enhanced the efficiency of extraction and also do not contradict the principles of green chemistry. Nevertheless, with such a promising set of characteristics, industrial-scale implementation of MAE is still marred by such challenges like uneven distribution of power, small depth of penetration of microwaves, recyclability of solvents, and high initial cost of equipment. However, the current developments being made in the field of reactor engineering, hybrid extraction methods, optimisation of the process and scale-up plans are gradually overcoming these obstacles. Comprehensively, MAE is an important platform of

increasing natural product extraction toward green and promoting a sustainable bioeconomy.

Keywords: Microwave-assisted Extraction (MAE); Natural deep eutectic solvents (NADES); Deep eutectic solvents (DESs); Green extraction techniques; Phytochemical Recovery.

I. Introduction

Microwave-assisted extraction (MAE) is a new extraction method that is used to select bioactive compounds in plants efficiently, reduces the limitations of the traditional methods in terms of energy consumption, processing time, and amount of solvent used, and is more useful in addressing the weaknesses of high energy consumption, processing time, and solvent requirement compared to the traditional method (Nonglait and Gokhale 2024). Traditional extraction methods like Soxhlet extraction, maceration, and hydro-distillation mostly depend on prolonged thermal exposure and excessive solvent usage, resulting in low selectivity, degradation of thermolabile compounds, and increased environmental burden (Sahu, Sahoo et al. 2025). Conversely, MAE utilizes electromagnetic radiation of high frequencies, typically 2.45 GHz, to cause heating by rotating the dipole and ionic conduction processes in polar molecules, resulting in rapid and uniform energy transfer in the system of the sample solvent (Zhao, Qing et al. 2024). This internal heating mechanism enhances mass transfer kinetics by increasing solvent diffusivity, improving solvent penetration into plant tissues, and promoting cellular disruption, thus facilitating the release of intracellular metabolites into the extraction medium (López-Salazar, Camacho-Díaz et al. 2023).

The physicochemical and operational factors such as structure of the plant matrix, temperature of extraction, irradiation time, intensity of microwave power, composition of solvent, solvent to solid ratio, and the area of effective contact, control the performance of MAE. The solvent dielectric values are also critical where polar

solvents like water and ethanol have a high capacity of absorbing microwaves relative to non-polar solvents and thus lead to higher rates of heating and better extraction yields. Equally, the ratio of the solvent and the solid should be maximized to achieve effective mass and the highest level of extraction (Ramesh, Shankar et al. 2024). Particle size reduction increases reachable surface area and solvent contact; however, very fine particles may lead to clumping and uneven overheating. Controlled stirring reduces thermal gradients and promotes uniform microwave energy distribution, thereby improving extraction reproducibility (Samakradhamrongthai 2024).

Within the last ten years, MAE has been moving towards a flexible platform technology, which has led to some highly specialized forms to suit particular difficulties in extracting natural products. Nitrogen-protected MAE (NMAE) employs an inert atmosphere to inhibit oxidative degradation of oxygen-sensitive bioactives, while vacuum MAE (VMAE) enables extraction at reduced pressures and temperatures, thereby preserving thermolabile compounds. Hybrid approaches such as ultrasonic-assisted MAE (UMA) exploit the synergistic effects of microwave heating and acoustic cavitation to intensify cell disruption and solvent penetration. Dynamic MAE (DMAE), incorporating mechanical agitation or continuous flow regimes, further enhances thermal homogeneity and extraction uniformity (López-Salazar, Camacho-Díaz et al. 2023).

At the same time, solvent innovation has contributed significantly to enhancing sustainability and selectivity of MAE. Natural deep eutectic solvents (NADES), which are biodegradable and plant-derived (sugars, organic acids and amino acids), have received a lot of interest because of their adjustable polarity, low volatility and good toxicological properties (Jauregi, Esnal-Yeregi et al. 2024). of interest because of their adjustable polarity, low volatility and good toxicological properties (Jauregi, Esnal-Yeregi et al. 2024). In combination with microwave energy, NADES have proven to be very effective in the extraction of phenolics, flavonoids, alkaloids, and other botanical materials (Aduloju, Yahaya et al. 2023). Ionic liquids (ILs) with zero vapor pressure and controllable physicochemical characteristics have also been utilized to selectively extract structurally complex compounds, although the high viscosity, cost, and recyclability make them hard to apply in the industry (Pletnev, Smirnova et al. 2021).

Other innovations that involve solvents are surfactant-assisted MAE, in which the micellar formation under the impact of microwaves allows the co-solubilization of lipophilic and hydrophilic constituents (Śliwa and Śliwa 2021). Alkaline-assisted MAE has shown to be useful in increasing the recovery of polysaccharides and matrix-bound phenolics by partial disruption of lignocellulosic (Sombutsuwan, Durand et al. 2024). Microwave heating solution combined with supercritical CO₂ extraction can achieve solvent minimal recovery of volatile oils and terpenes, although at the cost of a more complex and more expensive system (Herzyk, Piłakowska-Pietras et al. 2024).

Aqueous MAE systems, especially at regulated pH conditions is still appealing in extracting heat-sensitive compounds but organic solvent-based MAE with ethanol, methanol and acetone remains popular in extracting polar and semi-polar phytoconstituents. Other recent methodological developments are the use of mixed solvent-based MAE, in which binary or ternary solvent mixtures are used to tune polarity and enhance the solubility profiles of target compounds (Nonglait and Gokhale 2024). Combinations such as ethanol-water and methanol-acetone have demonstrated enhanced efficiency for polyphenol extraction compared to single-solvent systems. Similarly, deep eutectic solvent-based MAE exploits strong hydrogen-bonding interactions, reduced toxicity, and adjustable viscosity to improve the recovery of complex phytochemicals (Bashir, Dar et al. 2023).

The instruments created have also increased the use of MAE, including the open and closed-vessel systems, single and multimode and microwave reactors, real-time temperature and pressure measurements, and hybrid systems that combine both microwave and ultrasound systems and vacuum systems. Such adjustable systems enhance safety of processes, repeatability and control. However, large-scale application of MAE is still difficult because of the constraints on penetration depth of microwaves, uniformity of energy distribution, and calibration of equipment. Continuous-flow microwave reactors and modular process design are under investigation to solve these problems, especially when large-scale production of essential oils, natural colorants, functional foods, and phytopharmaceuticals is required (Belwal, Li et al.; Ercili-Cura and Barth 2021).

Even with significant advancement in technology, a number of limitations continue to exist, such as issues with solvent recovery (NADES

and ILs in particular), non-uniformity in heating in bulk systems, and the naturally small penetration depth of microwave radiation (Suthar 2025). The high cost of economic factors, the safety of equipment in high temperatures and pressures, and the absence of standardized operating procedures are also obstacles to commercialization on large scale basis. Ongoing research efforts in hybrid processing, computational modeling, life-cycle assessment, and regulatory alignment are actively addressing these barriers.

Overall, microwave-assisted extraction is a platform of strength, flexibility and environmental friendliness in the extraction of bioactive soluble compounds in both academic and industrial spheres (Chemat and Cravotto 2012). Further solvent system advancements, reactor designs, and process control logic make MAE one of the enabling technologies in the green extraction systems and contribute to the

principles of the circular bioeconomy and sustainable manufacturing of the future.

Principle and mechanism of microwave applied to natural product extraction

The progress in the extraction methods, especially for microwave-assisted extraction (MAE) have greatly enhanced the efficiency of extraction of bioactive compounds in plant matrices (Chemat and Cravotto 2012). The use of MAE is generally considered a relatively low-cost and greener process since it directly transforms electromagnetic energy into a thermal form by using microwave irradiation, reducing the level of solvent usage and solvent extraction time. Microwaves are electromagnetic transverse waves with a frequency more than 300 MHz that have alternating electric and magnetic fields that propagate in solid, liquid, gases, and even in vacuum space (Bhattacharjee 2023).



Fig.1 Schematic Representation Microwave Assisted Extraction

Dipole rotation and ionic conduction are the two basic phenomena that control the extraction mechanism in MAE. Polar solvents have a high absorption of microwave radiation, resulting in the high rate of oscillation of the polar molecules and the charge species, resulting in immediate internal heating of the extraction medium (Fig 1). The speed and localization of this heating result in a compromise of cellular barriers, which results in an increase in mass transfer compared to traditional forms of conductive or convective heating. In contrast to the water baths or mantle heating, which mostly heat the surface, the power of the microwave energy reaches the entire sample volume, leading to volumetric heating and an increase in extraction kinetics (Kalinke, Kubbutat et al. 2022).

A series of interrelated physicochemical processes taking place in the plant matrix also determine the efficiency of MAE. First, the solvent selectively absorbs microwave energy with low absorption thus permitting direct interaction with the solid matrix. The higher the temperature, the more dielectric losses in the matrix increase resulting in an additional microwave absorption and rapid internal heating (Deng, Huang et al. 2022). The swift increase in temperature causes the evaporation of solvent and subsequent rise in vapor pressure in

the interior in the plant cells. High accumulation of internal pressure is the effect that results in cell wall rupture resulting in mechanical perturbation of the cellular structure. These structural barriers are broken, which makes the processes of intracellular constituent release into the surrounding solvent fast, significantly increasing the extraction efficiency due to enhanced mass transfer (Nour, Oluwaseun et al. 2021).

Usually with a frequency of 2.45 GHz, MAE takes advantage of the ionic conduction and dipole rotation, a form of dielectric loss, to create rapid and homogenous heat in polar solvent-matrix systems. This volumetric heating process is the difference between MAE and traditional surface-heating methods with faster rates of extraction, enhanced selectivity, and minimized thermal destruction of labile compounds (Hu, He et al. 2021). Therefore, MAE has become an environmentally-friendly, efficient and multifunctional method of deriving high-value bioactive compounds out of plant-based materials.

Microwave Heating Equations

The efficiency of microwave-assisted extraction is governed by dielectric heating principles. The interaction of microwave energy with polar

molecules results in rapid heat generation within the material.

The power absorbed per unit volume is expressed as:

$$P = 2\pi f \epsilon_0 \epsilon'' E^2$$

The generated heat can be described using:

$$Q = mc\Delta T$$

The penetration depth of microwaves into the material is given by:

$$D_p = \frac{c}{2\pi f \sqrt{2\epsilon''}}$$

These equations indicate that microwave heating efficiency depends on dielectric properties, frequency, and electric field strength.

Factors Influencing MAE

A synchronized system of operation and experimental variables that control the interactions between the microwave energy and the plant matrix determine the efficiency and effectiveness of microwave-assisted extraction (MAE). Systematic optimization of these parameters can markedly enhance bioactive compound recovery, improve extraction selectivity, and substantially reduce processing time (Ramesh, Shankar et al. 2024). The accurate control of the extraction conditions was identified to reduce thermal degradation and also enhance antioxidant properties of the recovered polyphenols, thus obtaining functional quality (Antony and Farid 2022).

Comparative studies have also indicated the benefits of optimization of parameters in MAE as compared to traditional extraction methods. Microwave power and the length of irradiation time fine-tuning in the extraction of ginger (*Zingiber officinale*) rhizomes, which increased the yields of pungent phenolic compounds, especially gingerol, and reduced the extraction time by a factor of dramas compared to conventional processes (Mulyadi, Novenlityas et al. 2025). In the same way, the statistically optimized extraction conditions based on response surface methodology (RSM) were used to extract flavonoids and terpenoids maxims in *Citrus aurantium* and highlighted the importance of multivariate optimization strategies maximizing the performance of MAE (Abdallah, Abbassi et al. 2024).

Solvent System

The solvent system is critical in establishing the extraction efficiency, selectivity and

environmental friendliness of microwave aided extraction (MAE). Microwave energy absorption, mass transfer behaviour, and solute stability values during extraction are regulated by solvent properties especially polarity, mass transfer, and dielectric constant, and pH. Polar solvents like ethanol, methanol, acetone, and water have high dielectric constants that allow them to easily interact with the microwave radiation and hasten the heating process of the extraction medium, which is volatile (Hew, Ng et al. 2025). Most of these, ethanol water mixtures, are popular because of their moderate polarities that enable the concomitant solubility of hydrophilic and moderately lipophilic compounds, especially flavonoids and polyphenols (Plaskova and Mlcek 2023). An example of this is the MAE performed at 606 W in 2 minutes using an ethanol: water:acetone mixture with the proportions of 8:2:2 which showed the highest levels of phenolic recovery of fruit by-products, highlighting the benefits of mixed solvents to control polarity (Ngela Liberal, Molina et al. 2022).

In recent years the focus on green solvent systems, in particular natural deep eutectic solvents (NADES) which are generally based on choline chloride and organic acids or polyols, has been growing. NADES have good physicochemical characteristics such as low volatility, biodegradability, or high hydrogen-bonding capacity, which make them especially useful in extracting thermolabile bioactives at the MAE conditions (Aduloju, Yahaya et al. 2023). It is important to note that, MAE based on NADES gave 36 mg gallic acid equivalents (GAE)/g dry weight sunflower pomace. A study in Food Chemistry found that a citric acid-glycerol NADES showed greater polyphenol extraction of *Eleutherine bulbosa* bulbs using NADES (Ahmad, Shakti et al. 2024), whereas NADES used as an antioxidant solvent was also found to perform better at extracting antioxidants in hazelnut pomace than the standard solvents (Bener, Şen et al. 2022). Moreover, in MAE, hydrophobic deep eutectic solvents (DESs) have also shown a satisfactory performance of adopting alternative extraction media.

Among emerging solvent systems, hydrophobic DES formulations such as DecA: N4444-Cl have shown extraction efficiencies comparable to pharmacopeial standards Namely, this system presented baicalin extracts of about 106.96 mg/g of *Scutellariabaicalensis*, which emphasizes its ability to extract phytochemicals with high value (De, De et al. 2024). Ionic liquids (ILs), in

particular, 1-butyl-3-methylimidazolium bromide ([BMIM]Br) and 1-butyl-3-methylimidazolium tetrafluoroborate ([BMIM]BF₄), have also been effectively used in MAE because of their low vapour pressure, controllable polarity and high microwave absorption capacity. It is proven in a number of studies that IL-based MAE is more efficient than the traditional solvents in flavonoid extraction with better performance of extracting *Massoniana* than a water-based or ethanol-based system (Wang, Zhu et al. 2025). On the same note, DESs were found to be more efficient than ethanol in extracting flavonoids of *Flos SophoraeImmaturo* (Wang, Zhang et al. 2019).

Another factor that is of critical importance in determining the efficiency of MAE is solvent concentration. The level of the total flavonoid content of *Vernonia amygdalina* rose proportionally as the concentration of ethanol increased (78.21 to 91.12 mg/g) (Alara, Abdurahman et al. 2020). Other matrices, such as *Albizia myriophylla* bark (70.36% ethanol) and *Phyllostachys heterocycla*, have also been identified to give optimal ethanol concentrations with 78.1% ethanol being the highest extraction point (Mangang, Chakraborty et al. 2020). Generally, ethanol is the most common solvent in MAE with the best performance being normally realized at a range of 50-80 percent of concentration. Parallel to this, ILs like 1-butyl-3-methylimidazolium an ionic liquid keep on getting popularity in the sophisticated MAE protocols owing to their augmented dissolution efficacy.

The extractability of bioactive compounds is also affected by the pH of the solvent system, which changes the ionization state, solubility, and stability of bioactive compounds. The extraction of flavonoid is sensitive to pH, and the highest recovery is usually recorded at slightly acidic pH. As an illustration, the extraction of flavonoid in *Docynia indica* fruit in 2 to 5 PH improved the yield of flavonoids to 9.6 to 23.3 mg/g, but the extraction yield dropped to 16.6 mg/g as the PH was raised to 7 (Wang, Zhu et al. 2025). On the other hand, the *Ficus racemosa* fruit content of flavonoids declined with an increase in pH between 3.5 and 5.5 (Sharma, Kumar et al. 2020). Moreover, anthocyanins have been identified to be less stable under higher PH, and caution is necessary when using at least the extraction conditions in order to obtain a particular pH-sensitive compound (Doulabi, Golmakani et al. 2020).

All in all, the solvent system including the type of the solvent, solvent concentration, and pH is a key determinant of MAE performance. The current

movement towards making the traditional ethanol-water systems more water-clean systems, including NADES, ILs, and DESs, is indicative of a larger change towards sustainable, selective, and energy-efficient methods of extracting high-value bioactive compounds (Usman, Nakagawa et al. 2023).

Solvent-to-Material Ratio (SMR)

One of the most important operational variables in microwave-assisted extraction (MAE) is the solvent-to-material ratio (SMR), or the liquid-solid ratio (LSR) because it directly affects solutes solubilization, mass transfer behaviour, extraction efficiency and the overall sustainability of the process (Luo, Zhou et al. 2021). A properly chosen SMR is needed to allow full immersion of the plant matrix to be immersed in the solvent to assist in good absorption of the microwaves, homogenous heating of the volumetric temperature as well as constant extraction conditions. Overall, when SMR is increased, concentration gradients between the solid matrix and the solvent are increased to achieve better diffusion of the target compounds into the liquid phase. Nevertheless, large amounts of the solvents may result in the diluted extracts, low efficiency of heating in microwaves, increased energy consumption, and decreased economic viability (Veggi, Martinez et al. 2012).

A number of studies have also shown that the performance of extraction as related to the increasing SMR reaches optimal level after which the performance of extraction reaches plateau or even decreases. As an example, the extraction of flavonoid in *Citrus aurantium* peels maximized at a SMR of 30:1 mL/g, and the extraction did not increase further with the increase in ratio (Abdallah, Abbassi et al. 2024). Equally, MAE of *Camellia sinensis* recorded the most total phenolic at an SMR of 20:1 mL/g and retained a good working efficiency (Luo, Zhang et al. 2020). In a different study about curcuminoid extraction using turmeric, the relative yield of curcumin increased with an increased ratio of SMR 10:1 to 25:1 mL/g, and no longer (Jiang, Ghosh et al. 2021).

Pronounced matrix-dependent variability in optimal SMR values has been reported, particularly in MAE systems employing green solvents such as natural deep eutectic solvents (NADES). Due to their elevated viscosity and unique solvent-solute interaction mechanisms, NADES often require modified SMR conditions to ensure adequate mass transfer. Additional increases in LSR (10 to 50 mL/g) of NADES-based MAE of *Abelmoschus sagittifolius* roots led to about 6.7 and 9.6-fold

increases in the phenolic and terpenoid yields, respectively, and a marginal decrease at 60 mL/g due to the decreased efficiency of the distribution of microwave energy (Vo, Pham et al. 2023). Response surface methodology also determined optimum LSRs of 26 mL/g in MAE and 28 mL/g in UAE in the extraction of polyphenols in passion fruit peels and a compromise between the extraction yield and minimum solvent usage (Vo, Nguyen et al. 2023).

Extreme SMR conditions also exhibit high rate of extraction when under high-power microwave. As an illustration, *Careyasphaerica* flower yielded the highest levels of maximum phenolic recovery in 20 seconds with a solid-to-solvent ratio of 1:100 g/mL at 1,000 W (Sai-Ut, Kingwascharapong et al.). Also, the extraction of Pitugao fruit polysaccharides by MAE demonstrated statistically significant differences in yields under LSR values of 10-60 mL/g when an optimization was performed as a function of both the microwave power and extraction time (Wang, Wang et al. 2015). Similar patterns happened in extraction of eggplant peel, as SMR had a significant effect on the extraction of phenolics, flavonoids, and anthocyanins in a multi-factorial experimental system (Kainat, Ali et al. 2023).

The influence of SMR is further supported by theoretical and kinetic modeling studies. The increase in SMR increased the flavonoid extraction rate and mass transfer rate of *Phyllanthus emblica*. Conversely, the recovery of flavonoids in leaves of *Sedum aizoon* decreased with SMR beyond the optimal levels, presumably because of the effect of dilution or inadequate mechanical mixing to cause uniform heating (Jin, Wei et al. 2017). Further, beyond a certain limit, solvent volumes have been determined to decrease total extraction efficiency since they do not proportionally increase solute recovery even though more microwave energy is consumed (Eskilsson, Björklund et al. 1999; Mandal and Mandal 2010).

In turn, the effective SMR values of MAE can be expected to be in the range of 15:1 to 50:1 mL/g, depending on the character of the plant matrix, solvent system, and target bioactive compounds (Bhadange, Carpenter et al. 2024). Optimization of SMR provides high efficiency in extraction aiming at minimum solvent consumption, energy consumption, and operating expenses, thus the processes of MAE are consistent with the green extraction and sustainable process design.

Microwave Power

Microwave power also plays a very important role in MAE as it controls the rate at which cells undergo dielectric heating, the amount of cell wall rupturing, solvent diffusion and the release of intracellular chemicals (Destandau and Michel 2022). Since the extraction process is influenced by the energy input and efficiency of the process, and selectivity, it should be balanced to avoid the degradation of the bioactives which are sensitive to heat. The high rate and uniform heating of polar solvents and intracellular water under controlled microwave power is what results in the efficient solubilization and transfer of phytochemicals (Kumar, P et al. 2023). Many studies have demonstrated the advantage of moderate-high level (300 to 600 W) of microwave power as the best to extract (Peng and Hwang 2015).

As an example, the microwave power raised to 200 W and 600 W, respectively, increased flavonoid and total phenolic peels of *Citrus aurantium* peels by a large percentage with 600 W giving the highest concentration that did not degrade due to heat change (Rajabi, Amiri et al. 2023). A study on the *Curcuma longa* indicated that 500 W was the most effective power of extracting curcuminoids, but when the microwave power was applied over an extended amount of time, therefore, the values decreased to 600 W (Yaman, Arslan et al. 2025). When *Camellia sinensis* leaves were extracted using microwave power between 300 and 450 W, the antioxidant activity and catechin content rose; however, when exposed to 600 W for an extended period of time, these values dropped (Kaur, Gandhi et al. 2024).

The phenolic yield of the *Barlerialupulina* leaves under MAE decreased considerably as the heating caused some degradation of the product with increase in 200 W to 400 W. This was also found in olive pomace, where high power led to decreased yields of phenolic and flavonoid compounds, which is due to excessive localized heating (Ismail-Suhaimy, Gani et al. 2021). 800 W generated was found to lead to reduced yields of phenolic and flavonoid compounds which is due to excessive localized heating (ElGamal, Song et al. 2023). Mechanistically, the disintegration of cell walls and diffusion of bioactives are aided by microwave power, which increases the temperature and internal pressure in the plant matrix by encouraging ionic conduction and dipole rotation (Mishra, Yadav et al. 2024).

However, overload can lead to hot spots, localized heating and boiling of the solvent, leading to a decrease in the effect of thermolabile chemicals

and a decrease in extraction efficiency. A nonlinear power-yield relationship was observed in a series of plant materials, including materials with flavonoid-rich materials, such as the fruit of *Ficus racemosa* and the bark of *Albizia myriophylla*. (Mangang, Chakraborty et al. 2020) and asserted that the higher the microwave power beyond a specific level, the higher the temperature of the system, and the higher the temperature, the greater the flavonoid solubility, yet the faster the system deteriorated due to this. They however did not find a significant increase in flavonoid production between 360 and 450 W, which was caused by the effects of matrix type and power-duration synergy. However, at an increase in power to 720 W, the yield increased (Sharma, Kumar et al. 2020).

The production of quercetin was low (160-640 W) microwave energies but much higher at 800 W, which is also probable because of the potential to damage the cell wall more at high radiation levels (Aghajanian, Kazemi et al. 2020). Each application of MAE needs to be customized with microwave power to achieve efficient heating and recovery of the targeted chemicals with maximum sustenance of its integrity. Majority of the process and method optimally suggest the extraction of polyphenols, flavonoids, and curcuminoids with a range of power of 300-600 W. Nevertheless, the calibration of the viscous solvents like complex matrices or NADES can be as high as 800 W, depending on the type of solvent, stability of the solute, and the time of irradiation (Chevé-Kools, Choi et al. 2025).

Temperature

Temperature is a crucial element of MAE that directly affects the compound solubility, interaction between the solvent and the solute, the rate of diffusion, and the degree of breaking the cell walls of the plant cells (López-Salazar, Camacho-Díaz et al. 2023). The high temperature promotes the transfer of the mass, increases the mobility of the molecules, and improves the amount of bioactives extracted including flavonoids and polyphenols. This is largely attributed to the fact that because the heating is done in plant cells using the microwaves, the vapor pressure increases leading to the rupture of the cells and therefore releasing intracellular materials into the solvent. Nevertheless, a lot of thermolabile substances break down above a particular temperature, which lowers extraction effectiveness and risks bioactivity (Usman, Nakagawa et al. 2023). It has been established by many studies that

temperature tuning is necessary in order to achieve a balance between the stability of the compounds and the yield.

The temperature of 40 °C was also increased to 70 °C, which created a considerable enhancement in the extraction of phenolics and flavonoids of *Citrus aureus* peels (Veggi, Martinez et al. 2012). The highest yield was observed at 70 °C before they started to decline as a result of thermal degradation. Likewise, the catechins stability started to decrease at temperatures of 60 °C, reaching a point of maximum antioxidant recovery of *Camellia sinensis* leaf extract (Ahmad, Aldholmi et al. 2023). One study on *Curcuma longa* established that curcumin was destroyed at temperatures exceeding 100 °C even though the extraction of curcuminoid was most effective at 80 °C in 10 minutes (Binello, Grillo et al. 2020).

The relationship between temperature and irradiation time and the microwave power in MAE systems is direct. The longer the power and exposure time, the higher will be the internal temperature (Veggi, Martinez et al. 2012). The longer the power and lengths of exposure, the higher is the internal temperature. The higher the irradiation time of 4 to 5 minutes, the lower the yield of quercetin of 0.214 to 0.209 percent as the system temperature exceeded the quercetin degradation limit, which was set at 75 °C (Mukhaimin, Saraswati et al. 2019). The temperature maximized the yield of Flavonoid until 70 °C, and then it decreased with increased heating because of thermal degradation (Liu, Liu et al. 2022).

The majority of optimized MAE processes suggest a temperature between 50 and 70 °C in the case of flavonoid rich materials. This range however varies with respect to the particular plant matrix and the structural properties of the target chemicals. Very high temperatures in closed-vessel systems can lead to solvent boiling, local warming, and compound degradation, and the pressure accumulation in the closed-vessels should also be controlled to be safe (Shams, Abdel-Azim et al. 2015). Precise temperature control is essential for both laboratory and industrial MAE applications in order to optimize extraction yield, preserve molecular integrity, and ensure process consistency (Bhadange, Carpenter et al. 2024).

Microwave power and exposure time can significantly affect temperature during microwave-assisted extraction. The higher the power of the microwave, the faster it heats up, and the longer the extraction time the more thermal energy it generates.

Nonetheless, too much power and long exposure can result in degradation of thermolabile compounds. As such, to obtain maximum extraction efficiency, power, temperature, and time interaction must be optimized.

Microwave irradiation time

Microwave-Assisted Extraction (MAE) is directly influenced by the duration of microwave energy exposure, which is directly determined by the microwave irradiation period, and influences solvent heating, cell wall rupture, and release of individual phytochemicals (López-Salazar, Camacho-Díaz et al. 2023). Microwave heating is both volumetric and fast so short irradiation times can frequently be adequate to achieve high extraction efficiencies. To illustrate, it was found that after 3 minutes of 600 W irradiation, phenolics, and flavonoids of *Citrus aurantium* peels were recovered to the fullest, and further exposure of this compound resulted in lower yields as a consequence of catechin decomposition (Veggi, Martinez et al. 2012). Similarly, it was discovered that the stability of catechins began to decline after 5 minutes, when the best antioxidant recovery from *Camellia sinensis* leaves took place (Saleem, Ullah et al. 2024).

The irradiation of turmeric (*Curcuma longa*) at 500 W in durations between 8-10 minutes was the best time to extract curcuminoid; beyond 12 minutes oxidative deterioration occurred (Singh, Srichairatanakool et al. 2022). More details suggest that polyphenol extraction of chestnut processing waste was the most successful after 10 minutes of microwave irradiation, without affecting antioxidant capacity (Pinto, Silva et al. 2021). Waste and Biomass Valorization found that 8 minutes is the maximum time rate of polyphenol extraction in *Pithecellobium dulce* (Bacelar, Rodrigues et al. 2025), and 6-8 minutes is the time of maximal recovery of polyphenols in *Gossampinus malabarica* flowers.

Such studies indicate that the most effective irradiation duration between two and ten minutes that trade off the stability of compounds and energy efficiency are the most effective in most plant matrices (Tyagi and Lo 2013). Following this window, prolonged exposure may raise interior temperatures, which may cause heat-sensitive materials to degrade. In addition, the power of microwaves and the duration of irradiation have a simultaneous influence on temperature and energy input of the system.

It was also observed that the exposure to the microwaves at the absence of temperature

control resulted in the deterioration process and the decrease in flavonoid yields (Mukhaimin, Saraswati et al. 2019). In order to minimize the effect of heat degradation during long extraction periods, scholars have recommended several short cycles using novel solvent or temperature-regulated systems. The amount of flavonoid was found to increase with time and reach its highest point at approximately 20 minutes (Jin, Wei et al. 2017). Upon some time, duration of controlled temperature, also recorded a yield plateau in MAE of *Terminalia bellerica* flavonoids (Krishnan and Rajan 2017).

Hence, although the increase in irradiation time can be regulated to increase yield, excessively long exposure must be avoided to conserve energy, prevent degradation and process sustainability. In cases where the irradiation times are more than 10 minutes, preventive measures like temperature control, longer extraction periods, or alterations, like Vacuum MAE (VMAE) or Dynamic MAE (DMAE) are occasionally advised.

Contact surface area

The area of the contact between the plant material and the solvent is an important factor that determines the effectiveness of microwave-assisted extraction (MAE). Smaller particle size of the raw material enhances the heat transfer, solvent diffusion, and mass transfer since it increases the surface area available to be in contact with the solvent and the penetration of microwaves (Mao, Robinson et al. 2021). Finely powdered *Citrus aurantium* peel (0.5 mm) extracted with MAE gave a much higher extraction yield of phenolics and flavonoids compared with the larger particles (Veggi, Martinez et al. 2012). This was attributed to the fact that the finely ground peel had better absorption of solvents and microwave energy as indicated.

Smaller particle sizes also enhanced homogenous heating of the microwave in *Camellia* and enabled more efficient extraction of catechins and antioxidants to the plant. Nevertheless, too fine particles (<0.1 mm) may result into agglomeration, impede the flow of the solvent, re-adsorb the solvent, and make subsequent processes, such as centrifugation or filtration, more difficult (Hu, Tang et al. 2021). Indications of support show that there is an optimal range despite the general improvement of extraction with reduction in particle size. As an illustration, in *Curcuma longa* the authors have established that particles with a size range of 0.25-0.5 mm have the most ideal extractability to ease ratio with processing (Binello, Grillo et al. 2020).

The reduction of the size of particles to less than 160 μm in *Crataegus monogyna* almost doubled the recovery of polyphenols, but further reduction posed the risk of degradation and filtration issues (Martín-García, Razola-Díaz et al. 2021). In the same manner, an essential oil of *Lippia adoensis* study found non-linear yielding tendency, with the optimum particle size of 0.5-0.7 mm; insufficient penetration or re-adsorption led to a reduction in yield in both fine and coarse fractions (Bukhari, Ijaz et al. 2021). Bigger phenolic content and antioxidant activity in shiitake mushrooms increased mass transfer and cell disruption with a reduction in the size of the particle to 1.75 mm instead of 4.75 mm (Subramaniam, Jiao et al. 2021).

The extraction of plant materials was improved using MAE by pre-treating plant materials using grinding and sieving before pre-treatment, which increased surface area (Alara, Abdurahman et al. 2020). To achieve high yields, a particle of less than 0.25 mm in size was used, but (Chan et al. 2015) a size of between 0.25 to 0.60 mm was optimum to ensure that the extraction was not problematic. Consequently, selection is a key design parameter to optimize the particle size of MAE, as it is the guarantee of efficient phytochemical release, quick heating, and uniform energy distribution, and contact with solvents (Xu, Wu et al. 2021).

Stirring

Agitation or stirring is an essential yet, in most cases neglected, aspect of improving the efficiency and homogeneity of MAE (Dhotre 2025). The rapid volumetric heating of microwave radiation can be achieved, and the solvent-matrix interaction is not uniform thus hotspots, cold spots or partial extraction may occur, particularly in unstirred systems (Sahu, Sahoo et al. 2025). Stirring helps in reducing these problems by facilitating the constant circulation of the solvent, mass transfer and uniform dispersion of the microwave energy. Indicatively, a study hypothesized that moderate magnetic stirring greatly enhanced the extraction of polyphenols and flavonoids in *Citrus aurantium* peels by enhancing the diffusion of the solvent and decreasing the clumping of the particles (Rajabi, Amiri et al. 2023).

Equally, stirring at intervals reduced local deep heat damage in *Camellia sinensis*, resulting in more uniform catechin profiles, (Luo, Zhang et al. 2020). A study on turmeric (*Curcuma longa*) revealed that light and intermittent stirring enhanced curcuminoid production in open vessels without splashing the solvents (Singh, Srichairatanakool et

al. 2022). Moreover, MAE systems that lack embedded sample rotation or homogenization make the stirring very useful. The use of intermittent agitation in the ethanol-water MAE of olive leaf biomass also led to 12 percent higher yield oleuropein compared to the results of the static extraction (Barbu, Fierascu et al. 2025). Phenolic compounds were recovered in greater amounts by 15 percent or so by mechanical agitation compared to no agitation (Wang, Huang et al. 2023).

Moreover, another study revealed that magnetic stirring with 300 rpm in the course of MAE of grape seed extract enhanced the antioxidant yield and extract clarity (Chaji, Capaldi et al. 2024). In an experiment of the MAE of rosemary essential oil, intermittent stirring consumed less energy and produced greater yields of terpenes compared to the static or excessive agitation systems (Chetia, Ashraf et al. 2025). Agitation provided significance to uniform heating and solute release, which facilitated the extraction of flavonoids in *Terminalia bellerica* (Krishnan and Rajan 2016). Poor agitation may cause inefficient heating and low yield of extraction in larger-scale extractions, particularly when green solvents such as DESs are used (Eskilsson, Björklund et al. 1999).

Since it enhances extraction kinetics and reproducibility and at the same time saves energy, controlled stirring be it of a mechanical or magnetic or platform-based nature is thus a key characteristic in both laboratory scale and industrial MAE applications.

The plant matrix composition

The success of MAE mostly relies on the character of the plant matrix, comprising the lignocellulosic complexity, moisture content, tissue density and cell wall construction (López-Salazar, Camacho-Díaz et al. 2023). These inherent properties regulate solvent transport, the absorption of microwave energy and the release of chemicals, which are easy to intracellularly release (Zhu, Nie et al. 2013). In easier matrices with thin cell walls and a high porosity (petals and young leaves) the solvent-matrix interaction and spectrum penetration of the microwave are greater tending to easier extraction (Chen 2011). It was found in *Citrus aurantium* peel that its moisture content and low texture allowed it to internalize heat quickly and increase the yield of phenols during moderate conditions of microwaves (Hayat, Zhang et al. 2020).

But, thick and hardened materials, like roots, woody stems, and rhizomes, are less

permeable and more difficult to disintegrate their unbending cell walls with fewer microwave energy or pretreatment (Zhao, Baik et al. 2014). It was found that the lignin content of *Curcuma longa* rhizomes was too high in order to release curcuminoids and that power-time parameters had to be adjusted to overcome diffusion resistance (Jiang 2022). Concentration of moisture is also a serious factor that influences MAE operation as an internal microwave absorber. Fresh and moist leaves contained more catechins than dry samples due to the increased ability of water to couple microwave energy's energy in *Camellia sinensis* leaves (Saleem, Ullah et al. 2024). But when the water is excessive, solvent polarity may be diluted and the specificity of the extraction could be diminished. The other aspect of matrix is particle size. Smaller particles enhance mass transfer due to an increase in surface area, and too much shall result in hindrance of filtering and deterioration of compounds.

The experiment on *Crataegus monogyna* established that the overall polyphenol recovery was significantly enhanced with the decreasing particle size to 0.16 mm, whereas ultra-fine particles (under 100 nm in size) posed filtration problems (Martin-García, Razola-Díaz et al. 2021). Likewise, the *Lippiaadoensis* essential oil extraction exhibited an optimal range of particle sizes (0.5-0.7 mm) and yields of the oil dropped off above this particular range (Worku, Shibeshi et al. 2024). The decrease of the shiitake mushroom biomass (4.75 to 1.75 mm)

led to a sharp increase in the phenolic yield (around 4.9 to about 6.35 mg GAE/g) by increasing the extent of matrix disruption and solvent access (Chu 2021).

These results support the fact that it is the features of the matrix that are unique to plants such as the lignin/cellulose content, cuticle thickness, porosity, and particle size which are strongly associated with the MAE efficiency and are not influenced only by the operational factors. The MAE settings should be adjusted to the physical and biological characteristics of the matrix in order to maximize the yield, preserve compound integrity, and make the processing energy-saving (Bhadange, Carpenter et al. 2024).

The Development of MAE Techniques:

The microwave-assisted extraction (MAE) has been developed as a simple form of quick-heating technique to a multifaceted and multimodal green extraction system. Contemporary forms such as vacuum, nitrogen-penetrated, ultrasonic, and dynamic MAE enhance efficiency, selectivity and stability of the compound. The scalability of the MAE and the possibilities of its use in industry are growing as green solvent systems and reactor design keep improving.

The various types of MAE available are represented in Fig 2

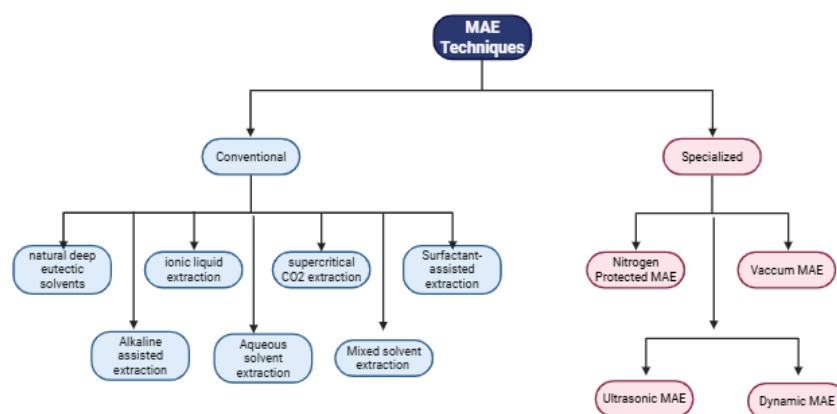


Fig. 2 Flowchart on Various Types of MAE

Nitrogen-Protected Microwave Assisted Extraction (NPMAE)

Nitrogen-protected MAE (NPMAE), a variant of the traditional MAE, is an oxygen-sensitive bioactives with an inert environment holding bioactives in extraction. This preservation

technique prevents oxidative degradations of labile compounds, including flavonoids, polyphenols and ascorbic acid by introducing nitrogen or argon inert gases into the closed extraction vessel following the removal of oxygen in the atmosphere by the use of a vacuum (Yu, Chen et al. 2009). NPMAE greatly

improved ascorbic acid recovery of guava, green pepper, yellow pepper and cayenne pepper and is better than conventional MAE, as well as Soxhlet technique since nitrogen retains antioxidants (Yu, Chen et al. 2009). Either or both nitrogen or argon, which are essentially nonreactive to oxidation, inert gas conditions, are effective to enhance stability of the extract and yield, particularly in thermolabile phytochemical systems (Pasquet, Chérouvrier et al. 2011). Recently to NPMAE how NPMAE can increase the yields of sensitive bioactives through its application to extract flavonoids in apple skins (Casazza, Aliakbarian et al. 2010). They got a high yield (13.9 mg/g) at 150 °C and at 90 minutes. Separating cellulose and Acer platanoides was performed using the capacity of NPMAE to keep target molecules free of oxidative and thermal stresses (Rizwan, Gilani et al. 2021). This experiment demonstrated better structural integrity and crystallinity at 100 W and 120 °C in nitrogen environment.

The vacuum variant, NPMAE, is a more advanced variant of MAE which can be used to propose a higher percentage of extraction with reduced pressure but without causing oxidative degradation (which occurs in the presence of oxygen) of thermosensitive and oxygen-sensitive (oxygen) chemicals, although its benefits are not yet proven, NPMAE remains a promising alternative to conventional MAE in flavonoid extraction (Wang, Zhu et al. 2025).

Vacuum Microwave-Assisted Extraction (VMAE)

Vacuum MAE (VMAE), a more advanced form of conventional MAE, increases extraction efficiency by using less pressure while protecting thermosensitive and oxygen-labile chemicals (Wang, Xiao et al. 2008). Reduction of the boiling point of solvents in a vacuum has the effect of reducing thermal degradation and oxidative loss and facilitating extraction at much lower temperatures. This is of great importance especially to bioactives such as flavonoids which are highly sensitive to oxygen and heat. As an example, flavonoids are destroyed easily when extracted at high temperatures hence the need to handle them with care (Moure, Cruz et al. 2001). VMAE is a mixture of rapid heating using microwave and solvent reflux using vacuum to maximize mass transfer without altering compound integrity. To isolate rutin, hyperoside and hesperidin in *Sorbus tianschanica* leaves, VMAE, MAE, and heat reflux extraction were performed in order to (HRE). They observed that VMAE yielded much higher concentrations of

all three (rutin: 0.71-0.04 mg/g, hyperoside: 1.18-0.06 mg/g, and hesperidin: 0.48 mg/g) than MAE and HRE (Gu, Chen et al. 2016). It was found that the yield of vitamin C and tocopherols increased 20-35 times relative. Other recent applications with industrial-scale further support the scalability and efficiency of VMAE (Li, Sun et al. 2017).

In a study on the *Punica granatum* pomace, the researchers showed that the highest yields of polyphenols and flavonoids could be obtained in 15 minutes with approximately 2,000 W of microwave power under vacuum, which is fast and energy-efficient (García, Fredes et al. 2021).

VMAE has been applied to extract larger proportions (62%) of heat-sensitive chemicals including myricetin and resveratrol out of traditional Chinese medicine, including *Rhizma Polygoni Cuspidati* and *Myrica rubra*, than MAE or reflux. The capacity of VMAE to create a solvent circulation in situ increases the interaction of the solvent and the matrix and gets homogeneity leading to additional gains in yield (Bhadange, Carpenter et al. 2024). According to recent evaluations, VMAE is a scalable, enthusiastic extraction device, which is environmentally amiable, solvent efficient, and can be utilized in the food, pharmaceutical, and cosmetic industries (Xiao, Wang et al. 2009). It is especially useful to extract polyphenols, essential oils, and antioxidants without the consumption of artificial solvents or consuming a lot of energy (Chemat, Abert Vian et al. 2019).

Ultrasonic Microwave Assisted Extraction (UMAE):

Ultrasonic MAE (UMAE) is an integrated method that uses volumetric heating of microwave energy with the cavitation actions of ultrasound to improve the extraction of bioactive compounds in a variety of plant and algal samples (García-Vaquero, Ummat et al. 2020). Thermal lability of chemicals, shortening of extraction periods, and enhancement of mass transfer are all the combined effects of ultrasound-induced cell disintegration and rapid heating with microwaves. UMAE on the pericarp of *Garcinia mangostana* with 200 W ultrasonic and 200 W microwave was found to greatly improve total phenolic content (caffeic and ferulic acids), as well as α -mangostin, as compared to the normal process decoctions (Kwansang, Chen et al. 2022).

Pilot-scale UMAE was successfully used to recover organic acids (lactic, malic and -ketoglutaric), phenolics and fucose sulphated polysaccharides in macroalgae such as *Ascophyllum*

nodosum and *Alaria esculenta* and SEM imaging has shown increased cell damage and solutes release (Das, Tiwari et al. 2025). UMAE had greater yield and quality than MAE and UAE, enhancing the recovery of pectin and retention of lycopene in tomato processing waste (Lasunon and Sengkhampan 2022). UMAE (10 min ultrasound plus 10 min microwave at 280 W) was better at *Andrographis paniculata*, which produces 1,066 mg/L of andrographolide and remains active as an antibacterial in constant mode (LC 50 -76mg/L) (Rubi, Olay et al. 2020). Also, power modification and solvent optimization of response surface methodology (RSM) using *Coptisteeta* UMAE selectively increased the yield of phenolic and berberine (Sarma, Patra et al. 2025). *Aronia melanocarpa* which used UMAE-NADES strategy to isolate anthocyanins with excellent purity (449 mg/g) demonstrates that the integration of solvents enhances the effectiveness of UMAE (Lin, Meng et al. 2022). The adaptability of UMAE has also been observed in the extraction of oil (e.g., 59% yield of the oil of the kernel of *Juglans mandshurica* with over 90% unsaturated fatty acids) and the recovery of polysaccharides in brown algae and *Dictyophora indusiata* (UMAE) (Liu, Ni et al. 2022). These illustrations demonstrate that UMAE is an efficient and effective system toward food, cosmetic, pharmaceutical, and biorefinery due to its high extraction kinetics, stability of compounds, and environmental friendliness (Nutrizio, Chemat et al. 2022).

Dynamic Microwave-Assisted Extraction (DMAE)

Dynamic MAE (DMAE) is another continued flow method, which improves the conventional MAE by extracting the extract and then adding more solvent continuously to the extraction vessel (Wu, Hu et al. 2016). Moreover, compared to the traditional system, this dynamic system can enhance the mass transfer, shorten extraction periods and assure a steady concentration gradient, lowering the thermal impact on the bioactive that is heat sensitive (Ramesh, Shankar et al. 2024). In comparison to the characteristics of MAE that is still, solvent saturation can limit efficiency, whereas localized overheating may occur, DMAE provides ideal extraction conditions by ensuring uniform energy allocation and solvent replacement. It was first used in analytical modes of selecting, fast and sensitive detection.

Cereal matrices Organophosphorus pesticides were successfully extracted in less than 4

minutes using DMAE-QuEChERS system and detector limits of less than 1.5 µg/kg and recovery between 76 and 100% (Li, Liu et al. 2020). In environmental research, Triazine herbicides were effectively removed with soil in the form of Dynamic Microwave-Assisted Micelle Extraction (DMAME) and cloud-point preconcentration which reduced thermal degradation and enhanced selectivity using non-ionic surfactant in continuous flow (Wu, Li et al. 2022). Plant bioactive extraction of *Saussurea medusa* cell cultures by use of DMAE was much more efficient than the traditional batch using a 60-minute solubilization of 4.97% flavonoid yield on Solvent/solid ratio of 1:500 at 1200 W (Yu, Yu et al. 2010).

The DMAE facilitates the effective solvent-matrix interaction in a mechanical manner; it consistently replenishes the layers of the solvent so that the layers absorb and distribute the microwave energy. This increases how fast the phytochemicals of interest are solubilized and disintegrated through the cell wall (Sahu, Sahoo et al. 2025). DMAE is also dedicated to green chemistry, ensuring a minimized energy input, and fewer solvents used, as well as the fact that it can be integrated in line with other analytical systems like GC-MS or HPLC. Most applications of DMAE in the food, pharmaceutical, and environmental sectors are highly versatile, green and scalable processes used where high-throughput, sanitary and thermal mild extraction is needed (Meher and Zarouri 2025).

Instrument and Equipment Setup In MAE

MAE systems consist of a microwave generator (typically a 2.45 GHz magnetron), temperature and pressure resistant containers (typically made of PTFE or borosilicate glass) and a multimode or single mode applicator cavity (Meher and Zarouri 2025). Each of these portions is controlled by software-controlled pressure, temperature and power sensors. Closed-vessel systems equipped with PTFE liners, PFA seals, and reinforced casings and built-in pressure relief valves can work in 200-250 °C and up to 18 bar to provide working safety and even pressure allocation. Modern MAE systems can also be used to interact with such analytical tools as HPLC, GC-MS, and ICP-MS to increase throughput in analytical and quality control workflows, as well as enable real-time extract monitoring (Saroj, Shah et al. 2018). Non-polar solvents can be also dealt with by safety features, solvent-adaptive power feedback loops, and microwave-transparent heating inserts (including

carbon-black or silicon carbide) that also enhance process efficiency.

Emerging solvents in MAE of bioactive compounds

There has been interest in recent developments in solvents for MAE (Hamid Nour et al., 2021). Significant interest in a few industries, such as food and beverage, cosmetics, medicines, biomass valorisation, and nutraceuticals (Fordos, Amin et al.). The possibility of solvents being used advanced to enhance extraction efficiency has been examined. These are ionic liquids (ILs), alkaline solvents, supercritical fluids, micellar system or surfactants, and natural deep eutectic solvents (NADESs). Besides maximizing the yield, the careful application of these new solvents also enhances affordability and sustainability in the environment (Bouizgma, Rabbah et al. 2025). DESs have become an attractive substitution to ILs because of the low cost of raw materials and ease of production, as well as because it is biodegradable by its nature (Kudlak, Owczarek et al. 2015).

The high extraction efficiency and reusability of ionic liquids aid in partially compensating the high cost of ionic liquids. In an endeavour to enhance their sustainability, the current studies are on production of IL alternatives that are more affordable and biodegradable. Although the cost of setup is high, supercritical carbon dioxide (SC-CO₂) has long-term cost-saving advantages of removing the need to use organic solvents and allows the easy recovery of solvents. The alkaline extraction with such agents as NaOH or KOH enhances the cell wall to be disrupted with a lesser amount of energy input which makes the processes more efficient. On the same note, the extraction with surfactant has been found to be a convenient and economical technique because it consumes less surfactant, enhances the extraction efficiency, and solvent can be recycled. These advances have made MAE techniques work on the extraction efficiency of flavonoids and polyphenols in various biological sources, particularly the waste materials of the plant-based and the byproducts of the food industry the target of many studies (Wang, Zhu et al. 2025).

Natural deep eutectic solvents with MAE

Among the most important aspects that impact the MAE process is the solvent system. It contains the type of solvent, concentration and pH level. The solvent should be of the correct polarity to microwave heating in order to effectively absorb the microwave energy. Examples of organic solvents

include methanol, acetone and ethyl acetate that have long been used extensively in extractions. Among the major limitations of these solvents are toxicology, low vapor pressure, burning, and environmental pollution (Isci and Kaltschmitt 2022). To address these limitations, more attention has been given to the development and the use of alternative green solvents, especially, NADES.

One is prepared by mixing a hydrogen bond acceptor (HBA), e.g., choline chloride, with a hydrogen bond donor (HBD), e.g., glycerol, into a eutectic mixture (Isci and Kaltschmitt 2022). The NADES attract a lot of interest because of their low toxicity, high extraction performance, biodegradability, and environmental friendliness (Huber, Muller et al. 2021). HBA molecules are generally combined with HBDs, like urea, ethylene glycol, or glycerol in the most popular DESs (Mushtaq, Butt et al. 2024). In the recent years, researchers have investigated the incorporation of MAE with new solvent systems, i.e., deep eutectic solvents (DESs) (Fu, Zhang et al. 2025) and ionic liquids (ILs) (Wang, Zhu et al. 2025). ILs offer many good qualities including low melting point, high thermal stability, low volatility, high conductivity, high surface tension, non-toxicity, and biocompatibility, which NADES also offer but are even more environmentally friendly (Turan, Isci et al. 2024). Consequently, DES-assisted MAE remains a promising technique as an eco-friendly way of extracting bioactive materials in an efficient manner, out of an assortment of natural sources.

Microwave assisted ionic liquid extraction

The thermal breakdown and microwave (MW) absorption properties of all of the analysed deep eutectic solvents (DESs) are closer to those of what ionic liquids (ILs) possess rather than to the established molecular solvents. The special properties allow DESs to become ecologically benign solvents of chemical processes facilitated by microwaves. Ionic liquids or ILs are salts that liquefy below 100°C and sometimes even down to -96°C. They are widely recognized as sustainable alternatives to volatile organic solvents (Nazir, Younis et al. 2025). Due to having low environmental impact during their life cycle, they are considered as green solvents (Nazir, Younis et al. 2025).

The combination of ILs and MW radiation has had a highly positive effect on areas of materials science and nanotechnology, especially regarding how to enhance the efficiency of extraction and synthesis [(ILMMAS)]. ILs have high dielectric

constants, and ionic conductivity, which makes ILs very good in absorbing microwave energy. This enhances the net effect of microwave assisted extraction (MAE). Nevertheless, the applied ILs would result in over-saturation of the microwave radiations, thus yielding lower extraction by decreasing the energy of which a cell rupture of solubilization can be performed (Nazir, Younis et al. 2025).

In addition to extraction ability, ILs have also exhibited special features to dissolve and alter biopolymers including chitin and lignocellulosic biomass, and this increases their applicability to new technologies in the biological and medical sciences (Wang, Feng et al. 2024). These developments have proven the bioactivity of ILs and its applicability to biomedical innovation (González-Rivera, Husanu et al. 2020). The use of ILs in sampling preparation in the last 20 years has increased significantly. In comparison to traditional organic solvents, ILs are much more usable in a wide range of applications because of their tunability to physical and chemical properties. because of their versatility, ILs have been called design solvents since their behaviour can be easily modified through the length of the cation, anion and alkyl chain (Zhou, Gui et al. 2023).

Microwave-assisted supercritical CO₂ extraction

For the efficient recovery of valuable bioactive chemicals, the sequential variations of microwave-assisted supercritical CO₂ extraction (MA-SC-CO₂) have emerged as a very promising green method (Pimentel-Moral, Borrás-Linares et al. 2019). This hybrid technique enhances extraction yield, selectivity, and sustainability by fusing the rapid heating capabilities of microwaves with the superior solvating properties of supercritical CO₂ (SC-CO₂). SC-CO₂ is a solvent that is commonly used to extract nonpolar and thermolabile chemicals at relatively low temperatures because it is non-toxic, non-flammable, and ecologically safe (Herzyk, Piłakowska-Pietras et al. 2024). However, its usage is often limited by the need for sluggish mass transfer rates and high operating pressures. Combining SC-CO₂ with microwave pretreatment overcomes these limitations by improving cell disruption, increasing solvent accessibility to intracellular chemicals, and significantly reducing extraction time.

The combination of supercritical fluid diffusion with microwave energy enables rapid

internal heating, enhanced solvent penetration, and enhanced extraction efficiency.

Integrated microwave-surfactant-assisted extraction:

Integrated microwave surfactant-assisted extraction (MSAE) is a green and effective method of extracting various bioactive chemicals by taking advantage of the solubilizing behaviour of surfactants and the rapid heating effect of the microwaves (Yamini, Feizi et al. 2020). Complex plant matrices can be used to extract hydrophilic and hydrophobic phytochemicals using this method. Another application is the creation of natural surfactant-mediated microwave-assisted extraction (NSM-MAE), which is used to obtain substances in *Acanthopanax senticosus* stems, including phenolic acids, coumarins, bisepoxy lignans, and phenylpropanoids (Wang, Pan et al. 2022). Among the ten evaluated surfactants, the soapnut saponin (SS) in ethanol was revealed to be the most effective solvent system with a large extraction efficiency (Wang, Pan et al. 2022).

MSAE employs cationic (as CTAB), anionic (as SDBS), non-ionic (as Triton X-100) or zwitterionic surfactants to be able to create micelles in aqueous solutions. These micelles enhance the solubility and accessibility of the target molecules because of its encapsulation (Shah 2016). Upon addition of microwave energy, the solvent-surfactant mixture quickly warms, breaking apart plant cells, and enhancing the transfer of the mass.

Water is a common choice of the main solvent because it has a large dielectric constant and is an excellent microwave absorber. It also promotes the formation of micelles when it is used together with the surfactants and improves the extraction of the hydrophobic materials (Dallinger and Kappe 2007). Aqueous alcohol solutions that increase the solubility and polarity of semi-polar substances can include 50-70% ethanol or methanol. The increased micelle fluidity of these solvents and improved ability to penetrate into plant tissues make these solvents even more helpful in extraction. Depending on the polarity of the target molecule, the type of matrix, and required trade-offs between environmental safety and efficacy, the choice of surfactants depend (Chemat, Abert Vian et al. 2019). In one instance, CTAB in aqueous solution provided by far better results with the use of microwaves than with the traditional approach to extracting alkaloids in the *Rhizomacoptidis* (Gao, Liu et al. 2023). All things being equal, MSAE is a fast, accurate, and sustainable means of extracting desirable molecules

with little solvent or energy consumption. It allows recovery of multiple compounds of different polarity simultaneously in a single process. The recovery of surfactants along with its cost-effectiveness and scalability to the level of scale have also remained under research despite its bright prospects. The factors such as the type of surfactant and concentration, power of the microwave, composition of solvents and the duration of extraction need to be maximized in order to maximize the application of MSAE in industrial-scale extraction of natural products(Nonglait and Gokhale 2024).

Alkaline-based microwave-assisted extraction

Alkaline MAE is a technique that is both fast and environmentally friendly and can extract proteins, phenolics and dietary fibres in a variety of biomasses using high PH and dielectric microwave heating(Capaldi 2025). It is a technique that involves the use of sodium hydroxide (NaOH) or other bases in order to establish alkaline conditions typically ranging between pH 11 and 12 to disperse the cell wall structures and solubilize target proteins(Capaldi 2025).

Compared to other more traditional alkaline or thermal extraction techniques, microwaves provide uniform and local heating that enhances the rate at which cells break down and increase mass transfer. A study on perilla seed meal, alkaline MAE performed at a pH scale of 11.5 using a power of 160 W of microwave power over 30 seconds, expanded protein yield by 10.6% and total phenolic content by 21.6% in comparison to a traditional alkaline extraction; although, bioactivity diminished a little in harsher alkaline circumstances(Kumar, Kamboj et al. 2023).

Even the use of the soft alkaline MAE with grass stalks 500 W with NaOH was capable of releasing ester linked p-hydroxycinnamic acids with moderate yields (~0.3 mg/g) most likely because of the mild extraction conditions(Bichot, Lerosty et al. 2019).

Ammonium hydroxide (NH₄OH) offers benefits on protein extractions because it volatilises better and is less difficult to eliminate unlike potassium hydroxide (KOH) which can be preferred in a particular cereal sample due to its gentler actions. Altogether, alkaline MAE is a scalable and efficient technique requiring the small amount of solvent and eliminating valuable biomolecules in a fast and efficient way.

The pH, microwave power, exposure time, and type of solvent are some important factors which should be well controlled in order to achieve

a high yield without decomposing the sensitive chemicals. Due to the fact that the process relies on the interaction of chemical disruption of the base and physical acceleration with the microwave energy, the latter is a strong instrument of biomass valorization in food, medicinal, and environmental practices(López-Salazar, Camacho-Díaz et al. 2023).

Microwave assisted Aqueous Solvents Extraction

MAE with aqueous solvents is one of the most common and environmentally-friendly extraction techniques and is commonly employed in the food, pharmaceutical, and cosmetic sectors (López-Salazar, Camacho-Díaz et al. 2023). The high dielectric constant and the high dipole moment of water as a solvent provide an effective method of microwave absorption leading to rapid internal heating and rupture of the cells. This allows the intrusion of bioactive substances into the aqueous media like polysaccharides, flavonoids and phenols.

Aqueous MAE is commonly utilized with microwave-treated plant material at controlled power (300800 w) and time (2-20 min) when the plant material has been pretreated in distilled or buffered water in order to maximize extraction yield and energy efficiency, as well as to comply with clean-label regulations. As an illustration, hot water microwave extraction of polysaccharides in *Ganoderma lucidum* showed a higher yield and bioactivity than the conventional methods(Yang, Wang et al. 2022).

Aqueous MAE has a limited number of disadvantages, such as non-polar compounds cannot be dissolved effectively in water, thermolabile compounds are likely to be destroyed during extraction, too much foam is generated in the course of extraction(Zia, Khan et al. 2022). Hybrid methods like surfactant-assisted aqueous MAE and alkaline water-based MAE can be employed to extract proteins and phenolic acids with high efficiency and volume out of plant biomass without causing them to significantly degrade under mild alkaline conditions (like Na₂CO₃) using microwave systems(Braga, Seabra et al. 2022).

Microwave assisted Organic Solvent Extraction:

One of the most universal and successful methods of organic solvent-assisted extraction is the microwave-assisted extraction (MAE), which continues to be widely used in the separation of bioactive compounds (pharmaceutical, cosmetic, and nutraceutical sectors, etc.)(Nonglait and Gokhale 2024). Ethyl acetate, acetone, methanol, and ethanol are common solvents that can dissolve

both hydrophilic and lipophilic components and dissolve the structures of the plant cells with the help of microwave radiation (López-Salazar, Camacho-Díaz et al. 2023). Recent studies have emphasized the benefits of binary solvent systems, e.g. ethanol-water or methanol-water mixtures, that combine the solubilizing properties of organic solvents and the microwave-absorbing properties of water (Dallinger and Kappe 2007). As an illustration, the antioxidant yield of flavonoid using 80% ethanol at 500 W was increased by 3040 percent in comparison with standard Soxhlet extraction (Nuerxiati, Mutailifu et al. 2022).

Ethyl lactate especially has been found to be promising in alkaloid and essential oil extraction. Still, it has issues with solvent flammability under high temperature and the possibility of degrading thermolabile materials (Abdullah, Hussein et al. 2021).

Microwave-Assisted Mixed Solvent Extraction:

Golden solvent system MAE Mixed solvent system is a highly effective green extraction method that integrates the dielectric heating ability of polar solvents such as water with the solvation strength of organic solvents such as ethanol, methanol, acetone, or ethyl acetate (Destandau and Michel 2022). The high dielectric constant of water is sufficient to enhance the rapid internal heating and disintegration of plant cells and organic solvents enhance solubilization of alkaloids, flavonoids, polyphenols, terpenes, and essential oils among other phytochemicals. Ethanol (5070) or acetone (6070) mixed with water are most often used as binary mixtures to maximize extraction efficiency, chemical stability, and microwave absorption (Gupta, Gupta et al. 2022). For example, MAE of *Camellia sinensis* and *Vaccinium myrtillus* yielded much more catechins and anthocyanins with the use of 6070 ethanol (or acetone)-water rather than absolute solvents or maceration (Pavlič, Mrkonjić et al. 2022). In the same way, the efficiency of acetone-water mixtures to recover terpenoid of *Salvia officinalis* and extract artemisinin of *Artemisia annua* was improved due to the increase in tissue penetration and a decrease in heat degradation (Aslam, Ahmadihosseini et al. 2025).

Artificial neural networks (ANNs) and response surface methodology (RSM) are two optimization tools, which enable the accurate adjustment of solvent ratios, microwave intensity, and time of irradiation to fit a particular plant matrix (Aslam, Ahmadihosseini et al. 2025). Such

mixed solvent systems continue to form the industry standard regarding the efficient and selective extraction of thermolabile compounds in the food, pharmaceutical, and cosmetic sectors, although the closed-vessel or vacuum-assisted MAE would be needed when extracting flammable solvents such as ethanol and acetone (Winterton 2021).

Microwave Assisted Deep Eutectic Solvent Extraction

Deep eutectic solvents (DESs) have become one of the promising, efficient and versatile approaches to the de-extraction of bioactive compounds in complex plant materials that are sustainable, efficient, and adaptable. Low-volatility, high-polarity, thermal stability biodegradable solvent systems called DESs are often prepared by reacting a hydrogen bond donor (glycerol, urea, or lactic acid) and a hydrogen bond acceptor (choline chloride) (Bizzi, Santos et al. 2021).

As an example, choline chloride lactic acid and choline chloride glycerol DESs have been effectively employed to extract polyphenols in olive leaves and tea trash with better results than traditional solvents (Fadel 2021). DESs led to more than 60% enhancement in yields of caffeic and chlorogenic acids of the MAE of *Helianthus tuberosus* leaves relative to ethanol water systems (Wang, He et al. 2021).

Hydrated DESs are usually prepared by the addition of minute portions of water to DES preparations, which diminish viscosity and do not affect extraction efficiency. However, the excessive viscosity of certain DES formulations can slow down the diffusion of solutes and mass transfer (Mustafa, Spelbos et al. 2021). Process variables such as the power of the microwave, exposure time as well as DES composition must be adjusted to achieve optimal yield and eliminate thermolabile chemical degradation. Despite everything, the use of DES-based MAE as a sustainable approach to phytochemical recovery in the food, cosmetic, and pharmaceutical sectors is a viable option because it combines the minimized use of energy with advanced green solvents (Eyube, Ohwoevwo et al. 2025).

Microwave Assisted Solvent Free Extraction:

Solvent-Free Microwave Extraction (SFME) is a solvent-free, eco-friendly method that is based on heating volatile bioactives and essential oils on plant material through the use of microwave heating, and only the intrinsic moisture of the plant is necessary to make steam to extract volatiles in-

situ (Yingngam, Navabhatra et al. 2021). SFME reduces its effects on the environment by removing the need of using organic solvents or additional water and simplifies the post-processing. Normally, it works with moderate power (200-600 W) and atmospheric pressure (Araujo, Périno et al. 2021). The process takes 15-30 minutes to extract, a factor that is much faster than the conventional hydro distillation (2-4 hours) and yields and retains oxygenated compounds needed to produce fragrance and bioactivity (Boukhatem, Ferhat et al. 2022).

Whereas SFME of *Thymus mastichina* essential oil yielded similar chemical and antimicrobial profiles in 30 minutes using significantly lower energy (Araujo, Périno et al. 2021), SFME of lemongrass got citral-rich oil (74) in 15 minutes, which is higher than 60% of citral obtained by hydro distillation (Boukhatem, Ferhat et al. 2022). The SFME scalability has been confirmed and its quality stability demonstrated through successful tests of industrial-scale applications using herbs such as thyme and rosemary in 75-L pilot reactors (Filly, Fernandez et al. 2014).

Chrysanthemum and *Piper longum* which have a better aromatic profile and bioactivities of essential oils of 0.19% and 0.75, respectively (Tang, Song et al. 2021).

Microwave-assisted Pressurized Hot Water Extraction

Microwave-assisted Pressurized Hot Water Extraction (PHWE-MAE) is an environmentally friendly method that involves the combination of microwave heating with subcritical water (100-250 C at 20 MPa). This changes the dielectric constant of water, decreasing the polarity of the water, and allowing the selective extraction of a wide range of bioactives without using organic solvents (Coelho 2021). The high internal heating rate of the microwaves enhances the rate of mass transfer and cell walls breakage, reducing the extraction time and conserving thermolabile chemicals. Microwave pretreatment at 445 W with 3.5 minutes of pretreatment time followed by PHWE, using response surface approach to optimization, increased the yield of anthraquinone by *Heterophyllaeapustulata* by a large margin with only one instance of pretreatment (Vázquez-Vázquez, Barajas-Salazar et al.).

Equally, in 14 minutes at 170 °C, PHWE on *Bambusa chungii* produced 22.6 percent phenolics which had strong antioxidant capacity (Deng, Chen et al. 2025).

PHWE-MAE is utilized in more and more green extraction procedures due to its low energy needs, the absence of toxic solvents, minimal environmental effects, and the ability to be applied to large-scale pharmaceutical, nutraceutical, and biorefinery processes. It is reported to provide a safe alternative to the conventional solvent-based methods of extraction (Jain, Kaur et al. 2024).

Advantages of MAE

MAE is the technology of the future in the effective, ecologically safe, and selective extraction of bioactive chemicals in plant matrices due to its numerous advantages over other conventional methods of extraction. The main advantage is it takes much faster and efficient volumetric heating eliminating extraction times by more than 90 percent in some scenarios. Phenolic extraction of *Citrus aurantium* peels was done in 3 to 5 minutes using MAE compared to several hours when using Soxhlet (Maksoud, Abdel-Massih et al. 2021). Moreover, MAE is one of the most effective methods to save solvents; researchers on *Camellia sinensis* demonstrated that up to 50% of solvents could be saved without affecting antioxidant production when compared to maceration (Luo, Zhang et al. 2020). This follows the principles of green chemistry while lowering operational costs and the environmental impact.

By its very nature being more energy-efficient than long-term conventional heating, MAE attempts to balance specific energy delivery with brief processing intervals to minimize overall electricity consumption and enhance protection of thermolabile chemicals (Singh, Johri et al. 2025). Its flexibility in open and pressurized formats, its ability to work with numerous solvents, such as deep eutectic systems and green solvents, as well as its flexibility in working on the various plant matrices, all make it industrially appealing. Furthermore, MAE systems can be improved with the help of hybridization with vacuum, enzymatic, or ultrasonic process intensification. Besides, they support high-throughput workflows because they can be easily combined with analytical systems such as GC-MS and HPLC (Caratti 2025). These synergies prove the increase in the relevance of MAE in the process of research and commercial extraction of nutraceutical, essential oils, and functional phytochemicals (Wen, Zhang et al. 2020).

Limitations of MAE

Though demonstrated to be very effective, MAE has a number of technical and practical

limitations which may prevent it becoming a popular application in industry. Low penetration depth and non-homogeneous distribution of microwave radiation especially in dense or heterogeneous plant matrices could lead to hot spots and cool regions that compromise the homogeneity of extraction and destroy thermolabile chemicals (Nonglait and Gokhale 2024). Since non-polar solvents, such as hexane do not possess the necessary dielectric properties to efficiently absorb the microwave energy, unless co-solvents or absorptive carriers are utilized, MAE systems are inherently restricted to polar or semi-polar solvents such as ethanol, water, or deep eutectic solvents. These also restrict their use with lipophilic compounds.

Furthermore, slurry-like residual contents may tend to complicate the processing of the post-extraction process especially when using high moisture or finely crushed plant materials. Such residues require further treatment such as centrifugation or filtration. Homogeneous electromagnetic fields and uniform temperature distribution in large volumes of samples may be hard to maintain during scale-up and this decreases reproducibility in batch or continuous processing (Li, Radoiu et al. 2012). Also, careful manipulation of variables, including the power, time and temperature of the microwave, is necessary to prevent the degradation of extracting heat-sensitive compounds, including anthocyanins or some polyphenols. This regularly necessitates iterative optimization techniques or predictive modeling techniques (Tian, Bai et al. 2025).

Lastly, microwave reactors, microwave sensors, and other pressure-handling components are expensive to install and purchase, which restricts MAE in terms of offering its services to large-scale operation or well-endowed research facilities. These restrictions collectively demonstrate the importance of the utmost care of system calibration, solvent choice, and integrating the whole process to reach the maximum potential of MAE without sacrificing its safety, efficacy, and scalability.

Scaling up Microwave-Assisted Extraction (MAE):

MAE is a popular and green method of extraction of bioactive substances of plant materials. The technique consists of rapid dielectric heating as its main principle or core component, a technique that utilizes microwave energy to disrupt cell structures and increase solvent penetration, increased yield of extraction and decreased

processing time. The solvent-to-material ratio (SMR) is one of the important factors in MAE because it influences the solvent saturation, the solute solubility, and diffusion (Li, Radoiu et al. 2012). In spite of the fact that consistent research has found out that a SMR of 20:1 to 30:1 mL/g usually produces some optimum yields of flavonoids and phenolics, the high amount of solvent can dilute the extract or decrease the amount of energy efficiency.

Likewise, heating uniformity and energy absorption are regulated by microwave power. Typically, optimal power level is 300-600 W since it allows extraction to be done effectively, without the risk of further raising the likelihood of thermolabile chemical degradation (Zhou et al. 2024). Beyond this point, excess energy may lead to localized overheating, solvent boiling, and a decrease in bioactive integrity. Phytochemicals are greatly affected by temperature and solubility. Most polyphenols and flavonoids are extractable at 50 to 80 °C; at higher °C, thermal degradation tends to take place (Antony and Farid 2022).

Because thermal strain on the system is enhanced by longer exposure times, temperature and power are directly proportional to the time of exposure to microwave. 3 to 10 minutes is the most common optimum irradiation time; past that, the yields level off or start to deteriorate, because of heat and oxidative damages. Stirring or agitation is required in the distribution of uniform microwave in the non-rotating vessels. To achieve repeatable extraction, gentle or periodic stirring promotes uniform heating, non-precipitation of particles, and increase transfer of mass (Cárdenas and Lucena 2017).

In order to optimize heating and safety, contemporary platforms like CEM MARS X or Milestone ETHOS provide vessel recognition technologies, magnetic stirring, and adjustable power (de Castro, Fernández-Peralbo et al. 2012). By using specific liners or inserts, these instruments can be modified to work with both polar and non-polar solvents and facilitate integration with analytical workflows (Byrne, Jin et al. 2016).

Regarding sustainability, MAE systems have adopted the use of the green solvents like Deep Eutectic Solvents (DESSs), which are mixtures of hydrogen bond donors and acceptors to form tuneable, biodegradable and microwave capable of media. Despite the preference of hydration to maintain efficiency of mass transfer in DESSs because of high viscosity, they enhance extraction

selectivity, permit solvent recycles, and decrease environmental impact (Isci and Kaltschmitt 2022).

The other green adjustment is Solvent-Free Microwave Extraction (SFME) that does not require any additional solvents because natural moisture is used to create steam in situ to extract the essential oils. The yields of SFME are similar or better than the conventional hydro distillation, preserving the integrity of volatile chemicals in a fast (15-30 minutes) scalable and energy-efficient way (Augoye, Sobowale et al. 2024). Although capital investment is a hindrance, as well as technical complexity, MAE is increasingly becoming a viable option that can be used in food technology, pharmaceuticals, nutraceuticals, and cosmetics because of its high energy efficiency, low solvent usage, and green chemistry and legislation.

II. Conclusion

MAE is an essential green extraction technique, which addresses the gap between the traditional system of extracting the plants extraction and the requirements of the modern processes which are environmentally friendly. MAE employs the dielectric attributes of solvents and matrices to enhance the recovery of the target bioactive chemicals by heating the interior of the vessel swiftly using the thermal radiation of the microwave (Nonglait and Gokhale 2024).

Physicochemical and operational parameters play a very important role in the functioning of MAE. The direct effect on the percentage of compounds liberated and dissolved is dependent on heat, irradiation duration, solvent polarity, solvent to solid ratio, microwave power, and characteristics of the plant matrix (Ramesh, Shankar et al. 2024). Also, such aspects as the surface area of contact and the stirring rate control the solvent-matrix contact and heating homogeneity. Although their contributions to the overall success of MAE in lab and industrial environments are modest, all these factors put together, shape success. By further optimization of these parameters, nowadays researchers can adapt MAE techniques to any type of plant-derived phytochemical, such as phenolics, terpenes, alkaloids, saponins, essential oils, etc. (Darwin, Valmon et al. 2025).

Complex versions of MAE have enhanced its versatility compared to the usual version of MAE. As an example, Nitrogen-Protected MAE (NPMAE) provides a regulated atmosphere to avoid oxidative breakdown of delicate morphology, including flavonoids and antioxidant. Vacuum MAE (VMAE) allows the preservation of aromatic

components and thermolabile volatiles in the process of low-temperature extractions under reduced pressure (Chan, Yusoff et al. 2011). In the meantime, Ultrasonic MAE (UMAE) and Dynamic MAE (DMAE) enhance the distribution of microwave energy and cell destruction, through the introduction of physical agitation cavitation. These developments have enabled the extraction of delicate complex bioactives that could not be extracted with either the static or the high-temperature system (Chan, Yusoff et al. 2011).

Green potential of MAE has progressed tremendously due to the development of new solvent systems. A shift in the choice of solvents is notable because of the use of the Ionic Liquids (ILs) or Natural Deep Eutectic Solvents (NADES), which are chosen due to their low toxicity, biodegradability and thermal stability along with their solubility (Kudlak, Owczarek et al. 2015). With MAE, these solvent solutions can be used to selectively extract bioactives with a minimum of the negative environmental impact. Solubilization of hydrophilic and hydrophobic components using an aqueous dispensing agent has also been proven with the use of MAE solubilized with a surfactant to create a microenvironment of micelles (Yu, Meng et al. 2020). Likewise, lignin-cellulose complexes of hard plant matrices could be degraded by alkaline-based MAE especially effectively. When combined with a microwave energy, supercritical CO₂ is used to extract volatile oils in solvent-free or low solvent.

Selectivity and polarity tuning has become possible with the introduction of mixed solvent systems, such as ethanol-water or methanol-acetone mixtures. Together, these developments confirm the fact that solvent engineering plays as an important role in ensuring maximum outcomes of MAE as that of temperature control (Barwick 1997).

Another major contributor to the development of MAE is the increased complexity of reactor designs and instrumentation. The hardware has greatly increased in complexity, starting with single-mode close-vessel microwave reactors in the analytical lab, through multimode, continuous-flow systems in the industry (Gude, Patil et al. 2013). To provide reproducibility and control of the process, modern systems have automated temperature and pressure sensors, magnetron controllers, and programmable software interfaces. Still, it is difficult to transition to large-scale industrial application. The key engineering limitations include solvent recyclability, equipment cost, even distribution of energy and microwave depth of penetration (Clarke, Tu et al. 2018). Designing

MAE systems that provide reliable outputs at high throughputs remains an active area of research and development, particularly when it comes to the manufacturing of such products as herbal formulations, nutraceuticals, aromatherapy, or functional food (Singh, Johri et al. 2025).

MAE has disadvantages in spite of its numerous benefits including reduced solvent consumption, improved yield, shortened extraction time and energy efficiency. As an example, low-polar solvents do not absorb in microwave frequencies without modification, and their viscosity may stop mass transfer as in the case of ILs or NADES (Chevé-Kools, Choi et al. 2025). This capital cost might discourage small and medium-sized companies when using microwave reactors. In addition, there are no set operational protocols making direct comparisons between studies difficult and hindering the adoption of the industry. Nevertheless, such problems are already being tackled actively with the help of a complex of computer modeling, process simulation, and pilot-scale optimization (Chevé-Kools, Choi et al. 2025).

Industrial relevance of MAE is constantly increasing with regard to scalability. Food and pharmaceutical sectors are progressively embracing hybrid systems that combine MAE with conventional lines of extraction or even downstream processing units (Nonglait and Gokhale 2024). Businesses are laying more emphasis on solvent recovery, extract concentration and microwave-assisted distillation systems, which increases the economic viability of MAE. With global standards regarding the use of solvents, emissions and purity of products, companies are looking into the future and will favour MAE, as it is compatible with clean-label and extraction without residues. Simultaneously, the university research is enhancing MAE to suit the needs of personalized medicine, green chemistry, circular bioeconomy, and zero-waste technologies (Shukla and Mallick 2025).

Altogether, MAE can be critically important to development of eco-friendly extraction technologies. It is found at the crossroads of thermodynamics, solvency engineering, process optimization, and sustainability science (Nonglait and Gokhale 2024). Daily changing to meet the demands of various chemicals, matrices, and industries, MAE is demonstrating that it is not only an extraction toolkit is a platform to innovate.

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Conflict of Interests

The authors declare that they have no conflict of interest regarding the publication of this publication.

Author Contribution

JR conducted the primary literature survey, organized thematic content, and drafted the manuscript. FJ contributed to comprehensive literature collection, critical analysis of reviewed studies, and refinement of the manuscript. TK assisted in structuring the review framework, verifying sources, and supporting manuscript revisions. PM supervised the work, provided conceptual direction, ensured academic rigor, and approved the final version of the manuscript.

Data Availability

Not Applicable

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