TRENDS IN ANIMAL AND PLANT SCIENCES
https://doi.org/10.62324/TAPS/2025.080
www.trendsaps.com; editor@trendsaps.com
E-ISSN: 3006-0559; P-ISSN: 3006-0540

RESEARCH ARTICLE

Extraction of Bio-active Compounds from Plant Sources using Novel Extraction Techniques-MAE (Microwave Assisted Extraction), UAE (Ultrasonic Assisted Extraction) and SFE (Supercritical Fluid Extraction): An Insightful Review

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Article History: 25-26 Received: 02-Jul-2025 Revised: 23-Jul-2025 Accepted: 11-Aug-2025

ABSTRACT

In recent years, focus on health and well-being has sparked a rising interest in bioactive compounds in food industries. These components are gaining much more popularity due to their numerous health benefits. Due to this reason, the demand for these compounds has also increased, whether it comes from edible or non-edible sources. Conventional techniques were time-consuming and were yielding low-extract products, so this problem raised the demand for modern extraction techniques. Novel techniques, including microwave-assisted extraction, ultrasonic-assisted extraction, and supercritical-assisted extraction, are better performing as compared to previous techniques. Their benefits include time saving, less solvent use, and better extract product yield, making them superior as compared to conventional techniques (maceration, percolation, and Soxhlet extraction). The drawbacks of old traditional techniques and the benefits of modern techniques make researchers and industries adopt new methods for extractions. At this point, novel techniques proved to be a sigh of relief for their users and changed the whole trend of extraction techniques. As the world is talking about environmental protection and sustainability, novel techniques also have a slight upper hand in this sector. Because some of the conventional techniques require high temperatures for the extraction process to be carried out. While on the other hand, novel techniques are non-thermal in nature, so they are more environmentally friendly and sustainable. The core aim of this review is to gain a comprehensive knowledge and understanding of principles and benefits of novel techniques in comparison to traditional techniques. A detailed overview of MAE, UAE, and SFE from different studies has been emphasized in this review, mainly focusing on the differences of different control parameters, bioactive compounds, and their benefits.

Key words: Bioactive compounds, Novel techniques, Plant sources and Phenolic compounds.

INTRODUCTION

Herbs are plants that provide essential oils that are used in cosmetics, medicine, and food (Nurdjannah & Bermawie, 2012). For thousands of years, they have been utilized in both medicine and cooking (Wu et al., 1998). As dietary nutrients and phytochemicals (Shan et al., 2005), herbs can provide a variety of health advantages, such as anti-inflammatory, cancer-preventive, cholesterol-lowering, blood-sugar-regulating, immune system- stimulating, mood and cognitive abilities vitamins, and polyphenols (Cuvelier et al., 1994) . Examples of the many contributions herbal medicine has made to commercial drug preparations today comprise reserpine from Rauwolfia serpentina, a naturally occurring β-adrenergic prohibiting agent with partial agonism, digitoxin from Digitalis purpurea, ephedrine from Ephedra sinica, and salicin (the compound that makes aspirin) from Salix alba (Biesalski et al., 2009) . Vitamins, polyphenols, anthocyanins, carotenoids, pectin, fatty acids, and triglycerides are examples of non-essential and essential bioactive substances that are present in nature and are a part of the food chain. Bioactive compounds have a profound impact on overall health and wellbeing through modulating metabolic processes

Cite This Article as: Fatima E, 2025. Extraction of bio-active compounds from plant sources using novel extraction techniques-MAE (Microwave Assisted Extraction), UAE (Ultrasonic Assisted Extraction), and SFE (Supercritical fluid Extraction): An insightful review. Trends in Animal and Plant Sciences 6: 54-65. https://doi.org/10.62324/TAPS/2025.080

(Jeyasekaran & Soumini, 2021), inhibiting or inducing enzymes, inhibiting receptor activities, and inducing and inhibiting gene expression (Correia et al., 2012). Another name for them is nutraceuticals, a phrase that was coined by (Stephan DE Felice) who explains both their biological function and their prevalence in the human diet (Kalra, 2003). Applications of bioactive compounds are becoming more and more popular in a variety of fields, including Nano bioscience, agrochemicals, modern pharmacology, plant science, geomedicine, cosmetics, and the food sector.

Extraction is the first step in isolating the natural goods that are wanted from raw materials. Acquiring the required elements from multiple sources, like plant or seed samples, is a requirement for most sectors, particularly the food processing sector. Solvent extraction, maceration, percolation, decoction, digesting, and infusion are examples of extraction techniques. These conventional approaches are out of date since they often require an abundance of organic solvents, demand a long period of time, and yield minimal. However, innovative or greener (environmentally friendly) extraction techniques including microwave assisted extraction (MAE), ultrasonic assisted extraction (UAE), and supercritical fluid extraction (SFC) have also been used in the extraction of natural substances (Zhang et al., 2018).

Advanced approaches have transformed the extraction of bioactive chemicals and have had a substantial impact on a wide range of sectors. Among its distinguishing characteristics is the method of extracting natural compounds from plant materials by heating the moisture in the plant material or solvents in contact with it by using microwave energy. With a better yield and less solvent use, a typical microwave-assisted extraction is finished in a few minutes (Desai et al., 2010).

Ultrasonic-assisted extraction (UAE) is a well-known extraction technique that is both extremely effective and harmless to the environment. The UAE might lessen its environmental effect by lowering or eliminating the demand for organic solvents. Using the cavitation, mechanical, and thermal effects. The cell wall is damaged by ultrasonic activity , which also speeds up the release and dissemination of cell components (Chemat et al., 2017). Supercritical fluid extraction (SFE) is a preferred technique in many food processing sectors and has made significant strides since its beginnings. SFE has gained popularity over the span of 20 years as a clean, eco- friendly "green" processing methods for organic solvent-based natural product extraction. Extensive studies have been written on the latest breakthroughs in SFE applications in food science, natural products, by-product recovery, pharmaceuticals, and environmental science (Herrero et al., 2010). With a concentrate on their extensive use in medicine, cosmetics, and the food sector, this study attempts to investigate the nutritional and therapeutic significance of herbs. It intends to identify the different bioactive substances found in herbs, including fatty acids, vitamins, polyphenols, and carotenoids, and investigate how they can support human health and defend off diseases. Focusing on the important contributions of herbal medicine to contemporary medication development such as ephedrine, salicin, digitoxin, and reserpine is one of the primary objectives. Additionally, the study aims to analyze the concept of nutraceuticals, emphasizing how these compounds influence metabolic functions, gene expression, and receptor activities. Additionally, it assesses both traditional and novel approaches for removing bioactive substances from plant materials.

Ultrasonic Assisted Extraction:

This non-thermal method uses acoustic energy to accelerate the release and diffusion of target compounds. Ultrasound-assisted extraction (UAE) is primarily based on the cavitation process, which causes matrix compression and expansion, resulting in cell wall permeabilization and increased extraction yield.

Graphical Abstract of Ultrasonic Assisted Extraction

Oil and protein can be found in abundance in Moringa oleifera seeds. It contains fatty acids like linoleic acid and behenic acid, an antibiotic called pterygospermin, oleic acid or ben oil, and phytochemicals such terpenoids, lectins, tannins,

Abstract Comparison: Conventional vs Advance Extraction Techniques

Parameter	Conventional Techniques (e.g., maceration, decoction)	Advanced Techniques (MAE, UAE, SFE)
Solvent Usage	🔴 High	🟢 Low to Moderate
Time Efficiency	🔴 Long (hours to days)	🟢 Fast (minutes to a few hours)
Extraction Yield	🟡 Moderate	🟢 High
Environmental Impact	🔴 High (due to solvent waste)	🟢 Low (green technologies)
Equipment Cost	🟢 Low	🔴 High (initial setup)
Selectivity	🟡 Low (non-specific)	🟢 High (targeted compounds)
Energy Efficiency	🔴 Low	🟢 High (especially MAE and UAE)
Scalability	🟡 Medium	🟢 Medium to High
Industrial Adoption	🟢 Widely adopted historically	🟡 Increasing rapidly

Legend:

🟢 Advantageous / High performance
🟡 Moderate / Mixed
🔴 Disadvantageous / Low performance

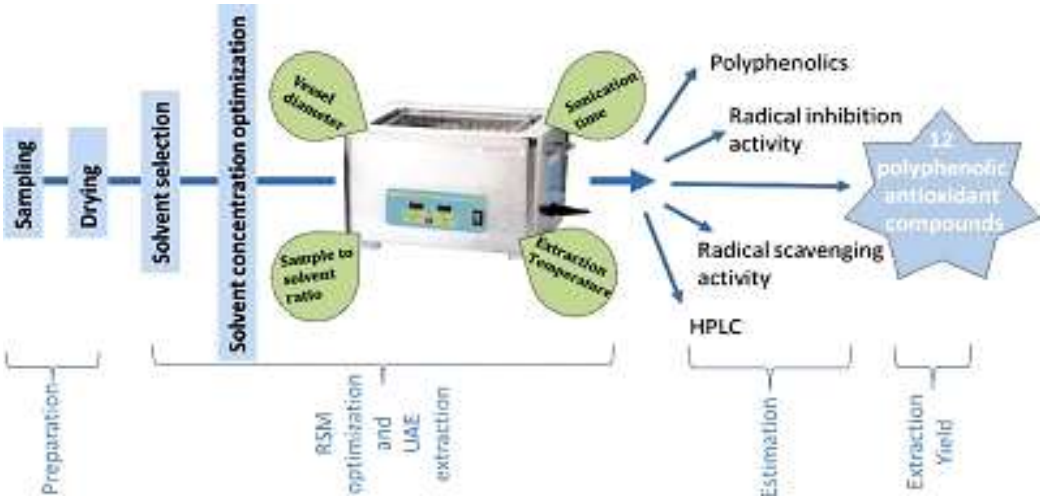


Fig. 1: Graphical representation of Ultrasonic Assisted Extraction adapted from(Pandey et al., 2018).

saponins, phenolics, flavonoids and phytate. In addition to proteins, lipids, fiber, and minerals, oleifera seeds also include vitamins A, B, and C and amino acids that are good for human skin. Seed oil can be used as medication to purify blood and improve cardiac function, make cosmetics, lubricate watches and precise equipment, treat rheumatism and gout, as well as creating edibles. At a frequency of 40 kHz and a temperature and S/L ratio of 30°C and 1:20, respectively, ethyl acetate was employed as the solvent (Fig. 1) (Buddin et al., 2018).

Skin, pomace, seed, and rind comprise some of the many by-products produced by the fruit and vegetable processing industries. These materials are rich in bioactive substances such polyphenols, dietary fiber, carotenoids and polysaccharides. Vasodilatory, anti-microbial, antioxidant, cardioprotective, anti-inflammatory, antithrombotic and anti-allergic properties are all exhibited by these substances. Bioactive chemicals have been extracted from fruit and vegetable by-products using a variety of solvents, including ethanol, water, acetone, acidified water, and alcohols, at frequency between 20 and 120 kHz and temperatures between 30 and 40°C (Kumar et al., 2021).

Wild thyme scientifically classified as Thymus serpyllum L, is a fragrant plant that contains a high concentration of essential oils and polyphenols. Antispasmodic, Antiseptic, carminative, diuretic, expectorant, antioxidative, and anthelmintic qualities are all carried by wild thyme. It also serves as an emmenagogue, analgesic, alexiteric and sedative. Aqueous extract from T. *serpyllum* has demonstrated antihypertensive and anti-nitric oxide properties. An essential class of natural oxidants, polyphenols and flavonoids may lessen reactive oxygen species accumulation in circumstances like diabetes mellitus, asthma, eye illnesses, and neurodegenerative and cardiovascular diseases. The ideal parameters to generate the highest production of polyphenols are 50% ethanol, 15 minutes, 25 °C, and 29 kHz (Jovanović et al., 2017).

Raspberry fruit is naturally high in fiber, ellagitannins, anthocyanins, and antioxidant chemicals. Carbohydrates are the main macronutrients, and water makes up about 80% of its composition. The secondary metabolites of raspberry fruit pomace, a byproduct of juice production, have been examined as a potential source due to their biological effects, which include anti-inflammatory (especially phenols and triterpenoids), anticarcinogenic and antioxidant characteristics. Epidemiological evidence supports the idea that eating enough fruit and vegetables (more than 10 servings per day) can help mitigate the effects of oxidative stress and inflammation, which are linked to diabetes and heart disease. Acidulated methanol is used to extract phenolic chemicals, flavonoids, and anthocyanins under the following conditions: 120 minutes, 50°C, and 50 kHz, respectively (Krivokapić et al., 2021).

Due to its curative effects against several chronic illnesses and digestive issues, cherimoya is widely employed in local traditional medicine. Plant-based proteins are becoming more and more popular than animal-based proteins due to their greater ethical qualities, rising concerns about animal health. It has been documented that phytochemicals and bioactive substances extracted from plant organs possess anticancer, antibacterial, antihyperglycemic, antioxidant and anti-inflammatory properties. It has distinctive secondary metabolites, comprising isoflavones, comparatively, coumarins, alkaloids and saponins. The primary bioactive substances identified in cherimoya fruit, leaves and seeds are terpenes, acetogenins and phenolic compounds respectively. The ideal conditions for ultrasound-assisted alkaline extraction were determined to be a pH of 10.5, a frequency of 35 kHz, and a temperature of 41.8 °C for 26.1 minutes (Orellana-Palacios et al., 2022).

Because of its numerous health benefits, high nutritional content, and superior sensory evaluation, blueberries are a particularly popular fruit. High levels of anthocyanins, phenolic acids, and flavanols have been identified in blueberries, and it is well-established that these substances have pharmacological merits for preventing several chronic illnesses, including high blood pressure, high cholesterol, diabetes and cancer.

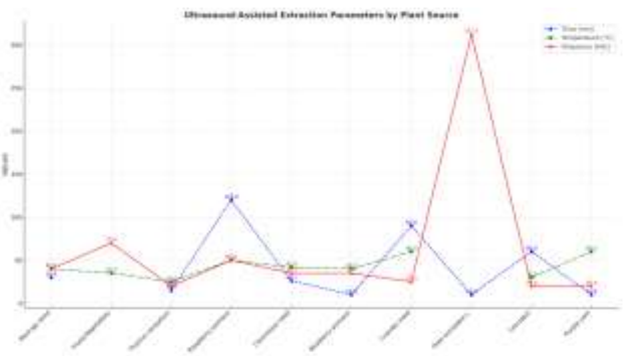
Natural polyphenolic chemicals are primarily discovered in fruit and vegetable by-products, and extraction seems to be the most effective method for optimizing their value. Using a variety of solvents, including acidulated ethanol and acidulated methanol, ultrasound-assisted extraction (UAE) was conducted at 35 kHz at various temperatures (20- 80 °C) and periods (5- 15 min). The solvent based on ethanol generated the highest yields of flavanol and phenolic acid (Lončarić et al., 2020).

The oil content of crambe seeds ranges from 30 to 51%. Vegetable oils are usually extracted using n-hexane, which also enhances reaction processes utilizing catalysts that are enzymatic. To determine the best conditions for extracting the maximum oil from seeds, a solvent mixture consisting of methyl acetate and n-hexane is used to evaluate the influence of process factors. The highest oil production was obtained by conducting the extraction at 60 °C for 90 minutes with a solvent to seed ratio of 1:10 and a frequency of 25 kHz. Approximately 86.5% of the oil composition was made up of oleic, linoleic and erucic acid, that the UAE gained (Tavares et al., 2017).

For countless centuries, people have been refining olive oil from Olea europaea L. Clean olives are crushed to create fruit paste, which is then subjected to paste malaxation treatment and centrifuged to separate out oil, water, and pomace. Heart health, bone health, weight loss, brain health, gut health, depression, cancer prevention, and anti-inflammatory capabilities are among some of the many health advantages of olive oil. An ultrasonic frequency of roughly 40 kHz to 585 kHz is used for 10 minutes to extract olive oil from Olea europaea L (Juliano et al., 2017).

There are several challenges associated with eliminating secondary chemicals from cannabis. Cannabinoids and terpenes break down in the presence of light and heat, making them unstable throughout the extraction, evaluation, and sample preparation procedures. Ethanol was selected as the extraction solvent because of its extensive use in the cannabis industry and it's standing as an "environmentally friendly solvent. Cannabis's therapeutic properties are mainly brought about by cannabinoids. Cannabis's euphoric, therapeutic, and medical effects are primarily attributed to cannabinoids like CBD and THC. Terpenes are the less recognized substances that give cannabis its distinctive smell and taste. Ethanol is used as a solvent in the extraction of cannabinoids and terpenes, and the ideal sample-to-solvent ratio is 1:15 for 30 minutes at 60 °C with a frequency of 20 kHz (Addo et al., 2022).

A popular plant in tropical regions that may be a fantastic supplier of anthocyanin is Dioscorea alata which is commonly known as purple yam. By neutralizing reactive oxygen species and preventing cellular damage under adverse circumstances, anthocyanins are potent antioxidants. They also contribute significantly to the prevention of diseases including diabetes, cancer, cardiovascular and neurological conditions. Additionally, anthocyanins are harmless and readily dissolved in water, making them potential natural water-soluble coloring agents. 20 kHz frequency, 60 °C temp, 60% intensity for 10 minutes, and an ethanol-to-water ratio of 80:20 are the optimal extraction conditions (Ochoa & Durango-Zuleta, 2020).



Ultrasound-Assisted Extraction showing different parameters [time (mins), temperature (°C) $and\ frequency\ (khz)$]

Table 2: Extraction of Bioactive compounds by Ultrasonic Assisted Extraction from different sources

Plant Source	Time	Temperature	Frequency	Solvent(s)	Bioactive Compounds	References
Moringa seed	30 min	40 °C	40 kHz	Ethyl acetate	Essential oil	(Buddin et al., 2018).
Fruits, vegetables, and by-products	Not specified	30–40 °C	20–120 kHz	Acidified water, ethanol, alcohols, acetone, water	Phenolic compounds, polysaccharides, polyphenols, carotenoids	(Kumar et al., 2021)
Thymus serpyllum	15 min	25 °C	20 kHz	Ethanol	Polyphenolic compounds	(Jovanović et al., 2017).
Raspberry pomace	120 min	50 °C	50 kHz	Acidulated methanol	Phenolics, flavonoids, anthocyanins	(Krivokapić et al., 2021).
Cherimoya seed	26.1 min	41.8 °C	35 kHz	_	Protein	(Orellana-Palacios et al., 2022)
Blueberry pomace	5, 10, 15 min	20, 40, 80 °C	35 kHz	Acidulated ethanol, acidulated methanol	Polyphenolics	(Lončarić et al., 2020).
Crambe seed	90 min	60 °C	25 kHz	Hexane	Essential oil	(Tavares et al., 2017).
Olea europaea L.	10 min	Not specified	40 & 585 kHz	_	Oil	(Juliano et al., 2017).
Cannabis	60 min	30 °C	20 kHz	Ethanol	Cannabinoids, terpenes	(Addo et al., 2022)
Purple yam	10 min	60 °C	20 kHz	Ethanol	Anthocyanins	(Ochoa & Durango-Zuleta, 2020)

Supercritical Fluid Extractions

To preserve the purity and active ingredients of essential oils to the maximum degree possible, supercritical carbon dioxide extraction techniques use fluid carbon dioxide as an extractant to extract useful components from plants. Carbon dioxide, which functions as an inert gas, does not undergo any chemical reactions throughout the extraction process, making it safe and environmentally benign. By choosing the right temperature, pressure, and extraction duration, essential oil components can be extracted and subsequently refined in a selected manner.

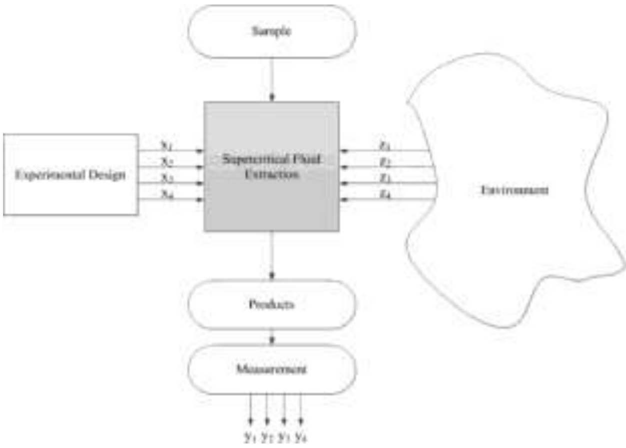


Fig. 2: Black box diagram Of Supercritical fluid Extraction adapted from (Castillo, 2007).

By using modeling and optimization strategies that have been proposed in recent years, SFE may extract seed oils effectively, rapidly, and economically. Supercritical fluid extraction has been employed sequentially in several industries, such as food, pharmaceuticals, and cosmetics, where a sustainable and "green" extraction is sought. Seed oils are extracted using supercritical fluid extraction techniques. Certain oils, for instance, are derived from citrus seeds, pepper, grapes, watermelon, sesame, annatto, cumin, sunflower, and tomato. Extraction utilizing ethanol, water, and CO_2 as solvents. Numerous fatty acids, pigments, amino acids, proteins, vitamins, polyphenols, and additional bioactive substances are obtained through extraction. The biological activity of the aforementioned seed oils such as their antibacterial, antiallergic, anticancer, and antioxidant qualities is well known to help treat cardiovascular and chronic degenerative conditions like macular degeneration and neurodegenerative diseases like Alzheimer's (Herrero et al., 2010).

About 15–20% of the fresh fruit is made up of mango peel (MP), which has been identified as a possible source of food molecules such as phenolic chemicals, carotenoids, and dietary fiber. Under SFE conditions (60 °C, 25.0 MPa, and 15% w/w ethanol), a representative sample of SFE-pre-extracted MP was produced. Mango peel extract recovered under optimal circumstances showed substantial anti-proliferative activity against the HT-29 colon cancer cell line via an antioxidant mechanism. The colony formation trend of several tumor cell lines, such as Caco-2 (30 µg/mL), HT-29 (90 µg/mL), and HCT116 (30 µg/mL) were also inhibited by hydro-alcoholic extracts of MP, which mainly contained methyl gallate, methyl-digallane ester, and gallic acid (del Pilar Sánchez-Camargo et al., 2021).

The most significant natural β-carotene generator, Dunaliella, is the focus of intense industrial and scientific study. In nutrition, cosmetic, and pharmaceutical industries, β-carotene serves as a colorant, antioxidant, and immunological stimulant. Combinations of polar and non-polar solvents based on petrochemicals can be used to extract lipophilic components, such as β-carotene, from Dunaliella. Tetrahydrofuran (THF), acetone, n-hexane, ethanol, ethyl acetate, and chloroform/methanol were used in solvent extraction tests. The supercritical extraction was carried out at 500 bar, 70 °C, and 30 mins. Cyanotech in Hawaii uses the technique on an industrial scale to collect astaxanthin from Haematococcus pluvialis. A simulation study was recently conducted to evaluate the economic and environmental aspects of extracting β-carotene from D. salina (Ludwig et al., 2021).

Bioactive chemicals are extracted from spices, medicinal plants, herbs, and aromatic plants using the SFE process. Bioactive substances include flavonoids, phenolic acids, fatty acids, carotenoids, and essential oils. Numerous substances, such as alcohol (methanol, isopropanol, n-butyl alcohol), aromatics (benzene, toluene), hydrocarbons (pentane, butane, hexane), and some gases (carbon dioxide, ethylene, propane), have been classified as SCFs. Because of its many advantages, CO_2 is without doubt the most often used solvent among the previously mentioned SCF. Because of its critical qualities (P_c = 73.8 bar; T_c = 31.1 °C), CO_2 is widely utilized as the supercritical fluid for extraction purposes in a variety of industries. It is therefore the perfect solvent for removing heat-sensitive bioactive substances. Supercritical carbon dioxide is a desired molecule for extracting antioxidants, pigments, fatty acids, tastes, perfumes, essential oils, and pigments from animal and plant sources because of its special solvent qualities. SC-CO_2 encompasses many advantages (Uwineza & Waśkiewicz, 2020).

Pitaya is a popular fruit that has numerous advantages for health. A waste product, pitaya peel has potential applications in the food industry as an antioxidant enrichment and natural coloring. As a result, there is an interest in finding pitaya species with more potential and reclaiming their constituents. The highest extraction yield (49.6 g kg−1) was obtained from S. monacanthus at 400 pressures, 35 °C, and 15% v/v ethanol. S. costaricensis (27.5 g kg1) and S. undatus (17.7 g kg1) were next in line. The antioxidant capacity was significantly affected by pressure, which favored the extraction of extracts rich in betalain at higher pressures, especially in the species S. mona canthus (0.3 g kg−1) and S. costaricensis (0.6 g kg −1). To improve the extraction process of S. undatus, a frequently farmed species, a series of extractions were performed. This procedure greatly increased the betalains' overall content, antioxidant activity, and extraction yield (Lacerda et al., 2024).

Propolis has been utilized as a treatment in folk medicine, apitherapy, biocosmetics, health foods, and for a variety of other applications. Extracts of Brazilian red propolis and green propolis were evaluated. Supercritical CO_2 at 50°C/300 bar, ethanol, methanol, water, and hexane (Soxhlet) were used to extract the extracts. Furthermore, $scCO_2$ was used to fractionate the red propolis ethanolic extract (EEP) at pressures ranging from 200 to 400 bars and temperatures from 40 to 60 degrees Celsius. For both red and green propolis, methanolic extraction produced the highest yield. Additionally, using $scCO_2$ to fractionate the red propolis ethanolic extract.

Compared to the original EEP extract, it yielded fractionated extracts with significantly greater flavonoid concentrations. Propolis is a desirable option for a natural preservative in novel food applications because of its antioxidant, antibacterial, and anti-fungal qualities, as well as the fact that some of its ingredients are found in food and/or food additives (Saito et al., 2021).

By-products of crustaceans may contain valuable lipids and carotenoids that can be used in biomaterials, food, cosmetics, and pharmaceuticals. Carotenoids are lipophilic substances that are present in both microbes and plants. They have antioxidant qualities and help to stabilize the photosynthetic system, shield cells from free radical damage, and preserve cell integrity. Lipid yields and carotenoids from crustacean waste can be increased using supercritical CO_2 extraction. Shrimp are rich in amino acids, lipids, fatty acids (FAs), minerals, enzymes, peptides, and bioactive proteins. Additionally, high-value carotenoid pigments such astaxanthin and Omega-3 FAs like eicosatetraenoic acid (EPA, 20:5n-3) and docosahexaenoic acid (DHA, 22:6n-3) can be extracted from shrimp (Ahmadkelayeh & Hawboldt, 2020).

Utilizing the unique properties of subcritical water heated water over the boiling point at high temperature-pressure conditions close to its critical point subcritical water extraction is an ecologically advantageous procedure (374 °C, 220 bar). SWE can be used at temperatures between 100 and 250 °C and pressures between 1 and 8 MPa. Pressurized hot liquid or hot water solvent extraction are other names for subcritical water extraction. Supercritical carbon dioxide and subcritical water are two possible techniques for recovering bioactive compounds. It has been demonstrated that bioactive substances derived from plants positively impact people's health and well-being. Phenolic chemicals, which include glycones, glycosides, monomers, and highly polymerized molecules, exhibit outstanding antibacterial, antioxidant, and anticancer properties. One significant class of plant bioactive chemicals is composed of phenolic compounds (Essien et al., 2020).

Cinnamomum camphor, another name for the camphor tree, is a unique kind of tree in China. It is a crucial raw element for the chemical, flavor, condiment, and medicinal sectors. Numerous chemical components, including linalool, eucalyptus, camphor, neroli tertiary alcohol, and others, are present in camphor tree essential oil. Among the many biological benefits of camphor tree essential oil are its anti-inflammatory, antifungal, antibacterial, insecticidal, and repellent properties. For example, the minimal bactericidal concentration (MBC) of linalool is 200 μL/L and has antibacterial, antiviral, and sedative properties. Furthermore, due to a possible neuroprotective effect, it can also be employed as a therapy method for neurodegenerative illnesses. Eucalyptus was used in pharmaceutical studies, dietary additives, and the manufacturing of oral condiments. Through intramedullary injection, in rats with respiratory conditions, it can also improve lung function due to its anti-inflammatory properties. Camphor lowers inflammation and aids in anesthesia. The yield of essential oil extracted at various temperatures (35, 40, 45, 50, and 55 degrees Celsius) was examined at a fixed pressure (20 MPa) and extraction duration (2 hours). At 45 °C, the maximum extraction rate was roughly 5%. Below 45 °C, as the temperature climbed, so did the extraction rate. The extraction rate decreased somewhat and was constant between 45 and 55 °C (Zhang et al., 2022).

The most common waste from the canning business that is utilized to make biogas is tomato peels and seeds (TP). TP is more sustainable than tomato fruits as a feedstock used, and it is high in lycopene. Prior to recently, TP was typically composted, but it is now also utilized as fuel for anaerobic digestion (AD). Using microbial activity, AD produces biogas through a biological process, a sustainable fuel made up of CO_2 and CH_4 (50–80 vol). The most potent antioxidant carotenoid, lycopene (Lyc), which is abundant in TP, is needed by the food, pharmaceutical, and cosmetic industries (Zuknik et al., 2012). With a compound annual growth rate (CAGR) of 2.3% and an expected global economic worth of 1.5 USD billion in 2017, the ability of Lyc to function to serve as a quencher of isolated molecular oxygen radicals makes it one of ten carotenoids that are most marketed (BBC Research, 2018). Because Lyc is lipophilic, it must be extracted using an apolar solvent like ethyl acetate, which may leave traces that are harmful to human health, particularly if taken regularly. In carbon dioxide (CO_2) supercritical extraction, a complement extraction method that forgoes the use of oxidant organics to produce cleaner and more ecologically friendly extracts, TP seed oil functions as a CO_2 co-solvent and the Lyc solubilization medium (Scaglia et al., 2020).

Table 3: Extraction of Bioactive compounds by Supercritical Fluid Extraction from different sources

Plant Source (Functional Food)	Temperature	Time	Pressure	Solvent(s)	Bioactive Compounds	Reference
Cumin, Sunflower, Sesame, Pepper	_	_	_	CO_2, H_2O, Ethanol	Various polyphenols	(Herrero et al., 2010).
Mango peel	60 °C	60–120 s	25.0 MPa	Ethanol 15% w/w	Carotenoids, phenolic compounds	(del Pilar Sánchez-Camargo et al., 2021).
Dunaliella salina	70 °C	30 min	500 bars	Acetone, n-hexane, ethanol	Lipophilic compounds (β-carotene)	(Ludwig, Rihko-Struckmann et al. 2021
Herbs, spices, aromatic & medicinal plants	31.1 °C	Optimum time	78.3 bar	Hydrocarbons (pentane, butane, hexane), CO_2	Essential oils, carotenoids, fatty acids, phenolic acids, flavonoids	(Uwineza & Waśkiewicz, 2020).
Pitaya	35 °C	1.5 hour	400 bars	Ethanol	Betalains	(Lacerda et al., 2024)
Green & red propolis	40–60 °C	_	200–400 bar	Ethanol, methanol, water, hexane, CO_2	Phenolic compounds	(Saito et al., 2021).
Crustacean (*Shrimps*)	_	_	_	CO_2	Proteins, peptides, amino acids, astaxanthin, omega-3 fatty acids	(Ahmadkelayeh & Hawboldt, 2020).
Plants	100–250 °C	_	1–8 MPa	Water	Phenolic compounds (glycones glycosides)	(Essien et al., 2020).
Camphor tree	45 °C	2 hours	20 MPa	CO_2	Linalool, eucalyptus, camphor, nerolidol (tertiary alcohols)	(Zhang et al., 2022).
Tomato pomace	_	_	_	CO_2	Lycopene	(Scaglia et al., 2020).

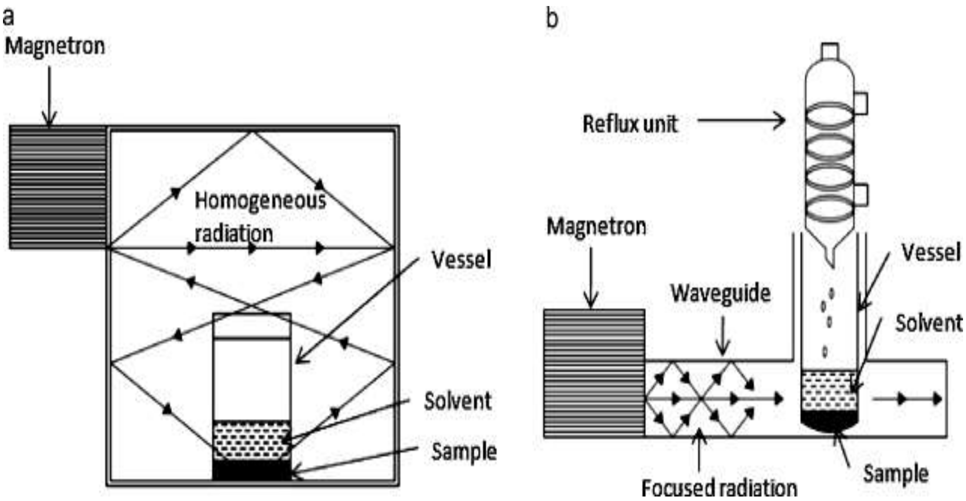
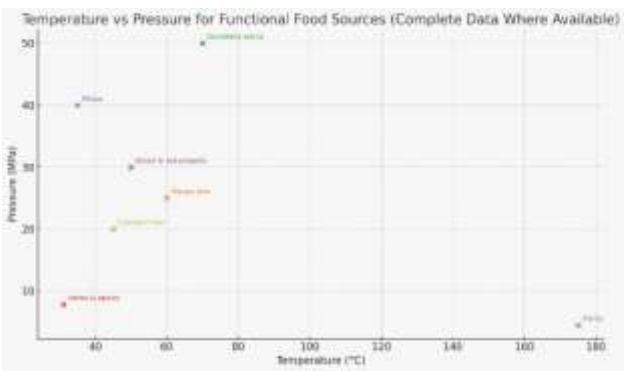


Fig. 3: Multi mode of Microwave Assisted Extraction (a) Closed type system,(b) Open type system is adapted from (Mandal et al., 2007).



Graphic presentation of temperature and pressure for functional food sources using Supercritical fluid Extraction Methods

Microwave-Assisted Extraction

Microwave-assisted extraction (MAE) is a relatively current, sustainable, and scalable technique for recovering highly valuable natural chemicals. It may also be a promising option for extracting macroalgal antioxidants or hybrid carrageenan. MAE enables quick and consistent extraction, little equipment, rapid startup, reduced solvent and energy consumption, and ionic conduction and rotation of dipoles are two ways that microwaves affect molecules. MAE is classified as multi-mode system and focused- system. The multi-mode system further classified as open and closed system that are Higher extraction yields have been obtained by studying the environmentally friendly process of microwave-assisted water extraction to produce hybrid carrageenan, carbohydrate, protein, and antioxidant substances from Mastocarpus stellatus red algae. The characteristics of the retrieved soluble extracts have been demonstrated to be significantly impacted by microwave temperature, with the highest protein values appearing at 150 °C. Kappa carrageenan can create hard, strong, or brittle gels, whereas iota carrageenan frequently makes soft, weak gels. As a result, hybridization makes it possible to create a sturdy elastic gel. There are numerous applications for kappa/iota hybrid carrageenan gels over various sectors. Among many other applications, the dairy industry could use it to make cakes, the cosmetics company to produce lotions or creams, the pharmaceutical industry to make semi-synthetic antibiotics, the chemical industry to form paints or shoe polish, the experimental medicine field to test anti-inflammatory medications, or the biotechnology sector to inhibit cells or enzymes (Ponthier et al., 2020).

Curcuma roots (Curcuma longa L.) have special antiseptic, antibacterial, anti-inflammatory, and antioxidant qualities that make it a useful plant for both medicine and food. The active ingredients in the oil of curcuma may be depleted by the prolonged extraction times and high heat required for standard processes. Microwave-assisted extraction was used to maximize Curcuma longa L. oil extraction yield using the response surface method and Box-Behnken experimental design. For the enhancement of curcuma oil extraction yield, a Box-Behnken design for experimentation with surface response examine was used alongside the microwave-assisted extraction (MAE) technology. To achieve an optimum yield of 10.32%, the MAE was tailored at 29.99 minutes, 1:20 w/v, and 160 W. Surprisingly, compared to the oil extracted using the traditional Soxhlet approach, the oil extracted with microwave assistance exhibited superior antioxidant activity and a higher TPC. TPC and antioxidant activity were influenced by the extraction treatments used for Curcuma longa L. oil. The three tests (DPPH, ABTS, and FRAP) showed that the oil from Curcuma longa L. that was extracted using the MAE method had more phenolic content and antioxidant activity (Fernández-Marín et al., 2021).

The present research is the first to look at how to maximize the number of bioactive substances with strong anti-inflammatory properties that can be extracted from avocado seeds using microwave assisted extraction (MAE). Avocado seeds contain a variety of extractable bioactive substances, including phenolic acids, flavonoids like catechin, other procyanidins, ketones, hydroxybenzoic and hydroxycinnamic acids, or condensed tannins. Numerous biological activities, including antioxidant, anticancer, antimicrobial, anti-inflammatory, and antihypertensive attributes, have been linked to the composition of these extracts. They have been used traditionally in dermatological applications and as infusions to treat various stomach disorders, high blood pressure, diabetes, and cholesterol. The most optimal extraction conditions were chosen by doing two experiments by using 70% acetone and ethanol: with 58.51 percent ethanol, 72.18 °C for 19.01 minutes, and 71.64 °C for about 14.69 minutes, respectively, to get extracts with the maximum antioxidant activity. In contrast with fiber residues obtained with ethanol, those obtained following MAE demonstrated bound phenolic compounds with significant antioxidant activity. Phenolic acids were among the 20 distinct substances found in the HPLC-ESI-MS investigation. Trimer A and B, dimer B, catechin, epicatechin, and percental are procyanidins with multiple isomer forms. MAE is a fast, green, and energy-efficient technology for extracting naturally active agents from avocado seeds without minimizing their antioxidant characteristics, leading to a desirable alternative approach in conventional herbal medicine and economic activity.

Onion leaves have the potential to be an excellent source of bioactive nutritional and medicinal components, but they have not gotten much attention. *Cipollotto nocerino*, or spring onion leaves (CN), a type of agricultural waste, have polyphenolic compounds that are high in flavonoids. Bioactive substances such as polyphenols, flavonoids, carotenoids, vitamins, and chlorophyll are numerous in fresh onion leaves. The model concluded that 60 °C, 22 minutes, and a 51% ethanol concentration were the ideal extraction parameters. The branches of green onions from the "Cipollotto Nocerino" (CN) cultivar have antioxidant properties. Perhaps 6-7 times the size of its bulb, they are the main by-product of CN and range in length from 15 to 30 cm (Aquino et al., 2023).

The saponins observed in the seed coat are the main target of *Sapindus mukorossi*. Saponins can be utilized for creating natural detergents and have good decontamination properties. Oil from Sapindus mukorossi seeds was extracted utilizing the microwave-assisted extraction (MAE) method, which was compared to Soxhlet extraction (SE) for the purpose of enhancing extraction quality and efficiency. The optimal MAE condition, as determined by the Box-Behnken design, was an extraction solvent consisting of a mixture of n-hexane and ethanol (4:1, v/v), microwave power of 460 W, solvent-material ratio of 8 mL/g, extraction at 72 °C, and extraction duration of 42 minutes. The oil output of 40.12% under optimum conditions was comparable to that of SE (40.63%). Its biological movement is diverse and includes inflammatory disorders, phlegm ejection, and allergies. Among its many biological functions are phlegm extraction, anti-inflammatory, and anti-anaphylaxis properties (Hu et al., 2021).

Potassium, magnesium, calcium, iron, and vitamins C, A, and B6 are among the many nutrients found in jackfruit. The current method uses microwave-assisted extraction (MAE) with pulsed electric fields (PEF) to extract pectin from jackfruit waste. These inedible parts, which include the outer rinds, central core, and inside perigones, are typically thrown away as waste because they are not utilized. The current process extracts pectin from jackfruit waste by using microwave-assisted extraction (MAE) with pulsed electric fields (PEF). The extraction yields have been examined using two optimization tools: artificial neural networks (ANN) and Box-Behnken design (BBD). Following a desirability analysis, PEF strength (11.99 kV/cm) and PEF treatment time (5.47 min) were found to be the ideal operating conditions. Pectin is a polysaccharide with hydrocolloid, gelling, and stabilizing properties (Lal et al., 2021).

Avocado peel is a waste that is obtained in huge amounts in the food industry and has no further uses, although having a high concentration of useful components. In such a situation, an efficient "green" microwave aided extraction (MAE) method was created to maximize the extraction of bioactive polyphenols. Additionally, generated green avocado extract's phenolic composition was determined using HPLC coupled to MS analyzers, and the food industry's prospective applications were investigated by evaluating various bioactivities. Extraction is the most important step in eliminating the most amount of target chemicals from the sample matrix. Furthermore, response surface methodology (RSM) has been shown to be a successful strategy for improving the extraction process. MAE used the response surface approach (RSM) to successfully optimize the conditions for the extraction of polyphenols from avocado peel. The TPC was impacted by each of the selected extraction elements. The optimal MAE parameters were 130 °C, 39 minutes of extraction time, 36% ethanol concentration, and 44 mL/g solvent-sample ratio. The experimental TPC obtained under these optimal MAE settings agreed with the expected TPC (Figueroa et al., 2021).

Microwave-assisted extraction (MAE) and natural deep eutectic solvents (NADES) are two eco-friendly methods for removing bioactive compounds from hazelnut pomace. Natural deep eutectic solvents (NADES) are made from organic materials such sugars, amines, organic acids, amino acids, and alcohols. They are becoming a great substitute for expensive, difficult-to-make, and environmentally harmful ionic liquids. It was discovered that the proposed CC-PG solvent was more effective than traditional solvent systems for microwave-assisted antioxidant extraction from hazelnut pomace and flour samples. Following the determination of optimal NADES, the operational parameters for the MAE generation of antioxidants from hazelnut pomace were modelled and optimized using response surface approach. For the best antioxidant recovery, the MAE process's operating parameters were determined to be 24% water, NADES outperform other solvents in terms of availability, low toxicity, extraction efficiency, and biocompatibility at 18 mL/0.1 g-DS, 92 °C, and minutes. To extract antioxidants from hazelnut pomace, the optimal combinations of eight different NADES were found. Response surface methodology (RSM) was used to investigate and optimize parameters of operation for the MAE process of antioxidants utilizing choline chloride:1,2-propylene glycol (CC-PG), the best solvent for antioxidant extraction (Bener et al., 2022).

Because of their low toxicity and increased solvation power, natural deep eutectic solvents, or NADES, have been emerging as novel green solvents for use in pharmaceuticals, cosmetics, and food products. Using the microwave aided extraction method (MAE), turmeric extracts were made from five NADES with binary combinations of fructose, sucrose, lactic acid, and choline chloride. The MAE approach was modelled and optimized using response surface methodology to estimate the total antioxidant capacity and maximum curcumin concentrations (CC). (TAC) in each NADES' extracts. Except for NADES-1, which contains fructose and choline chloride, all NADES extracts had higher TAC and CC than 80% methanol. After caramelization and subsequent pyrolysis, sugar-containing NADES break down at high temperatures (150–200 °C), whereas phenolic structures are not broken down by lower temperature extractions. For the food and pharmaceutical industries, the suggested MAE is a potentially effective and long-term technique for removing curcumin and antioxidants from turmeric. Antioxidant, anti-inflammatory, antibacterial, antidepressant, antidiabetic, and anticancer properties have all been demonstrated for curcumin (Bener et al., 2016). Because of these properties, curcumin is used as a protective and preventive medication against major illnesses as cancer, AIDS, neurological, lung, liver, and cardiovascular diseases (Doldolova et al., 2021).

In this work, phenolic compounds from tomatoes were extracted using a novel technique called microwave-assisted extraction (MAE), which was contrasted with traditional solvent extraction. The phenolic components of the tomato were extracted using 80% methanol (Sigma) and 1% HCl (Honeywell, Germany). To determine the optimal conditions for tomato extraction, a multi-level factorial design was employed. For this, different powers (360, 600, and 900 W) and timings (30, 60, and 90 s) were used for MAE, while different temperatures (40, 50, and 60 °C) and times (10, 20, and 30 min) were used for CSE. The phenolic compounds in tomato extracts were identified using Fourier transform infrared (FTIR) spectroscopy and high-performance liquid chromatography (HPLC). Because of their health benefits, which include intestinal anti-inflammatory activity, tumor suppression, and cancer prevention, bioactive compounds (flavonoids, anthocyanins, and polyphenols) are utilized in the food and pharmaceutical industries (Baltacıoğlu et al., 2021).

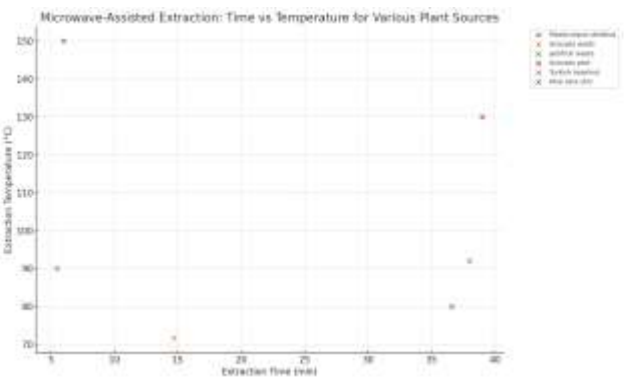
Aloe vera skin (AVS) is one of the primary byproducts of aloe processing factories around the world. The response surface approach was used in this study to optimize the microwave-assisted extraction (MAE) of bioactive compounds from AVS. The impacts of extraction parameters, specifically ethanol concentration (%Et), extraction temperature (T), time (t), and solvent volume (V), were investigated in relation to total phenolic content (TPC), antioxidant activity (DPPH and FRAP methods), aloin content, and extraction yield (Y). It was determined that the optimal extraction conditions were 50 mL, 80 °C, 36.6 minutes, and 80% ethanol. The antioxidant activity and

Table 4: extraction of Bioactive compounds by Microwave assisted Extraction from different sources

Plant Source (Functional Food)	Microwave Power	Time	Temperature	Solvent	Bioactive Compound	Reference
Mastocarpus stellatus	_	6 min	150 °C	_	Phenolic, sulphate content	(Ponthier et al., 2020).
Curcuma root	160 W	29.99 min	Not Specified	_	Curcuma longa L. Oil	(Fernández-Marín et al., 2021).
Avocado seeds	_	14.69 min	71.64 °C	Ethanol	Procyanidins, phenolic acids, Catechin	Error
Spring onion leaves	_	5–25 min	60–100 °C	Ethanol/Water	Phenolic	(Aquino et al., 2023).
Sapindus mukorossi seed oil	_	Not Specified	Not Specified	n-hexane and ethanol	Fatty acid, Triglyceride	(Hu et al., 2021)
Jackfruit waste	_	5.47 min	90 °C	_	Pectin polysaccharide	(Lal, Prince et al. 2021
Avocado peel	_	39 min	130 °C	_	Polyphenols	(Figueroa et al., 2021).
Turkish hazelnut (Corylusavellana L.)	_	38 min	92 °C	Choline Chloride:1,2-propylene glycol	Phenolics	(Bener et al., 2022).
Turmeric	_	_	150–200 °C	NADES	Polyphenols	(Doldolova et al., 2021).
Tomato	_	30,60, 90 s	40, 50, 60 °C	_	Flavonoids, anthocyanins, polyphenols	(Baltacıoğlu et al., 2021).
Aloe vera skin	_	36.6 min	80 °C	_	Aloin A, Aloin B, Aloesin,Aloe-emodin, AloeresinD, Orientin, Cinnamicacid, Chlorogenic acid	(Solaberrieta et al., 2022).
Sweet lemon peels (SLP)	700 W	3 min	_	_	Pectin	(Rahmani et al., 2020).

polyphenol contents of the optimized extracts were fascinating. Aloe vera has been associated with therapeutic or medicinal qualities since ancient times. Numerous studies have demonstrated its antioxidant, antiviral, anti-inflammatory, antibacterial, and anticancer qualities. The culinary, cosmetic, and pharmaceutical sectors have used aloe vera in countless product compositions, and its use has only increased recently (Solaberrieta et al., 2022).

The microwave-assisted pectin extraction method from sweet lemon peel (SLP) was optimized using the Box-Behnken design. The highest pectin production (25.31%) was seen at optimal conditions (microwave power of 700 W, irradiation time of 3 min, and pH of 1.5). The physicochemical, structural, and certain bioactive properties of the optimally separated SLP pectin were evaluated. The SLP pectin included a considerable amount of galacturonic acid and galactose (87.2%), a low degree of esterification (1.2–35.1%), and a high molecular weight (615.836 kDa). One kind of complex carbohydrate that is mostly present in fruit and vegetable cell walls is pectin. The two basic polymers that comprise the primary structure of pectin are homogalacturonan (HG) and rhamnogalacturonan-I (RG-I). Pectin is used extensively in the production of pharmaceuticals (as an antioxidant and in drug encapsulation), cosmetic products, and food composition (as a thickening, stabilizing, and emulsifying agent). Furthermore, the chemical has numerous health benefits for people, including reducing lipase activity, avoiding cancer, mending wounds, lowering cholesterol and ulcers, and functioning as an antioxidant (Rahmani et al., 2020).



Graphic representation of Microwave-Assisted Extraction for plant sources.

Conclusion

Revealing the beneficial role of bioactive compounds has increased their demand for consumption day-after-day. Extractions form conventional methods were time and solvent consuming. A few plant sources have been used for extraction of various bio-active compounds using novel techniques controlling various parameters like temperature, pressure, and amount of solvent. Different techniques perform differently but their focus was to enhance the efficiency of extraction, meeting the demand of bioactive compounds and cost efficiency. Different studies have been analyzed in this review to elaborate the useful aspects of novel techniques and the beneficial aspects of bio-active compounds. Collectively bio-active compounds are antioxidant, anti-inflammatory, and have numerous health benefits.

Three methods of extraction, namely UAE, SAE, and MAE are trending because of their beneficial aspects in every field. These techniques require less solvent, are time saving, cost saving, and efficiency in bio-active compound yielding, and are safe towards environment. But a lot of work is yet need to be done in this regard because there is less acceptability of these modern techniques by industries and researchers due to their high initial set-up cost, less trained employs, and many other challenges. Effective work needs to be done upon these cons of novel techniques. If these setbacks are controlled, then novel extraction techniques can have their peak usage in laboratories and other fields.

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