Microwave-Assisted Extraction of Phytochemicals

S. Nithya, Rohan R. Krishnan, Nachiketha R. Rao, Kamakshi Naik, N. Praveen, and V. L. Vasantha

Abstract Microwave-assisted extraction (MAE) has emerged as a promising technique for the extraction of phytochemicals and has received substantial scientific attention in recent years. MAE involves the utilization of microwaves to heat the sample, which facilitates the release of bioactive compounds from the plant matrix. MAE offers several advantages over traditional extraction methods, including faster extraction times, higher extraction yields, and reduced solvent consumption. To improve the efficiency of the extraction process, research has concentrated on optimizing various parameters, including the extraction temperature, extraction time, and solvent type. Additional studies have investigated the effect of MAE on the chemistry and bioactivity of the extracted phytochemicals. Several classes of phytochemicals, including phenolic compounds, flavonoids, and alkaloids, have been successfully extracted using MAE. These compounds possess various biological activities, such as antioxidant, antimicrobial, and anticancer properties. Essential oils from aromatic plants have also been extracted using MAE, which is widely employed in the food, cosmetic, and pharmaceutical industries. Despite its many advantages, the major challenge in the application of MAE is the potential degradation of the extracted compounds due to the high-temperature and high-pressure conditions during extraction. Additionally, the cost of microwave equipment and the need for specialized expertise may stunt its widespread adoption. In diverse omics disciplines, MAE shows promise, notably for the development of analytical platforms for research in genomics, proteomics, metabolomics, and related subdisciplines. Nonetheless, more investigation is required to optimize the extraction conditions and guarantee that the chemical makeup and biological activity of the isolated phytochemicals are preserved.

Keywords Microwaves · Phytochemicals · Natural pigments · Omics · Pharmaceuticals

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S. Nithya · R. R. Krishnan · N. R. Rao · K. Naik · N. Praveen · V. L. Vasantha (✉)
Department of Life Sciences, CHRIST (Deemed to be University), Bangalore, India
e-mail: vasantha.vl@christuniversity.in

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1 Introduction

For the separation, identification, and usage of valuable chemicals from various plants, extraction is a crucial step. Depending on the characteristics of the desired chemical, a suitable technique must be chosen in order to achieve the highest yield and purity. Compounds from plants are extracted using a wide range of chemical and mechanical procedures, including solvent extraction and steam distillation. The extraction of essential oils, fats, and oils is now done using Soxhlet, hydrodistillation, and alcohol-maceration methods. Reproducibility is a significant problem because these techniques involve manual operations. Low extraction yields are the result of the heating process degrading thermally sensitive components. The mentioned restrictions, along with the sharp rise in demand for bioactive components, essential oils, fat, and oils, have motivated the need for appropriate, selective, economical, and environmentally friendly extraction technologies that are quick and yield more (Stévigny et al. 2007).

Many efforts have been made to enhance the Soxhlet extraction in order to shorten the extraction time, use less solvent, and do away with the requirement for concentration and evaporation at the end of the extraction. Randall presented a three-step extraction process that includes boiling, rinsing, and solvent removal as a significant enhancement to the Soxhlet extraction equipment (Randall 1974). It is well known that microwave energy, with a frequency of 2.45 GHz, significantly affects the speed of numerous processes in the chemical and food industries. The use of microwave dielectric heating in analytical chemistry has garnered a lot of attention due to the shorter analysis times, easier manipulation, and improved purity of the end result. All of the applications that have been documented have demonstrated that microwave-assisted solvent extraction (MAE) is a practical substitute for traditional methods for such matrixes. The key advantages are the decreases in solvent, energy, and extraction time (Virot et al. 2008).

2 Fundamentals of Microwave Extraction (Microwave Theory)

Gedye, Giguere, and Ganzler were the first to discuss the use of microwave energy in chemical laboratories for organic synthesis and the extraction of biological matrices for the creation of analytical samples, respectively, in 1986 (Ganzler et al. 1990). Ultrasound-assisted extraction (UAE) is a technique that is around 35 years older than MAE. The huge potential of this non-conventional energy source for synthetic, analytical, and processing applications has nevertheless been investigated in great detail by numerous laboratories. Dielectric heating has been used in synthesis and extraction thus far, and over 7000 and 2000 articles, respectively, have documented this utilization. Early investigations, which did not measure the temperature or power, described the microwave-assisted extraction in a screw-capped vial with a volume of only 3 mL using conventional microwave ovens. Techniques for extracting bioactive chemicals from plants were developed. Microwaves (MW) are electromagnetic radiation with frequencies ranging from 300 MHz (radiofrequency radiation) to 300 GHz. In chemistry research, 2.45 GHz and 915 MHz are employed as frequencies for lab equipment and industrial equipment, respectively.

The following categories can be used to group microwave interactions with materials: (Gupta and Wai Leong Wong 2007)

Opaque Materials Microwave applicators are made of opaque materials, which are often conducting materials with free electrons, such as metals, that reflect electromagnetic waves but do not allow them to pass through.

Transparent Materials Transparent materials, such as low-loss dielectric materials or insulating materials like glass, ceramics, and air, allow microwaves to travel through easily with minimum attenuation. These materials are used to make reactors that are put within microwave applicators.

Absorbing Materials Materials that absorb energy include those with conductivity and insulating characteristics. These materials, which are the focus of microwave extraction, are commonly referred to as high-loss dielectrics or high dielectric loss materials because they absorb electromagnetic energy and convert it to heat.

Since it is lower than the typical ionization energies of chemical bonds (3–8 eV) or even hydrogen bonds, the MW photon energy corresponding to the frequency used in microwave heating systems, ranging from 3.78×10^{-6} to 1.01×10^{-5} eV, acts as a non-ionizing radiation that has no effect on the molecular structure (0.04–0.44 eV). The interaction with materials happens by heating them since microwave radiation is non-ionizing. Only substances that can take in microwave energy can be heated. Heating can come from dielectric and magnetic losses caused by interactions between the microwave's electric and magnetic field components and the materials. For non-metal materials, the importance of the dielectric losses is greater. Ionic conduction and dipole rotation serve as their foundations. Ionic conduction, the first of these, is the term used to describe the induced electrophoretic migration of charge carriers (such as ions and electrons) when the electric field of the microwaves is present. The migrating ions and the medium experience "friction" as a result of the migration, and this can result in heating. When dipolar molecules strive to align themselves with the alternating electric field in a medium created by microwaves, the second principle, known as dipole rotation, takes place (Zhang et al. 2011). These dipolar species' oscillation causes them to collide with nearby molecules, which generates heat. Temperature is a major factor in determining the relative importance of the energy conversion mechanisms, dipole rotation, and ionic conduction. Ionic conduction rises with rising sample temperature, whereas dipole rotation decreases for small molecules like water and some other solvents. This means that when microwave energy is used to heat a sample that contains both ionic and polar chemicals, the heating is first dominated by the contribution of dipole rotation and, as the temperature rises, it becomes dominated by ionic conduction. The mobility, concentration, and sample relaxation time of the ions all affect the relative contribution of these two heating mechanisms. This information is crucial for the MAE (Lee et al. 2016). The extraction yield drastically alters when the plant material's microwave absorption capacity exceeds that of the solvent. Having an estimate of the medium's reaction to microwave radiation is crucial for achieving the best possible microwave applicator design (permittivity). This information will enable the process to be characterized (including its heating rate, penetration depth, and temperature distribution, among other things), and it will aid in understanding its behavior (Vinatoru et al. 2017).

MAE extraction technology has been used for both large-scale and laboratory applications. The MAE method has been applied in recent years to isolate essential oils, fats, and oils. In terms of speed, safety, and cost, microwave technology has been found to be an effective extraction method (Bélanger et al. 1997). The closed-vessel MAE system and the open-vessel system comprise the two types of MAE systems. Closed containers are used for extraction. Whereas open-vessel systems are for extractions of target chemicals at high-temperature and high-pressure conditions performed under circumstances of atmospheric pressure.

The selection of the proper solvent is a key element that influences extraction. The choice of solvent is mostly determined by the desired analyte's solubility, the solvent‘s capacity to interact with the matrix, and its microwave absorption. The chosen solvent should be compatible with additional chromatographic analysis steps and should have a high selectivity of the target analyte over matrix components. Transparent solvents are not heated in the microwave, and those that have a high capacity for absorption are heated more quickly to speed up the extraction. Hexane is regarded as a top-notch solvent for absorbing microwave energy (Virot et al. 2008). For the best extraction yields, researchers have combined solvents with high and low microwave absorbabilities.

3 Instrumentation of the Microwave Extraction

Instrumentation systems for microwave-assisted extraction and its laboratory application are available in two varieties (Pastor et al. 1997; Luque-García and Luque de Castro 2004), namely:

(a) Closed extraction vessels/multimode microwave ovens.
(b) Focused microwave ovens.

Controlled pressure and temperature drive extraction in a closed extraction vessel/multimode microwave oven. In contrast, in focused microwave-assisted Soxhlet or solvent extraction (FMASE), as the name implies, only the portion of the extraction vessel containing the sample is targeted for microwave irradiation. Closed-vessel and focused vessel systems are both commercially available as multimode and single-mode or focused systems (Luque-García 2003). A multimode system provides for the random distribution of microwave radiation throughout the microwave cavity, ensuring that every zone in the cavity and the sample is evenly irradiated. Focused MAE systems allow subjecting the sample to a much restricted and focused delivery of microwave radiations under a strong electric field. Domestic microwave oven behaves as a modified multimode open-vessel extraction system (Moen et al. 2012).

The sample and solvent are also situated within the sealed vessel, which is commonly made of microwave-transparent materials such as polyether imide or trifluoromethoxy polymers in the pressurized MAE system (Fig. 1). The following are the general operating conditions for MAE:

- Pressure: 200 psi
- Temperature: Between 110 °C and 145 °C
- Power Setting: 100% at 900 W

3.1 Fundamental Components in an MAE Device

The microwave extraction assembly is composed of four major parts:

1. Magnetron/ Microwave Generator: Used to generate microwaves.
2. Wave Guide: Used to direct the microwaves from the source to the microwave cavity.
3. Applicator: Contains the sample holder which houses the sample.
4. Circulator: Used to regulate microwave propagation only in the forward direction.

In the case of multimode systems, the applicator is a closed cavity within which a random dispersion of microwaves occurs (Kristenson et al. 2006). Beam reflectors or turntables aid in the consistent distribution of microwave energy inside the cavity, regardless of sample placement position. The microwave waveguide serves as the applicator in focused microwave systems, and the extraction vessel is placed immediately in the cavity. Only a few inches of the vessel's bottom are exposed to microwaves, and because glass is microwave-transparent, the upper area of the vessel remains cool. As a result of the microwave‘s integrated architecture, an effective condensing process occurs (Figs. 2 and 3).

3.2 Advantages of Closed-Vessel Systems

Higher temperatures can be obtained in a closed-vessel system due to greater pressure inside the vessel, which raises the boiling point of the solvents utilized. In a closed vessel system, there is virtually no loss of volatile compounds and just a little

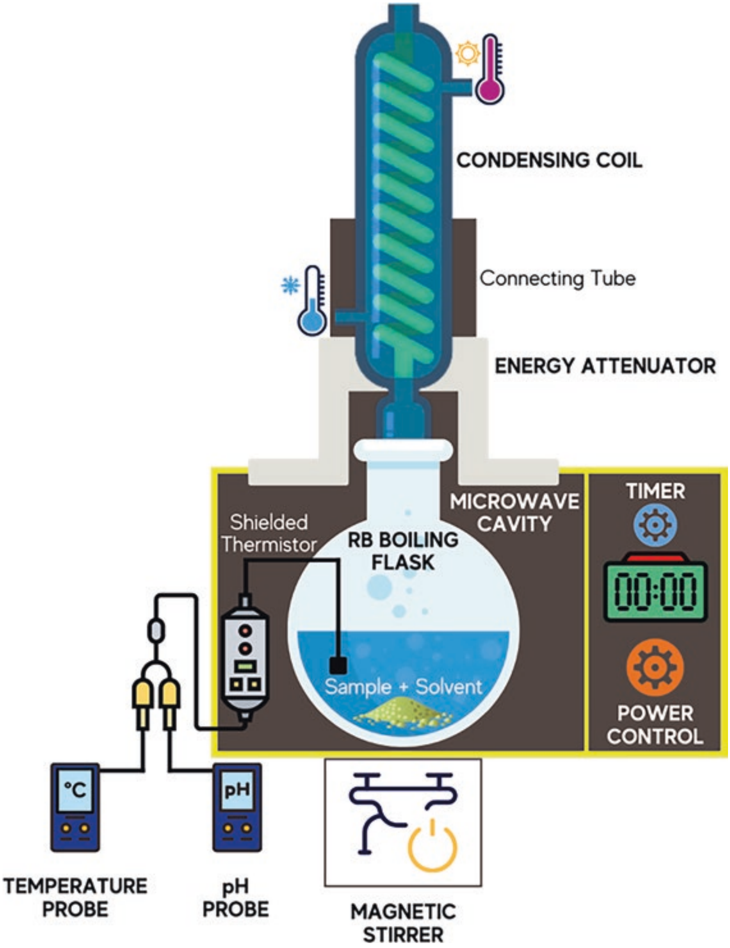

Fig. 1 Scheme of a modified multimode domestic microwave oven for MAE (open-vessel extraction)

amount of solvent is required. Because there is no need to add solvent/s frequently, the risk of air-borne contamination is reduced. The vessel is capable of containing all the potentially hazardous fumes produced during an acid microwave extraction and doesn't require any additional provision for the same (Tatke and Jaiswal 2011).

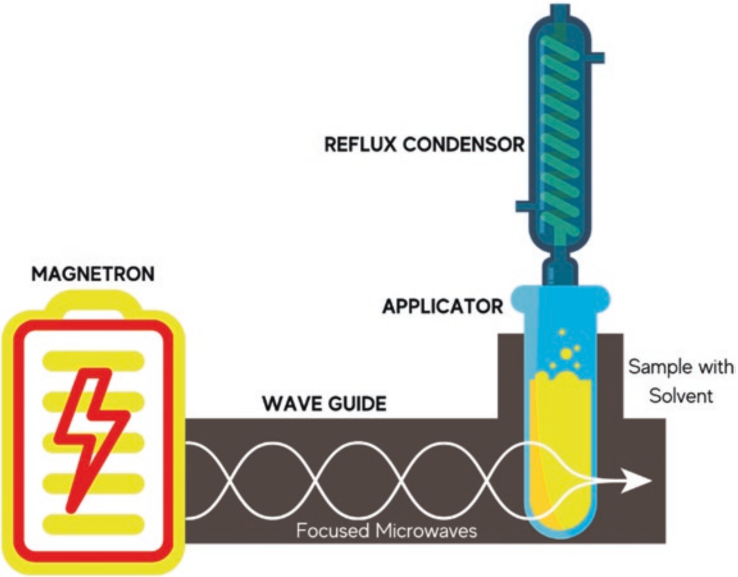

Fig. 2 Schematic view of focused microwave oven

3.3 Limitations of Closed-Vessel Systems

A closed-vessel system's shortcomings include the risk of using high pressures and the limited volume of samples that can be processed. The material utilized for vessel construction, such as PTFE (polytetrafluoroethylene), does not allow for high temperatures, and when utilizing volatile compounds, the vessel must be opened only after a cooling process to avoid the loss of extracted volatile elements. The high pressures used in closed-vessel systems pose a safety risk as they are prone to explosions. The single-step procedure also excludes the addition of reagents or solvents during the operation of the system (Tatke and Jaiswal 2011).

3.4 Atmospheric Pressure or Open MAE System

Atmospheric pressure or open-vessel systems offer much more effective microwave sample preparation than closed-vessel systems. The usage of atmospheric pressure systems has several substantial advantages over pressurized-vessel systems (Tatke and Jaiswal 2011), including:

(a) Open vessels have increased safety as they can be operated at atmospheric pressure and the reagents can be added at any time during the treatment.
(b) The oven containers can be made of PTFE, glass, or quartz, and surplus solvents can be easily removed.

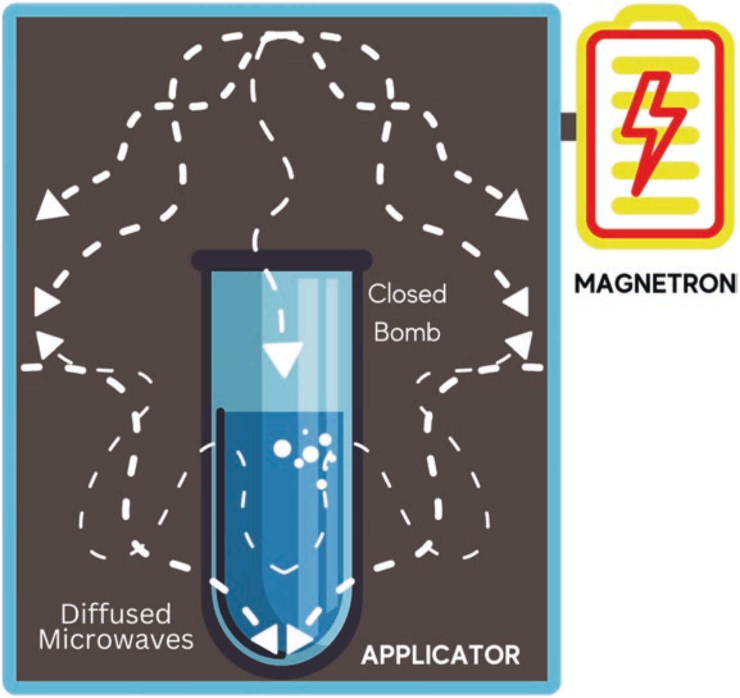

Fig. 3 Schematic view of multimode microwave oven

(c) The instrument's main advantage is its capacity to process huge samples without the need for a cooling process.
(d) The equipment is inexpensive, and complete automation with open-vessel operation is possible.
(e) It has the ability to go through leaching cycles until quantitative removal of the target species is achieved.
(f) The atmospheric system is best suited for thermolabile species as it utilizes lower temperatures compared to closed-vessel systems.

Notwithstanding their many benefits, open-vessel systems have significant shortcomings (Tatke and Jaiswal 2011), which are as follows:

(a) Methods employed in open-vessel systems are typically less precise than those used in closed-vessel systems.
(b) The open-vessel system cannot process many samples at the same time, but closed-vessel systems can handle 10 to 14 samples at a time.
(c) Open-vessel systems require longer extraction durations to achieve extraction efficiencies comparable to those of closed-vessel systems.

4 Scaleup of Microwave-Assisted Extraction

Although MAE has been successfully employed for several years and laboratory studies have shown promising industrial potential, the commercialization of this technology seems very stale. Environment Technology Centre (ETC) and Environment Canada made the first step towards the scale-up of MAE technology. The instrumentation is represented in Fig. 4. As depicted, the system is a continuous process where materials and solvents are pumped into the TEFLON tube located in a microwave cavity. Within the cavity, microwave-assisted extraction occurs. This flowing continuous process allows this technique to be scaled up to 0.5 tonnes/hr. with a microwave power of 6 kW. System analyses have shown that the continuous-flow pipe system used for this technique can only be applied when the temperature is below the boiling point of the solvent (preferably nonpolar) used for the extraction with a mechanism given by Paré and Bélanger in 1997 (Bélanger et al. 1997). Notwithstanding, in most cases, the extraction is performed in reflux conditions for a short duration (a few minutes to hours) where the equipment cannot be employed. In such cases, a batch-fed MAE system equipped with a condenser is much more economical (Dai 2006).

5 Factors Influencing Microwave-Assisted Extraction

When we speak in terms of extraction procedures, there are various methods that can be followed. One of the most commonly followed extraction method is microwave-assisted extraction. In this method, there are various factors which will

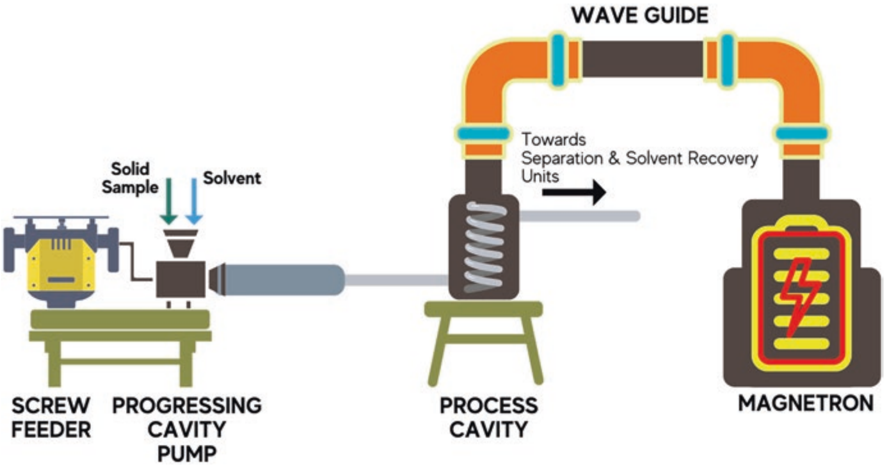

Fig. 4 Schematic diagram of a scaled-up MAE equipment

influence the extraction procedure of which some will accelerate the process and others will hinder the process of extraction (Bagade and Patil 2019).

Here are some key factors which will influence the process of extraction:

- A blend of microwave-assisted solvents should be used for the isolation of specific active compounds from the plant sample. This helps to obtain a good yield (Bagade and Patil 2019).
- Time of heating (temperature) during extraction is a very important factor because if more heat is provided then the main elements to be extracted may also get degraded. The temperature should be optimized and generally set in a range of 60 °C to 120 °C (Llompart et al. 2019).
- The microwave power should be appropriate or else will lead to the loss of plant constituents.
- Extraction efficiency of microwave-assisted extraction is affected by the particle size of the matrix (Bagade and Patil 2019) (Fig. 5).

6 Microwave-Assisted Extraction of Fats and Oils

A group of lipids known as acylglycerides, or esters in which two or three fatty acids are linked to a glycerol molecule to create monoglycerides, diglycerides, or triglycerides, respectively, are collectively referred to as fats. Triglycerides, which are triesters of glycerol and fatty acids and can either be solid or liquid at room temperature depending on their specific structure and composition, are the most

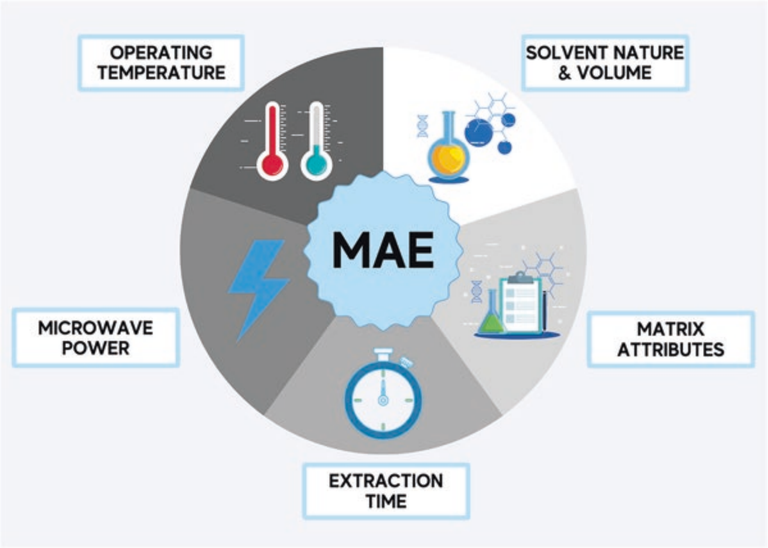

Fig. 5 Factors affecting microwave-assisted extraction of herbal matrices

prevalent types of fats. The terms "oils," "fats," and "lipids" are frequently used to refer to fats, but they typically refer to lipids that are liquid or solid at room temperature, respectively. The main sources of raw materials with extractable fats and oils are either plants or animals. A unique process is used for each raw material to produce ambient-temperature solid fats made from plant sources (such as cocoa butter, coconut fat, and palm butter). These fats are commonly utilized as fat filling in the food industry (e.g., cocoa butter in the chocolate industry) (de Castro et al. 2012).

Olives are an example of a fruit from which vegetable oils are derived (e.g., sun flower, soybean, corn, cotton). Fruit or seed oils are used for frying in both domestic and commercial settings (de Castro et al. 2012). Seed oils can be used to make margarine by hydrogenating them to raise their melting point. Additionally, albeit less frequently, edible oils can be made from grape seeds and dried fruits like pecans, hazelnuts, or almonds (a by-product of wine production). The cosmetics sector also makes use of several vegetable fats and oils. Linseed oil is also utilized in varnishes and paints because of its high polyunsaturated fatty acid content and semidrying qualities.

7 Types of MAE Extractants

Depending on the individual extractant, there are a variety of methods by which extraction under heating might occur. The sample can therefore be submerged in a single solvent or a mixture that can effectively absorb large amounts of microwave energy (mechanism I). As an alternative, the sample can be extracted into a mixture of solvents with a changeable ratio of both high and low dielectric losses (mechanism II). A sample with a significant dielectric loss can also be extracted using a solvent that is transparent to microwaves (mechanism III). Using specialized bars made of a chemically inert fluoropolymer can achieve heating if the sample and extractant are both transparent to microwaves (mechanism IV). Usually, one of these mechanisms—or a combination of them—is used for solute extraction and partitioning.

In order to assure the quantitative extraction of both neutral lipids and membrane-associated polar lipids, the analytical extraction of lipids from tissues necessitates the use of an extractant or extractant mixture that is sufficiently polar. The solvents that are most typically employed for MAE of lipids are mixtures of n-hexane and acetone (Lopez-Avila 1999). However, combinations of ethyl acetate and cyclohexane have also proven successful for tissue extraction. The ethyl acetate/cyclohexane azeotrope has a composition that is approximately equal in volume (54:46) and a boiling point that is 23 °C higher than the n-hexane/acetone mixture's boiling point at 72.8 °C (Shackelford and Alexander 2000). Additionally, it doesn't require a microwave transformer to be heated directly because it has a high enough dielectric constant. It also performs a dual function since it functions as a nonpolar system but accepts some water. Water in the sample evaporates, breaking down the cell's structure and enabling the separation of lipids from their interaction with lipoproteins and cell membranes. From this perspective, having water in the sample is beneficial for speeding up extraction (particularly under microwave irradiation). Water, on the other hand, makes the extraction solvent more polar, which reduces its effectiveness and, potentially, lipid yields. Aqueous tissue samples are often dried before extraction because of this. The debate over whether to use less toxic or nontoxic solvents in place of toxic ones like n-hexane has been reignited by the current trend toward green processes in extraction (Virot et al. 2008). One example is the discovery that limonene, a significant component of the citrus fruit industry's by-products, is more effective than n-hexane for the MAE of oil from olive drupes (de Castro et al. 2012).

8 Microwave-Assisted Extraction of Antioxidants

Without endangering essential molecules, antioxidants interact with free radicals to stop chain events, such as those that lead to lipid peroxidation. Balance reactive oxygen species (ROS) by eating foods high in antioxidants to reduce such health hazards.

In order to extract high-quality antioxidant extracts from a range of plant matrices, microwave-assisted extraction (MAE) is a very helpful technique. Its benefits come from microwave (MW) heating, which is quick and efficient since heat is supplied directly to the material. As a result, phytochemical substances are released from plant cell compartments more rapidly and easily (Camel 2000). Additionally, MAE operations take much less time and use less solvent than Traditional Solvent Extraction. The most efficient parameters in the microwave-assisted extraction process were determined to be temperature, microwave power, solvent concentration, solid-to-solvent ratio, and extraction time (Hayat et al. 2009). A closed-vessel microwave technology is generally utilized, which automatically adjusts power to balance temperature variations, and the temperature is optimized rather than the power. According to temperature variations, the system-applied microwave power is in the range of 0 to 1500 watts (Şen et al. 2019).

Response surface methods is used to optimize the key parameters, including extraction temperature, extraction time, solvent concentration (ethanol in water), and solid-to-solvent ratio. The extraction efficiency for antioxidants rose as the ethanol content of the water decreased from 80% to 58%, whereas there was little change at lower concentrations. It is believed that ethanol breaks the link between antioxidant chemicals and plant matrix while water acts as a plant-blowing agent. The concentration of 58% ethanol in water was found to be the ideal solvent composition, and the mixture of water and ethanol was found to be the most effective solvent for the extraction of antioxidants. For a high extraction yield, the ethanol concentration in the water should have a limiting value to speed up the damage to the plant cell membranes. However, once the critical ethanol concentration is reached, protein coagulation and impurity extraction may take over as the main factors that negatively affect solvent penetration (González and González 2010). The solvent ratio of ethanol to water is found to have a statistically significant impact on extraction yield, reducing power, and total phenolic content for lemon grass, galangal, holy basil, and rosemary. Solvent concentration is the parameter that has the greatest impact on MAE antioxidant yield.

Because the analytes are more soluble in the matrix's active sites at higher temperatures, extraction efficiencies rise as a result. Additionally, the analytes can be dissolved by the solvents at higher temperatures, and as the temperature rises, the surface tension and viscosity of the solvents both decrease, improving sample wetting and matrix penetration, respectively. The extraction of antioxidants is said to increase with temperature in the literature, while structural disintegration begins at high temperatures. High temperatures should also not be used for safety and energy efficiency reasons. Therefore, the ideal working temperature may be 78 °C (Şen et al. 2019). The MAE system offers advantages over traditional extraction methods due to features like multiple sample extraction, the capacity to work in closed vessels beyond the boiling point, speed (minutes), simplicity of use, automatic temperature control using power at various voltages, and high extraction efficiency. The MAE approach is therefore probably a significant alternative method for the easy, affordable, quick, and highly successful extraction of antioxidants from plants (Dorta et al. 2013).

9 Extraction of Natural Pigments by Microwave-Assisted Technology

Nearly all plant parts, including leaves, flowers, fruits, seeds, and roots, can be used to make natural colorants and dyes. Because chlorophyll can transform sunlight into chemical energy through photosynthesis, green is thought to be the hue that is most frequently found in plant leaves. In addition to shielding plants from natural predators, other colors in plants can also draw in insects or other creatures that can act as intermediaries in pollination and ultimately reproduction (Dangles 2012).

In order to make our living world vibrant and colorful, it is important to note that all of these natural hues can be utilized to add color to an infinite range of products (textiles, food, varnishes, cosmetics, etc.). The majority of the color compounds that make up natural pigments are from one or more of the following groups: carotenoids, anthocyanins, betanin, chlorophyll, curcumin, and flavonoids (Velíšek et al. 2008). Additionally, chromophores and auxochromes are the two main chemical groups that make up a pigment molecule, according to chemical studies of pigment. The chromophore is typically compared to an aromatic ring with unsaturated bonds because of its coloring property, and the number of unsaturated bonds determines the color intensity. In order to impart color, the auxochrome can aid in combining the pigment molecule with the substrate (Siva 2007). In order to improve the aesthetic value of foods, colorants have been widely utilized in a variety of food products. The use of natural colorants and dyes has been rapidly declining as a result of rising market demands, which have led to an increase in the usage of artificial colorants and dyes made from petrochemical sources. However, due to its benefits to human health, safety, and the environment, people choose to utilize natural colors (Velíšek et al. 2008). Natural colors haven't, however, been a commercial success due to several technical issues (lack of extraction knowledge, challenging plant gathering, etc.). The greatest class of naturally occurring colorants are carotenoids. In fact, carotenoids, which are orange-red pigments found in many plant species including tomato, orange, and carrot as well as in some animals, make up a large portion of the natural food colors (Dangles 2012).

A chain of isoprene units makes up the structure of carotenoids. The number of distinct carotenoid molecules has increased to above 500. With at least 40 carbon atoms and a long chain of carbon–carbon conjugated double bonds, carotenoids are hydrophobic compounds. Because carotenes only contain carbon and hydrogen and xanthophylls also contain oxygen atoms, they can be distinguished from one another in the carotenoids class (Gedye et al. 1986).

9.1 Recovery of Natural Pigments by Microwave Assistance

In order to improve the aesthetic appeal of foods, colorants have been utilized for a very long time in a variety of food products. The use of natural colorants and dyes has rapidly decreased as a result of rising market demand, which has led to an increase in the usage of artificial colorants and dyes made from petrochemical sources. Although several technical issues (lack of extraction knowledge, difficulty in plant gathering, etc.) have stopped natural colors from being successful commercially, people are eager to utilize them because of their health, safety, and environmental benefits. One of the cutting-edge extraction methods, microwave-assisted extraction, has been used to get beyond natural color extraction.

Red raspberries were processed by Sun et al. using the MAE technique to extract anthocyanins (Acys) (Sun et al. 2007). Twelve different types of Acys were successfully extracted without causing any damage to the chemical structure, and the compositions of the extracted Acys were comparable to those obtained using traditional solvent extraction (Liazid et al. 2011). Additionally, Liazid et al. created a new technique for analyzing anthocyanins in grapes and discovered that the solvent employed in MAE is the key factor in determining the optimal Acys extraction yield (Chen et al. 2006). Additionally, the MAE technique has been used to study other natural colors like curcumin and carotenoids, with results that are comparable (Lianfu and Zelong 2008; Mandal et al. 2008). Safflower yellow and flavonoids were extracted using dynamic microwave-assisted extraction as opposed to traditional techniques (Gao et al. 2006). By using this derivative technique, the extraction process may be conveniently tracked and continuously measured. Vacuum microwave-assisted extraction (VMAE), a derivative MAE technique, was put up against MAE in a comparison of the extraction of microalgal pigments

(Dabiri et al. 2005). They found that the mechanical barrier—that pigment must be extracted from microalgae with a robust frustule—can be significantly reduced by the use of microwaves. In order to extract safflomin A from Chinese herbs, Wang et al. also used this method; nevertheless, they concluded that VMAE was preferable for extracting thermosensitive chemicals (Sun et al. 2007). An intriguing study on coupling techniques for lycopene extraction found that ultrasound and microwave-assisted extraction (UMAE) produced a higher yield of lycopene (97.4%) while using less solvent and less time (367 s) than ultrasound and microwave-assisted extraction (UAE), which produced a yield of (89.4%) in 29.1 minutes.

With the presence of water in the extract, the combined UAME approach may prevent the generation of hydroxyl radicals by the ultrasonic cavitation effect, which could break down lycopene. Green extraction has emerged as the future trend, as we covered in the antioxidant part. Zill-e-Huma et al. (2011) explored a solvent-free microwave hydrodiffusion and gravity extraction of flavonol from onions. The advantages of the prior microwave-assisted approach were preserved by this new, original methodology, but they were also enhanced in terms of extraction time, solvent, efficiency, etc. It is noteworthy to note that microscopic examinations of the extracted tissues revealed that microwave irradiation might cause a significant disturbance in the structure of plant tissue (cell walls, vacuoles, etc.), allowing for the effective extraction of target substances (Hemwimon et al. 2007).

10 Extraction of Personal Care Products

Pharmaceuticals and personal care products (PPCPs) have been reported in a variety of natural matrices from numerous locations (Golet et al. 2002; Ternes et al. 2004). PPCPs include medications ranging from analgesics and antibiotics to contraceptives and lipid regulators, in addition to the active ingredients in soaps, detergents, perfumes, and skin, hair, and dental care products (Peck and Hornbuckle 2003; Ferrer et al. 2004). Continuous introduction of PPCPs into the environment, multiple dispersal mechanisms, and their pharmacological activities may result in detrimental impacts on wildlife and humans (Kolpin et al. 2002; Ternes et al. 2004).

The extent of exposure from contaminated matrices remains largely unknown; however, studies have reported the bioaccumulation of some PPCPs in lobster, clams, and human breast milk (DiFrancesco et al. 2003; Ohoro and Okoh 2019). Increased hermaphroditism in organisms exposed to female reproductive hormones has also been observed (Kuster et al. 2004). In addition, increased bacterial resistance among colonies subjected to widely used antibacterial agents has been documented (Prat et al. 2006; Lima et al. 2022). The discovery of multiple classes of PPCPs coincident in environmental samples further necessitates the consideration of potential interactive effects (Kolpin et al. 2002). For instance, a mixture of 13 pharmaceuticals resulted in a 10–30% reduction in growth of human embryonic kidney cells after 2 days of exposure in vitro, while no effects were observed when one of the chemicals was presented individually (Prat et al. 2006). Wastewater treatment plant (WWTP) effluents are considered a primary source for PPCP introduction to the environment. Pharmaceuticals may enter wastewater via excretion or disposal of unused medications (Cunningham et al. 2006).

Personal care products are incorporated through washing and bathing practices. During wastewater treatment, some removal of PPCPs occurs through sorption to sludge (Ternes et al. 2004). Over one-half of the sewage sludge generated annually in the United States is further stabilized, then referred to as biosolids, and applied to agricultural fields, golf courses, and residential lawns as fertilizer/soil conditioner (Renner 2000; la Guardia et al. 2003). The remainder is placed in landfills or incinerated (Kuster et al. 2004). Following biosolid application onto land, incorporated contaminants may enter soil or be translocated via leaching, volatilization, or transport on eroded particles (DiFrancesco et al. 2003; la Guardia et al. 2003). Some contaminants in biosolids are likely to be available for uptake by plants, microorganisms and animals which inhabit or feed on soil and sediment (Renner 2000; DiFrancesco et al. 2003; Kuster et al. 2004). Biosolids have high nutrient and organic carbon content; however, the identities and levels of organic contaminants therein are largely unknown and unregulated. Diverse chemicals constitute the compound class known as PPCPs and, hence, such chemicals will exhibit a variety of fates in WWTPs and the natural environment. The incorporation of polar functional groups in many suggests considerable water solubility, while others are more hydrophobic or possess positively charged moieties which may lead to significant interaction with solids. Many PPCPs contain combinations of these structural properties, complicating the prediction of their behavior and necessitating their quantification in multiple matrices (Ternes et al. 2004). The synthetic steroid Ethinyl-estradiol has been detected in sewage effluent, surface waters, activated and digested sludge, and river sediment (Gomes et al. 2004), while the over-the-counter anti-histamine diphenhydramine was found in sediment at concentrations that are believed to exceed those in aqueous matrices by three orders of magnitude (Ferrer et al. 2004) (Table 1).

11 Extraction of Pharmaceuticals

More than 3000 distinct compounds, such as antibiotics, antidiabetics, beta-blockers, contraceptives, lipid regulators, antidepressants, or nonsteroidal anti-inflammatory medications, are utilized as pharmaceutical components to treat illnesses in humans or animals (NSAIDs) (Guedes-Alonso et al. 2016; Muzammil et al. 2023). Human-use pharmaceuticals and their metabolites are partially eliminated in urban Wastewater Treatment Plants (WWTPs) from domestic and medical effluent. As a result, several environmental components (such as water, sediments, but also biota) play a role in their ultimate fate (Kumirska et al. 2015).

The majority of the samples of sewage sludge from wastewater treatment plants have been subjected to analytical procedures based on MAE to identify pharmaceuticals (WWTP). Numerous classes of pharmaceutical substances have

Table 1 Target compounds selected for development of mixed PPCP method

Target compound	Function	References
Caffeine	Stimulant	Kuster et al. (2004)
Diphenhydramine hydrochloride	Anti-histamine	Ferrer et al. (2004)
Epicoprostanol	Molecular marker for fecal waste (steroid)	Kuster et al. (2004)
17-Estradiol	Female reproductive hormone	Gomes et al. (2004)
Ibuprofen	Anti-inflammatory; analgesic	Ferrer et al. (2004)
Ketoprofen	Anti-inflammatory; analgesic	Ferrer et al. (2004)
Musk ketone	Synthetic fragrance	Peck and Hornbuckle (2003)
Naproxen	Anti-inflammatory; analgesic	Gomes et al. (2004)
Triclosan	Anti-bacterial agent	Ferrer et al. (2004)

been examined in this matrix, including steroid hormones (Snow et al. 2012), nonsteroidal anti-inflammatory medicines (NSAIDs) (Petrie et al. 2016), antiepileptic drugs (Mohapatra et al. 2012), and antibiotics (Montesdeoca-Esponda et al. 2011; Dorival-García et al. 2013). Additionally, MAE has been effectively used to identify pharmaceuticals in a variety of solid matrices, including compost (Speltini et al. 2015), sediments (Tong et al. 2016), biota (Kazakova et al. 2018), and air samples (Jiao et al. 2014). The most significant class of steroid hormones are the estrogens, and their release into the environment, particularly into aquatic environments, can have detrimental impacts on aquatic animals.

The major extraction solvents used for the MAE optimization of steroid hormones in sewage sludge and sediments were MeOH (Snow et al. 2012), water (Azzouz and Ballesteros 2015), and a combination of MeOH/water (3:2, v/v) (Kumirska et al. 2015). Following MAE, extract evaporation and reconstitution in MeOH was used as a concentration step before the LC-MS analysis of 20 synthetic and natural steroids and their associated metabolites in sediments (Snow et al. 2012) and 15 sex hormones and corticosteroids in sludge (Guedes-Alonso et al. 2016). Prior to analysis, SPE was also used as an extra clean-up step. In every instance, LODs and good recoveries between 71% and 102% were realized at the low ng/g^{-1} (Vega-Morales et al. 2013).

Antibiotics are used to treat bacterial infections. Due to their wide range of activity and effective oral absorption, fluoroquinolones are arguably the most significant class of synthetic antibiotics. They have been found in wastewater effluents, and because they are lipophilic, they can gather in sediments or sludge (Dorival-García et al. 2013; Alves et al. 2023). Fluoroquinolones have been successfully extracted by MAE from compost and sewage and wastewater sludge (Montesdeoca-Esponda et al. 2011).

In order to extract 54 multiclass pharmaceuticals (NSAIDs, sedatives, sulfonamides, quinolones, and other popular medications) and PCPs from fish samples, innovative techniques including MAE combined with hollow fiber-liquid/solid phase microextraction (HF-L/SME) have recently been developed

(Zhang et al. 2017). In this instance, microwave energy was used during the HF-L/SME operation on a synthesized SPME fiber since it demonstrated high capacity, concentration rate, and efficiency. Combining these two options provides for a faster rate of target compound diffusion, which cuts down on extraction time (12 min). For all substances, LODs between 0.01 and 0.50 ng/g^{-1} were attained (Huang et al. 2016) (Table 2).

12 The Role of Microwaves in Omics Disciplines

12.1 Omics

Genomics is the exploration of all genes and their interrelationships in order to determine their collective influence on an organism's growth and development. Proteomics, on the other hand, is concerned with the study of the expression, localizations, functions, and interactions of all proteins expressed by an organism's genetic code. Finally, metabolomics is concerned with quantifying all low-molecular-weight metabolites (sugars, amino acids, organic acids, fatty acids, and others) in an organism's cells at a certain time under precise environmental/biological conditions. Omics is currently a magical suffix from the Latin "ome," which means mass or gigantic, and alludes to the massive amount of analytical data generated and required to gain the information sought by the so-called omics disciplines. To gather the data required for an omics investigation, an analytical procedure must be performed. Microwave (MW) energy can be used to expedite, improve, or allow the gathering of target analytical data during one or more steps of the analytical process (Delgado-Povedano and Castro 2017) (Fig. 6).

12.2 Microwave Equipment for Assisting Omics

Microwaves have been employed to varying degrees to facilitate research on analytical platforms in various omics disciplines. Metabolomics has reaped maximum advantage of the great number of methodologies created under the umbrella of reductionist theory in molecular biology over several decades by employing microwaves to optimize sample preparation stages. Other omics, on the other hand, have used MWs primarily to speed up sluggish procedures like sample preparation and/or detection, which are substantially slower when done without the aid of microwaves. In the three major omics and their subdisciplines, a number of microwave devices have been employed to perform analytical MW-assisted tasks (especially sample preparation). For this reason, both monomode and multimode MW generation have been utilized. In addition, to speed up standard omics procedures, commercially available devices, laboratory-made designs, and household ovens have

Table 2 List of pharmaceuticals extracted from MAE

Analyte	Sample	Sample pretreatment	MAE condition	Extraction treatment	Determination	LOD	*References*
Sex Hormones and Corticosteroids	Sludge	Freeze-dried	10 mL MeOH MAE (500 W, 65 °C, 4 min)	Filtration, Evaporation and Reconstitution	LC-MS/MS	1.1 to 7.9 ng g^{-1}	Snow et al. (2012)
19-Norethindrone, DES, Norgestrel	Sewage Sludge	Homogenization and Air-Dried	5 mL MeOH MAE (200 W, 6 min)	Filtration, Dilution and SPE	LC-MS/MS	0.1–0.7 ng g^{-1}	Kolpin et al. (2002)
Fluoroquinolones	Compost	Homogenization and Air-Dried	10 mL mg (NO3)2 6 H_2O and NH3 aqueous solution MAE (200 W, 135 °C, 20 min)	Dilution and SPE	LC-MS/MS	2.2–3 ng g^{-1}	DiFrancesco et al. (2003)
Multiclass Antibiotics	Aquifer Sediment	Air- Dried and Sieved	MeOH MAE 5 min ramp up to 60 °C (held at 25 °C),100 W	Centrifugation and SPE	LC-Q-Orbitrap MS	0.1–3.8 ng g^{-1}	Kumirska et al. (2015)
Sulphonamides, Tetracyclines, Fluoroquinolones, Amphenicols, and NSAIDs	Fish	Lyophilization	50 mL Proteinase-K solution+5 mL formic acid +5 mL ACN/H_2O (1:1, v/v) MAE (5 min)	Evaporation and reconstitution	LC-MS/MS	0.6–12 ng g^{-1}	Kuster et al. (2004)

(continued)

Table 2 (continued)

Analyte	Sample	Sample pretreatment	MAE condition	Extraction treatment	Determination	LOD	*References*
Tetracyclines, Oxytetracyclines, Chlortetracyclines, Deoxytetracyclines	Soil, Sludge, Atmospheric Particulate Matter	Lyophilization and Homogenization	5 mL MeOH + mSPE device MAE (400 W, 60 °C, 20 min)	Sonication with MeOH	LC-UV	0.1–6.3 ng g^{-1}	Morales-Toledo et al. (2016)
Carbamazepine	Waste water sludge	Freeze-Dried and Homogenization	20 mL MeOH MAE (1200 W, 10 min ramp up to 110 °C, Held for 10 min)	Concentration and Redissolution (Water)	LDTD-APCI-MS/MS	12 ng g^{-1} (Waste water) 3.4 ng g^{-1} (Sludge)	Huang et al. (2016)

Abbreviations: *LC* Liquid Chromatography; *LDTD-APCI* Laser Diode Thermal Desorption-Atmospheric Pressure Chemical Ionization; *LOD* Limit of Detection; *MAE* Microwave-Assisted Extraction; *MeOH* Methanol; *MS* Mass Spectrometry; *MS/MS* Tandem Mass Spectrometry; *NSAIDs* Nonsteroidal Anti-inflammatory Drugs; *DES* Diethylstilbestrol

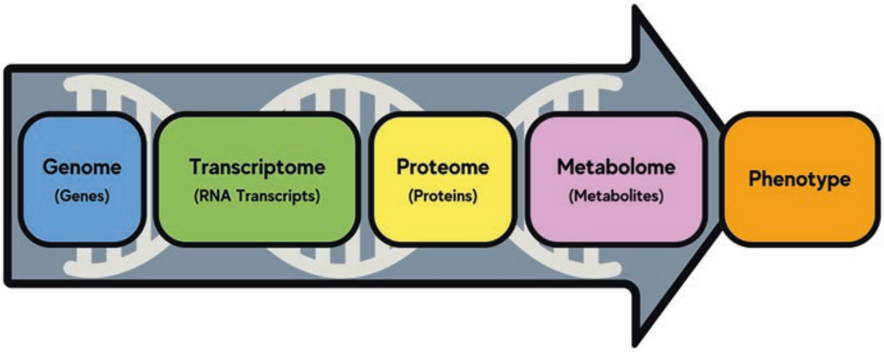

Fig. 6 General scheme of omics disciplines

been used. Two factors characterize the use of MW in omics disciplines: (1) The device used to apply this sort of energy, which entails decisions on two aspects: MW mode and continuous or batch performance of the MW-subjected target step; (2) The medium or solvent with which the sample (or, after separation, the portion of it to be analyzed) comes into contact when MW is applied (de Castro et al. 2012).

A number of MW systems have been commercialized for specialized biological and biochemical applications. CEM, for example, sells a piece of specialized equipment for high-throughput digestion. The setup consists of a Discover system with a screw-top container that can store numerous microvials or Eppendorf tubes, as well as an insert for a fiber-optic temperature probe. The fiber-optic probe is designed to aid in temperature stabilization by monitoring magnetron power while simultaneously cooling to allow energy input while keeping the comparatively cool temperature required for the desired reaction. This equipment is appropriate for metabolite digestion and/or extraction (particularly from solid matrices). CEM offers a 45 mL vapor-phase hydrolysis jar for use with the Discover MW device, which can handle up to ten 300 mL samples in concurrently. A valve panel is included in the system to simplify connecting the hydrolysis vessel to the vacuum and nitrogen sources. To promote hydrolysis under inert, anaerobic conditions and hence prevent oxidative deterioration of the sample components, the sealed sample vessel is alternatively vacuum evacuated and purged with nitrogen (Delgado-Povedano and Castro 2017; Almeida et al. 2022).

Furthermore, numerous businesses have marketed systems designed with omics operations in mind. The CEM MARS 5, a microwave system with PTFE tanks for MW-assisted digestion, is one example. The MW-accelerated reaction system was created for digesting, dissolving, and/or hydrolyzing a wide range of materials in the laboratory. It rapidly heats samples in polar or ionic liquids at high pressures using MW energy. Its primary application is to prepare samples for atomic absorption (AA), inductively coupled plasma emission spectroscopy (ICP), or gas or liquid chromatography. A number of laboratories employ the vacuum-assisted automatic MW histoprocessor MFX-800-3, which has an in-built vacuum system and temperature stabilizer to allow for quick tissue processing without compromising the original structure. This is an environmentally friendly, quick, cost-effective, fully automatic microprocessor-controlled histoprocessor that can also be used manually and is ideal for a wide range of applications (Delgado-Povedano and Castro 2017).

12.3 Microwave-Assisted Steps in Various Omics

Microwave irradiation can help to speed up some procedures in genomics, proteomics, metabolomics, and related subdisciplines. The specific omics procedures that can be accelerated by employing microwaves (MWs) vary, as do the MW devices used to accomplish this, which include focused or multimode MWs, single continuous or high-throughput formats, and laboratory-adapted, commercial, or dedicated equipment. Cell fixation, DNA extraction, deparaffinization, digestion, PCR hybridization, rolling circle amplification, and metal-enhanced fluorescence are the specific activities most efficiently aided by MW in genomic applications. Proteomics can advantage from MW effects for operations such as enzyme quenching and proteolysis (enzymatic or chemical), identification and characterization of posttranslational modifications or metal-catalyzed reaction sites on proteins and lipase selectivities, dissociation of protein complexes and protein quantitation using commercially available processes such as ICATR® and iTRAQR®, or traditional procedures based on sensitive phenomena such as fluorescence. In any event, metabolomics has benefited the most from MW assistance, particularly for drying, digesting, solid–liquid extraction (or, more precisely, “leaching”), steam distillation, liquid–liquid extraction, and derivatization of a wide range of metabolites from diverse matrices (Delgado-Povedano and Castro 2017).

12.4 Solvents Used in MW-Assisted Steps in Various Omics Disciplines

Because MW heating can induce a sudden increase in the internal temperature of a solution, which can result in an explosion, solvent characteristics must be thoroughly tested ahead of time. In order to accelerate proteolytic digestion, it has become more popular to incorporate a tiny quantity of organic solvent in digestion buffers to partially denature the substrate protein, allowing better access to the proteolytic enzyme. Furthermore, the presence and composition of surfactants in the working medium can have an impact on the MW-assisted sample preparation stage (Lin et al. 2005). Enzymes that can catalyze in non-aqueous environments, on the other hand, are frequently highly compatible with MW assistance, in which they tend to be exceedingly thermally stable without notable inactivation. Because of the large range of metabolite polarity, choosing an adequate solvent in metabolomics is more complex (Sandoval et al. 2007). There is no such thing as an ideal solvent when it comes to extraction. When designing the overall analytical process, consider the option of directly introducing the digested extract, eluate, and so on (i.e., the analytical sample) into the analytical equipment. This entails choosing a solvent that satisfies the unique needs of the analytical equipment being employed.

12.5 Microwave Assistance Trends in the Omics Approach

Despite its rapid expansion, MW's analytical help in omics is still in its infancy. Unanswered questions include the precise mechanisms of action of MW in comparison to conventional heating, as well as the actual usage and potential of this area. So far, the kinetics and specificity of MW-assisted incubations and reactions in genomics, transcriptomics, and proteomics have only been investigated in a few regions and on a few systems. MW-assisted processes involving metabolites, on the other hand, have been developed almost from the advent of MW devices in the analytical laboratory.

Past research and current demands indicate the following predictable trends in the use of MW to help omics:

(a) Magnetite beads are used to speed up MW-assisted enzymatic digestion and other SP procedures (Chen and Chen 2007).
(b) Quantum dots, which are widely utilized as fluorescent reporters in biomedical research and are now being used in the omics arena (Dua et al. 2010), will almost certainly necessitate technological improvements based on MW support.
(c) Nanostructured materials, which have been widely used in the therapeutic field (Phan et al. 2009; Feliu and Fadeel 2010), would benefit from MWs to improve target processes, notably in integrated omics investigations (Gibb et al. 2011).
(d) Microfluidic technologies, which are becoming more prevalent in omics (Brouzes et al. 2009), nanomedicine in general (Sakamoto et al. 2010), and nanoscale platforms (Soundararajan et al. 2010), can be predicted to gain from MW support, increasing and accelerating their performance.
(e) Bioinformatic approaches (Cho et al. 2007), such as nanoparticle ontology (Thomas et al. 2011) and nanoinformatics (Maojo et al. 2011), could make it easier to interpret interactions of micro- and nano-omics systems with MW.
(f) New commercially available miniaturized MW devices can solve the question of what type of MW device to utilize for MW-assisted omic processes at the micro- and nanoscale (Aydoğan et al. 2020).

13 Conclusion

As a result of groundbreaking research, microwaves are being used to extract phytoconstituents from diverse herbal specimens. Conventional extraction procedures are time-consuming, need more solvents, and are no longer appropriate for thermally sensitive plant components. The extraction stage must be more yielding; rapid, specific, and solvent-free, while also preserving the stability of thermolabile components, and microwave extraction meet these demands. Heat is generated while employing microwave energy in this unconventional method. The significant characteristics that determine extraction efficiency are solvent attributes, volume, duration of exposure, microwave control, system attributes, temperature, and application. Microwave-assisted extraction is a green technology when compared to other extraction techniques. Thus, MAE is an effective green technology that has become one of the key strategies for extracting bioactive components from environmental, biological, and geological matrices.

MAE approach was developed in the mid-1980s to isolate bioactive chemicals from plants. From an existing perspective of green chemistry, this is an environmentally benign and human-friendly technique. It is currently widely accepted as a method for extracting bioactive natural chemicals from plant sources. In today’s herbal isolation context, extraction techniques for plant matrix are key tasks that must be completed in order to meet quality control attributes. In this case, microwave-aided extraction can be used as a guide for the extraction of new and selective bioactive compounds from the plant sample matrix. This method outperforms conventional methods in terms of selectivity, specificity, and extraction efficiency. Furthermore, several research studies reveal that microwave-assisted extraction offers substantial advantages over conventional approaches, such as shorter extraction times, higher extraction yield, and lower solvent usage.

Furthermore, heat- or oxygen-sensitive chemicals should be extracted under controlled circumstances (such as a vacuum or inert atmosphere) to avoid oxidative and thermal destruction. Solvent-free microwave extraction yields a more valuable product with higher levels of oxygenated chemicals. Some highly polar chemicals can be employed in suitable proportions in a solvent blend under increased heat and pressure. As a result, microwave-aided extraction can produce higher quality samples (in particular chemical classes of substance) than other conventional approaches. It also allows full control over extraction factors like as duration, energy, and temperature, which improves reproducibility. Several aspects, including solvent composition, solvent quantity, and plant material loading, influence microwave-aided extraction. To efficiently recover the chemicals of interest, thorough process optimization with parameter regulation and control is required. New batch microwave assemblies are more intelligent than prior designs. For sample loading and recognition, these systems employ a sample set time program. At a single moment in time, microwave operators can now choose the temperature for each sample as well as the sample type for different extraction systems.

Unfortunately, relatively few studies have been published on microwave-assisted extraction of bioactive components from plants on a significant scale. This could be attributed to crucial control points in industrial microwave design, such as the processing facility, processing conditions, safety and operation-related hazards, and product parameters. As a result, specific efforts should be undertaken to address technical challenges connected to the design of microwave extractors and their suitability for isolating bioactive components from plant matrices in order to encourage the use of microwave-aided extraction in the food and pharmaceutical industries. To facilitate the application of microwave-assisted extraction to the food and drug industries, special efforts should be made to solve conceptual and practical problems such as the unveiling of the extraction mechanism, the development of microwave-based extractors, and the diagnostic testing of plant materials.

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