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Recovery Of Bioactive Compounds From Mango Processing Industrial Waste Using Various Extraction Methods

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ABSTRACT

Extraction of valuable bioactive compounds from plant matrices and food by-products is essential for developing value-added products in nutraceuticals, pharmaceuticals, cosmetics, and functional foods. This study represents the various extraction techniques helps to extract the compound, majorly it classified into conventional (traditional solvent-based) and non-conventional (modern, often green) techniques. The traditional technique like maceration, percolation, soxhlet extraction are widely used, they often require longer extraction times, higher solvent volumes, and greater energy input. In contrast, non-conventional techniques including ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), natural deep eutectic solvents (NADES), are presented as advanced, sustainable alternatives. These offer superior efficiency, reduced solvent and energy use, shorter times, better preservation of thermolabile compounds, and environmental benefits, though challenges like equipment costs and scale-up persist. The study also compares the sustainability, scalability, economic feasibility, and application potential of each method. Overall, the transition from conventional to innovative green extraction technologies reflects the growing demand for environmentally friendly, high-efficiency, and industrially viable processes for bioactive compound recovery.

Keywords: Bioactive compound, Extraction, Green Technology, Eco-friendly

I. INTRODUCTION

The agri-food sector generates huge number of plant-based residues and by-products whose disposal poses economic, environmental, and public health challenges, yet these streams are often rich in value-added bioactive compounds such as polyphenols, carotenoids, vitamins, dietary fiber, essential oils, and other phytochemicals with antioxidant, antimicrobial, and anticarcinogenic properties. Recovering these compounds from fruit peels, seeds, leaves, pomace, and other plant materials enables their incorporation into food, nutraceutical, cosmetic, and pharmaceutical products, supporting circular economy goals by reducing waste, mitigating pollution, and creating new revenue sources for industry. Extraction is the process of isolating the targeted compound from the complex plant materials and food waste by transferring them into value added products for application in food, agriculture, pharmaceutical, and cosmetic industries. Extraction methods are majorly categorized into two-type conventional and non-conventional method such as microwave assisted, maceration, soxhlet, ultrasound assisted etc. The technique will depend on polarity of the compound, thermal withstanding, purity and sustainability. The conventional techniques such as maceration, soxhlet extraction, and hydro distillation. These methods are simple and well-established but typically require long processing times, high energy input, and large amounts of organic solvents, which can lower extraction efficiency, compromise thermosensitive compounds, and raise environmental and safety concerns. In response to growing demand for sustainable and cleaner processes, a range of green and advanced extraction approaches has been developed, including ultrasound-assisted extraction, microwave-assisted extraction, supercritical and pressurized liquid extraction, and other non-thermal or low solvent technologies. These emerging methods aim to enhance yield and selectivity while reducing solvent consumption, processing time, and environmental impact, thereby improving the techno economic feasibility of converting plant materials and agri-food waste into high-value bioactive ingredients. This study aims to comparing traditional and green extraction strategies is essential for designing efficient, scalable processes that align with sustainability targets and enable the full valorization of bioactive-rich plant resources (Yadav et al., 2024; Mungwari et al., 2024; Nirmal et al., 2023).

II. CONVENTIONAL EXTRACTION TECHNIQUE

Conventional extraction methods refer to traditional techniques that use solvents (organic and water based) and physical processes to separate desired compounds from plants. The common conventional extraction methods shown in Fig.1 (Jha and Sit 2022).

2.1 Maceration

Maceration is a conventional solid-liquid extraction technique wherein plant compounds are soaked in an appropriate solvent, typically at room temperature for a certain period to isolate bioactive compounds such as flavonoids, tannins and polyphenols. The mechanism of maceration depends on the passive diffusion of the solvent inside the plant matrix, where the soluble phytochemicals can migrate from the plant cells into the solvent because of the concentration gradients. This process is enhanced through occasional agitation that will increase mass transfer and extraction efficiency. It is done through the initial penetration and wetting of the plant matrix by the solvent, followed by the dissolution of intracellular components and finally the slow passive diffusion of the metabolites out of the cell structure and into the solvent. Maceration is particularly appropriate for extracting heat liable compounds, as it avoids high temperatures that might cause the degradation of sensitive phytochemicals. The effectiveness of maceration is affected by several factors such as solvent to solid ratio, temperature, solvent type and polarity, time, particle size and agitation. While maceration is simple and economical method, it generally requires longer extraction periods and larger solvent volumes compared with more advanced techniques, but it remains a widely used for producing extracts from various plant materials for food, pharmaceutical and cosmetic applications (Baladraf et al., 2022; Tourabi et al., 2025; Sen et al., 2023).

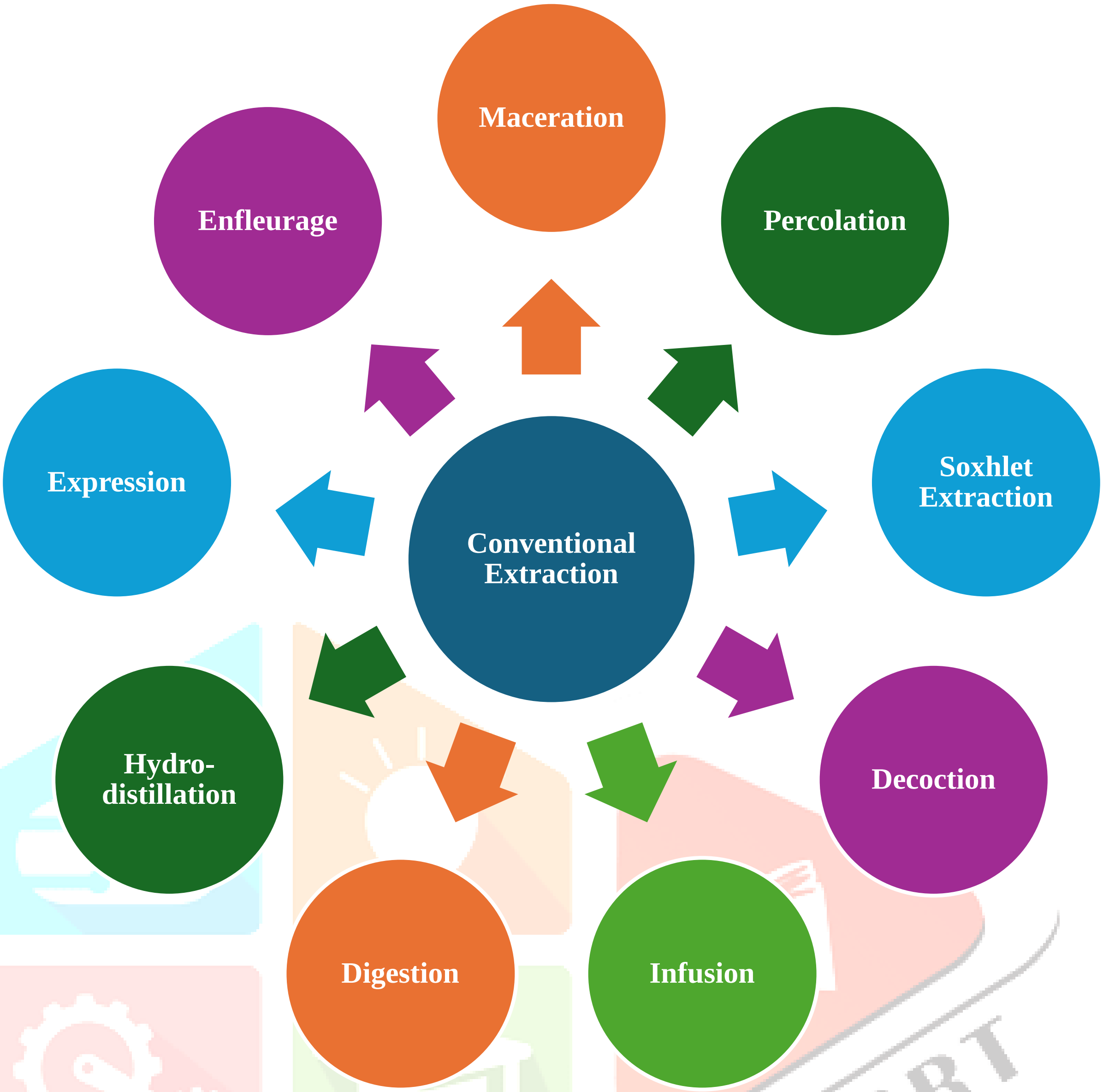

Fig 1: The types of conventional extraction methods

2.2 Percolation

Percolation constitutes a dynamic method of solid-liquid extraction, where a solvent is in a continuous flow through a column of plant material so the solvent exerts percolation pressure and at the same time, it extracts bioactive compounds and moves down by gravity or under controlled pressure. The salient feature of percolation is that during the whole process, a constant concentration gradient is maintained between the solvent and the plant matrix, by continuously introducing fresh solvent this result in a mass transfer efficiency that is higher than in static methods such as maceration. The procedure starts with the plant material being moistened to swell the tissues and thus allow entry of the solvent. The solvent is then added on top of the percolator and gradually goes through the packed plat bed, where it dissolves target compounds as it continues its journey. The solvent collected at the bottom is now laden with extract and the is repeated using a fresh solvent until the desired extraction level is reached. Percolation can be performed at ambient temperature, making it suitable for extracting heat-sensitive compounds and further it can be optimized by charging different parameters such as type of solvent, flow rate, pressure and particle size. The technique is recognized for its superior efficiency, shorter processing time and high extract volume production compared to maceration. Percolation has found extensive application in producing herbal tinctures, liquid extracts, extracting polyphenols, essential oils and bioactive substances (Cao et al., 2025; Sridhar et al., 2021; Tabarasu et al., 2024).

2.3 Soxhlet Extraction

Soxhlet extraction is the earliest and most widely used solid-liquid extraction methods for isolating bioactive compounds from plant materials. The basic idea of this process is process is to wash the solid sample repeatedly with the volatile solvent in a special apparatus, where the solvent is heated, vaporized and then condensed to flow through the sample, dissolving the compounds of interest. When the solvent in the extraction chamber reaches a certain height, it siphons back into the boiling flask taking the extracted solutes with it and the cycle continuous automatically. The mechanism provides a reliable and thorough extraction as the sample continuously comes into contact with the fresh solvent without the need of manually operation. The soxhlet extraction is frequently utilized in the analysis of plant oils, polyphenols and other phytochemicals for food, pharmaceutical and environment research, also in producing high grade materials like graphene oxide and essential oils. Its primary advantages are high extraction efficiency and suitable to use with a broad variety of solvents but it might not be the best option for heat-sensitive compounds, as they would be exposed to high temperature for a longer time (Trolles-Cavalcante et al., 2021; Mhemmed et al., 2025).

2.4 Decoction

Decoction is an old practice of extraction that entails immersing the plant parts in water and boiling them for a fixed time to gain the constituents that are withstand heat and soluble in water, like polyphenols, flavonoids, and among other bioactive substances. Decocting is based on the temperature application of the solvability and subsequently the diffusion of the targeted plant compounds matrices into the aqueous phase, which is the reason why it is particularly good at extracting compounds that are stable at high temperatures but not those that are sensitive or heat/light affected (Alara et al., 2021; Sridhar et al., 2021). With respect to mechanism, decoction increases mass transfer by boiling with disruption of the cell walls in the plant, thus enable water to penetrate the tissues, and dissolve the targeted constituents, which are then separated by cooling and filtration (Sridhar et al., 2021; Tena et al., 2022). This technique is utilized in many areas like traditional medicine, food and drink industries for herbal teas, medicinal extracts, and functional ingredients and also in the pharmaceutical and cosmetic sectors for antioxidant-rich and aromatic extracts, among others. Decoction is praised for its simplicity and also for extracting the active substances effectively, especially antioxidants, however, there are instances where it might not be the best option for volatile or heat-sensitive substances and may even lead in extracting the unwanted impurities (El et al., 2022; Muala et al 2021; Sridhar et al., 2021).

2.5 Infusion

The infusion extraction method is a classic technique that consists of immersing the plant material in hot or boiling water for a brief duration to get the water-soluble and heat-sensitive bioactive compounds out. Infusion operates on the principle of the target compounds dissolve in water at high temperatures, yet avoiding prolonged boiling which helps to retain the heat-sensitive constituents. The process of infusion involves pouring hot water onto the plant material and allowing it too steep for a while, consequently the solvent will invade the plant matrix and dissolve the desired compounds through diffusion and osmosis, and then comes the filtration step, which removes the solid residue and yields the extract (Tena et al., 2022; Grabowska et al., 2022). This method is generally used for making herbal teas, medicinal infusions, and extracts which are used in pharmaceuticals, cosmetics, and food because of its simplicity, cost effectiveness, and capacity to extract phenolic compounds, flavonoids, and other antioxidants. Infusion gives very potent extracts with high antioxidant activity and very low levels of degradation of sensitive compounds hence it is the preferred method for both home and industrial preparation of functional beverages and plant-based remedies (El et al., 2022; Tena et al., 2022; Grabowska et al., 2022).

2.6 Digestion

The digestion-extraction technique is a modified form of maceration, where the material of plant is soaked in a suitable solvent with gentle heating up to a temperature that will not destroy the active phytochemicals. This implies that the solubility and diffusion of polyphenols and other bioactive compounds which are poorly soluble in the solvent are increased by the mild heat and also the mass transfer rate of bioactive compounds is enhanced without losing the quality of heat-sensitive constituents (Alara etal., 2021; Bitwell et al., 2023). The process gently heats the mixture for a specific period, thus facilitating diffusion of the solvent into plant tissues, and consequently, dissolution and liberation of target constituents are achieved while the risk of thermal degradation is minimized. Solid residue is filtered and separated from the extract. Digestion is a very efficient method for isolating polyphenolic substances and other bioactives from plant materials that are not easy to dissolve at room temperature; hence, it is a significant method for the production of herbal medicines, nutraceuticals, and functional food ingredients. However, this method is limited to its simple procedure, low cost, and ability to extract only those compounds that need mild heating for optimal recovery; nevertheless, it is not appropriate for substances that are highly thermolabile (Alara et al., 2021; Kumar et al., 2023; Bitwell et al., 2023).

2.7 Hydro-distillation

Hydro-distillation also known to be steam distillation is among the oldest and most recognized techniques in extracting the essential oils and other volatile compounds from plant materials. Hydro-distillation process can be carried out very differently, depending on whether plant compound is completely immersed in water (hydro-distillation) or laid partially in steam (steam distillation); however, in both cases the mixture is gradually heated until it reaches the boiling point of the water. The main idea is to allow the compounds that one wants to extract to be distillated together with the water vapor and to subsequently freeze their boiling point by the vapor; thus, thermal degradation does not occur during extraction. The way it works is, when water or steam is allowed to flow through the plant material, it disrupts the cell walls, thereby releasing and carry the oil which vaporized with the steam. The vapor is cooled down and the essential oil is extracted from the water because of their different densities and solubilities. Hydro distillation and steam distillation are preferred methods to their simplicity, non-use of solvents, and large-scale production possibilities, but they also entail significant energy consumption and may cause some hydrolysis or degradation of sensitive compounds. These extraction methods are widely used in food, cosmetic, and pharmaceutical factories not only for the separation of essential oils- herbs, spices, and fragrant plants but also for the production of fragrances and natural flavorings (Kapadia et al., 2022; Lainez-Ceron et al., 2021; Wainer et al., 2022).

2.8 Expression

Expression, otherwise called mechanical pressing or cold pressing, is a technique in which solvent is not used for extraction. It is a method that relies on using heavy machinery to press oils or bioactive substances out of the plant materials; primarily, seeds, fruits, and vegetable peels are used for this extraction. The method is basically relying on the application of physical pressure most of the times through screw or hydraulic presses to break plant cell walls and release the oils or juices contained in them without the use of heat or chemicals, thus keeping the natural make-up and bioactivity of the extract. On the other hand, during this process, plant material is placed under a press and it is subjected to high pressure is applied and as a result, the oil or juice is segregated from the solid matrix; the liquid is then gathered and the leftover solid waste (cake or pulp) is removed. This method is frequently done at low temperatures (below 40°C) so that these sensitive clients like polyphenols and antioxidants do not get destroyed which leads to extracts with lesser quality and functional borderline quality. Expression is an extraction method widely adopted in several sectors namely food, nutraceuticals, cosmetics, pharmaceuticals for high-value oils (e.g., olive, flaxseed, citrus and seaweed oils) as well as for protein-rich juices from plant biomass. A drawback of mechanical pressing is that although it is environmentally friendly and produces pure and solvent-free products, it usually offers lower recovery rates than the solvent extraction methods. Hence, they are sometimes combined with the enzymatic or solvent-assisted techniques to maximize the output in industrial applications (Juul et al., 2021; Kapadia et al., 2022; Vovk et al., 2023; Rahim et al., 2023; Geow et al., 2021).

2.9 Enfleurage

Enfleurage is an ancient extraction technique, continues to be present and sometimes is even the only way to extract the very fragile and volatile essences from flowers that cannot be subjected to heat. The essential concept of enfleurage is to take pure and neutral fats at ambient temperature and to let them absorb the fragrance molecules that can be released through fresh flower petals thereby keeping the scent untouched in its natural form and allowing no further treatment (Wu et al., 2021). More technically, fresh petals are laid over the surface of a layer of fat and after some days the fat becomes impregnated with the aromatic substances, the used petals is replaced by new ones in order that fat is filled with fragrance. The scented fat or "pomade" is then merged with alcohol for the purification of the essential oil because the fragrance dissolves in the alcohol while the fat is left behind (Bolouri et al., 2022). Enfleurage is extremely useful in extracting the flower scents of jasmine, tuberose and gardenia, which are very delicate and would be ruined by heat or harsh solvents. Although modern methods which are more efficient and faster have somewhat replaced enfleurage, it is still regarded as important in the perfume industry for providing the finest and most genuinely natural floral extracts and sometimes being the way of artisanal or niche fragrance production. Moreover, extracts made through enfleurage have been used in cosmetics, foods and pharmaceuticals not only as their purest source but also as the most tempting and sometimes even active aroma (Wu et al., 2021; Sattayakhom et al., 2023; Bolouri et al., 2022).

Table 1: Advantages and Disadvantages of Conventional Extraction Methods

S.No	Method	Advantages	Disadvantages	References
1.	Maceration	Simple, low cost, minimal equipment, preserves heat-sensitive compounds	Long extraction time, lower yield, possible batch variation	El et al., 2022; Santos et al., 2022; Sridhar et al., 2021
2.	Percolation	Higher yield, faster than maceration, efficient solvent use	Requires specialized equipment, not ideal for all plant types	El et al., 2022; Wilson et al., 2022; Sridhar et al., 2021
3.	Soxhlet Extraction	High yield, effective for exhaustive extraction, appropriate for thermostable compounds	High solvent and energy use, not appropriate for heat-sensitive compounds, long duration	El et al., 2022; Santos et al., 2022; Sridhar et al., 2021
4.	Decoction	Simple, effective for hard plant materials (roots, bark), water as solvent	Incompatible for heat-sensitive compounds, possible loss of volatiles, limited to water-soluble	Sridhar et al., 2021; El et al., 2022
5.	Infusion	Simple, preserves some heat-sensitive compounds, minimal equipment	Lower yield, limited to water-soluble compounds, not suitable for hard materials	El et al., 2022; Sridhar et al., 2021
6.	Digestion-Extraction	Faster than maceration, moderate temperature increases extraction rate	Risk of degrading heat-sensitive compounds, not suitable for all phytochemicals	Sridhar et al., 2021
7.	Hydro-distillation	Good for volatile oils, no organic solvents needed	Loss of heat-sensitive or water-soluble compounds, high energy use	Kant & Kumar 2022; Santos et al., 2022
8.	Expression	Simple, solvent-free, preserves natural aroma/flavor	Limited to high-oil content materials (e.g., citrus), low yield for most plants	Kant & Kumar 2022
9.	Enfleurage	Preserves delicate, heat-sensitive aromas, solvent-free	Labor-intensive, time-consuming, low yield, mainly for specific flowers	El et al., 2022; Sridhar et al., 2021

III. Non-Conventional Extraction Technique

Fig. 2 represents non-conventional extraction techniques, like supercritical fluid extraction, ultrasound-assisted extraction, pulsed electric field extraction, and microwave-assisted extraction, present considerable benefits higher than the classical ones. Extraction efficiency increased,and use of solvent and energy is minimized, and the sensitive bioactive compounds are vastly preserved, thus rendering the methods environmentally friendly and fit for large-scale manufacturing. Nevertheless, the selection of a technique is subject to the type of compound and matrix as well as the requirements for process optimization (Jha and Sit et al., 2022; Shen et al., 2023; Quiterio et al., 2022).

3.1 Ultrasound-Assisted Extraction

Ultrasound-Assisted Extraction (UAE) is an exceptional green isolation process that use ultrasonic waves, or inaudible sound frequencies, to significantly enhance the extraction yield of various bioactive substances from different sources, which include plants and food waste (Shen et al., 2023). The underlying procedures of UAE is the cavitation effect, where in a liquid medium rapid cycle of formation and collapse of tiny bubbles lead to the creation of very strong local shear forces and micro jets. The physical phenomena of UAE thus aid the extraction process by breaking down the cell walls, allowing the solvent to enter and more difficult molecule to move into the solvent (Deng et al., 2022). The UAE method essentially helps the cavitation effect to lead to the disintegration of plant parts thus facilitating their dissolving in the solvent such as polyphenols, carotenoids, and polysaccharides (Sanjaya et al., 2022). Besides these, the process conditions like ultrasonic frequency, amplitude, solvent type, and duration of extraction significantly influence the final yield and quality, thus can be tuned for optimum extraction. The UAE technique has an extensive field of application in the natural pigment, lipid, protein, and other bioactive extraction for the food, pharmacy, cosmetic sectors while reducing usual isolation time, solvent usage, and even thermolabile compounds incompatibility that are main factors of it being regarded as an eco-friendly method (Das et al., 2022).

3.2 Microwave-Assisted Extraction (MAE)

Microwave-Assisted Extraction (MAE) is an advanced extraction method that makes use of microwave energy to enhance the extraction of bioactive compounds from plant sources. It offers many benefits over the conventional methods like a lesser volume of solvent, quicker extraction times, etc (Nour et al., 2021). The principle of MAE is based on the interaction of the microwave radiation with polar molecules present in sample and solvent. This in turn, causes vigorous oscillation, then the heating coming internally which results in cell walls being broken and mass transfer becoming easier (Lopez-Salazar et al., 2023). In the case of a mechanism, microwaves would cause dipole rotation as well as ionic conduction, which would lead to the localized heating, increase in vapor pressure, and ultimately rupture the plant cell walls thereby achieving the liberation of targeted compounds into the solvent (Elakremi et al., 2023). MAE finds extensive application for the isolation of phytochemicals with a large market value like phenolic, flavonoids, pigments, oils from different types of sources such as food waste, medicinal plants, and microalgae, which again proves that it is a green and sustainable alternative for the pharmaceutical, food, and cosmetic sectors (Alvi et al., 2022). The type of solvent, extraction time, microwave power, and temperature among others that can be adjusted for higher yields determines the microwave-assisted extraction efficiency and better-quality extracts (Georgiopoulou et al., 2023). Furthermore, MAE is an eco-friendly method due to the lower energy requirement, minimal destruction of thermolabile compounds (Lopez-Salazar et al., 2023). This method has also been effectively combined with others like ultrasound, to further improve extraction effectiveness and quality of product (Zhang et al., 2023).

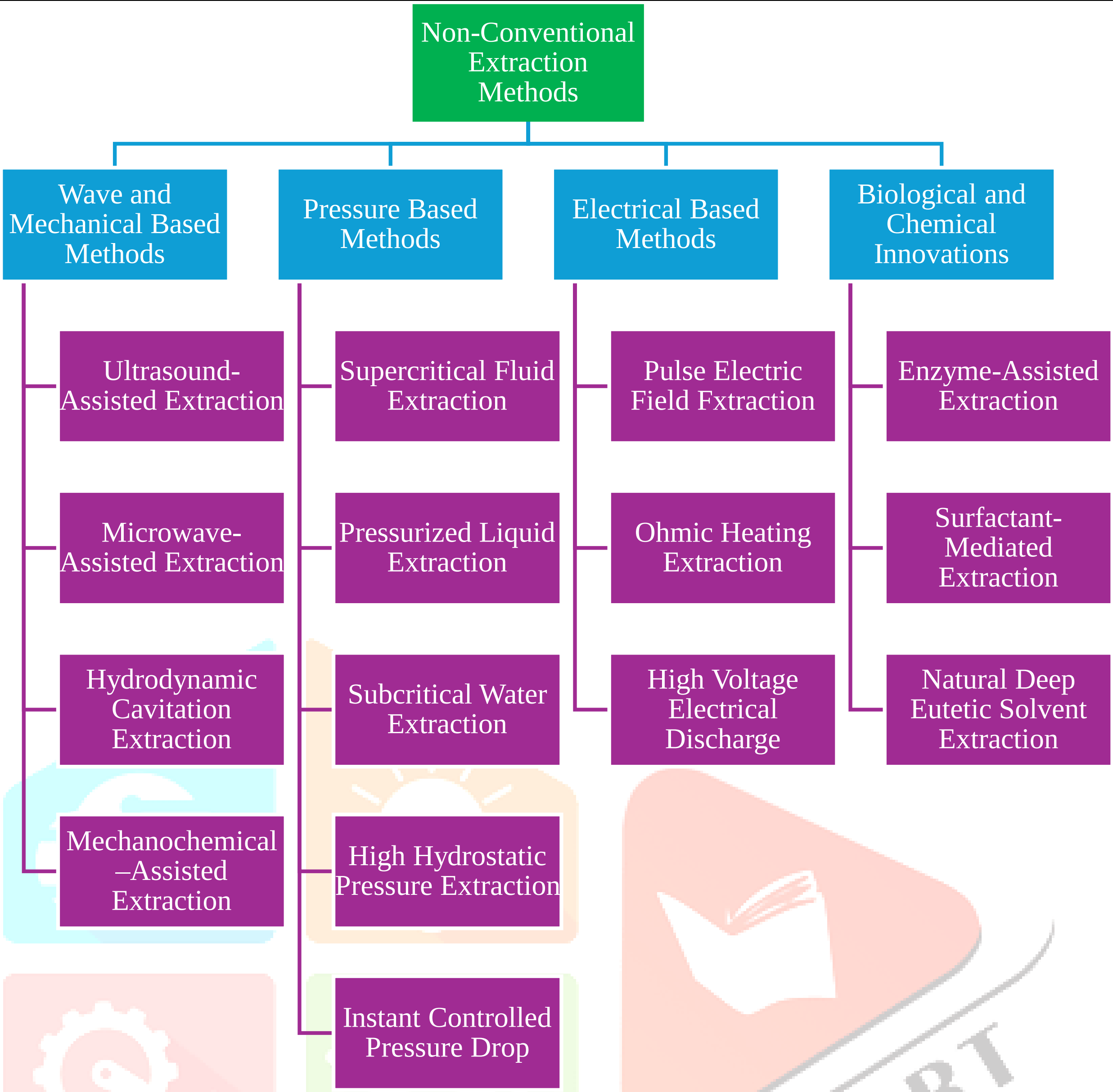

Fig 2: The types of non-conventional extraction methods

3.3 Hydrodynamic Cavitation Extraction (HCE)

Hydrodynamic Cavitation Extraction (HCE) is an eco-friendly technique to extract which vapor bubbles in a liquid are formed, grown and then violently collapsed, using the liquid, passed through a device like orifices or venture tubes, as the transferring agent, to enhance the mass transfer and cause cell wall distruptions (Arya et al., 2023). HCE's principle is to create localized low-pressure zones in the flowing liquid, and this causes the vapor cavities to form; at the time of the collapse of the cavities, energy is released as heat and pressure as well as shockwaves and microjets (Mittal & Ranade 2023). This process ultimately enhances the rupture of cell walls and membranes promoting the release of intracellular compounds such as polyphenols, proteins, and pigments, which are dissolved and are thus ready for extraction by the solvent (Ciriminna et al., 2023). HCE is a very advantageous and effective method for the isolation of bioactive compounds from plants and algae since it functions at lower temperature, which means that the heat-sensitive molecules are preserved and the use of solvent is minimized (Sun et al., 2022). The approach allows scale up and can be performed along with other extraction methods, like microwaves or enzymatic treatments, for yield and selectivity to be further improved (Cako et al., 2023). HCE is utilized in the areas of food processing, extraction of natural product, treatment of sewage and making of biofuels, and all of these fields take advantage of HCE's benefits like increased yield, improved quality of output, and less environmental pollution when put alongside traditional methods (Zheng et al., 2022).

3.4 Mechanochemical-Assisted Extraction (MCAE)

Mechanochemical-Assisted Extraction (MCAE) is a sustainable, highly efficient extraction method that brings out the good side of nature by applying strong mechanical forces like grinding or milling to make raw materials undergo physical changes and then releasing the eco-friendly active compounds. It is a bet made not to use harmful organic solvents (Fan et al., 2022). The MCAE technique is very simplistic since it involves cellular treatment whereby the cell membrane is destroyed, and some physical and chemical changes take place, thus, increasing the solubility and speeding up the extraction process at low temperatures, even often at room temperature (Wu et al., 2017). In terms of mechanistic perspective, MCAE enlarges surface area, raises the material porosity, which in turn allows the solvent to penetrate and mass transfer to take place thus decreasing the time of extraction and reduced solvent consumption and energy requirements relative to traditional techniques (Shen et al., 2022). This extraction process can be assisted with solid acids, alkalis, or surfactants to improve the effectiveness and selectivity of isolation even more by encouraging chemical reactions or safeguarding the delicate compounds (Fan et al., 2023). The usage of MCAE includes the extraction of flavonoids, polysaccharides, alkaloids, saponins, and proteins from diverse natural sources, showing higher yields and increasing the bioactivities like hepatoprotective and antioxidant effects (Guo et al., 2021; Liu & Xi 2021). The simplicity, environmental friendliness, and potential for sustainable industrial production attached to MCAE have made it to be very favorable in food, pharmaceutical, and nutraceutical sector (Fan et al., 2022; Wu et al., 2017).

3.5 Supercritical Fluid Extraction (SFE)

Supercritical Fluid Extraction (SFE) is a green extraction technique that mainly employs carbon dioxide (CO2) in supercritical state to isolate target compounds from different sources in controlled way at low temperatures and high pressures which are quite specific (Ahangari et al., 2021). The basis of SFE lies in the unconventional features of supercritical fluids which are gas-like in their ability to diffuse and liquid-like in their power to dissolve at the same time, making it possible for very efficient permeation into the matrix and dissolving of target compounds (Herzyk et al., 2024). The mechanism changes the density and dissolving power of the supercritical fluid by varying pressure and temperature, which consequently allows selective extraction and easy separation of the solvent by degassing free from toxic residues (Zhou et al., 2021). SFE has become a processing method in the food industry, pharmaceutical, cosmetic, and nutraceutical industries, it is implemented for extracting seed oils, cannabinoids, essential oils, antioxidants, and pigments with the highest purity and bioactivity Ahangari et al., 2021; Rantasa et al., 2024; Dashtian et al., 2024). This method comes with the advantages of low extraction temperatures, significantly decreased solvent consumption, quicker processing, and isolation of heat liable compounds (Li et al., 2022). One of the latest developments is the SFE integration with supercritical fluid chromatography for the online and analysis that makes the compound isolation process more efficient and automatic (Gros et al., 2021).

3.6 Pressurized Liquid Extraction (PLE)

Pressurized Liquid Extraction (PLE) is among the first for revolutionizing extraction by using the combination of increased temperature and pressure. This technique (Soriano et al., 2024) allows the isolation of bioactive compounds from solid and semi-solid matrices with efficiency. One of the main factors that lead to better penetration and solubility of the solvent thus faster and more efficient extraction is increasing temperature and pressure (Visnjevec et al., 2024). Thus, the elevated pressure maintains the solvent in liquid state while the high temperature accelerates the desorption of compounds from the matrix, which in turn makes it possible to use less extraction times and less solvent as compared to the traditional methods (Barp et al., 2023). PLE also allows the clean-up steps to be done during the extraction by using adsorbents in the extraction cell to trap the interfering substances; hence, selectivity and flexibility are improved (Soriano et al., 2024). The number of applications of PLE is extensive, one of which is the isolation of phenolic compounds, contaminants, and bioactives from food, environmental, and plant matrices like grape pomace and seaweeds (De et al., 2024; Perez-Vazquez et al., 2023). PLE is regarded as a highly promising method for the sustainable isolation of the food, pharmaceutical, and environmental sectors because of its automation, high throughput, and eco-friendly nature (Fraguela-Meissimilly et al., 2023).

3.7 Subcritical Water Extraction (SWE)

Subcritical Water Extraction (SWE) is a technique of extracting which is not harmful to the environment, which is characterized by utilization of water at high temperatures (between 100°C and 374°C) and pressure above the 218 atm point so that it remains in the liquid phase. This technique is able to boost the solubility and diffusion of the target molecules, and therefore the extraction of them (Mikucka et al., 2022). The basic idea behind SWE is to take advantage of water's special characteristics under subcritical conditions; these being that the dielectric constant of water is reduced which allows water to act as an organic solvent with a wide range of bioactive compounds being extracted (Costa et al., 2023). The technology increases the matrix density and hence the transfer of mass which leads to using less energy for the extraction of phenolics, polysaccharides, and the like without the downside of using harmful solvents (Basak & Annapure et al., 2022). In contrast, SWE can retain even more of the fragile compounds than the conventional methods; for instance, pectin isolation where SWE keeps the areas of structure intact that are usually destroyed by acid extraction (Pereira et al., 2024). Specific applications of SWE include the recovery of antioxidant compounds from distillery stillage, the popping of polysaccharides with increased antioxidant activity from mushrooms, and the isolation of bioactive from seaweeds and fruits and their waste for the food, pharmaceutical, and environmental sectors (Zhang et al., 2022; Gan & Baroutian 2022). The green extraction method, which is also able to vary the extraction parameters so as to get the maximum and best quality yield, is going to be the sustainable professional extraction processes of the future (Benvenutti et al., 2022).

3.8 High Hydrostatic Pressure Extraction (HHPE)

High Hydrostatic Pressure Extraction (HHPE) is a non-thermal extraction method that works by applying extremely high pressures, usually in the range of 100-600 MPa, to disrupt cellular structures and it enables the bioactive compounds to be extracted from different matrices (Tepsongkroh et al., 2023). HHPE operates on the principle of uniformly applied pressure, which alters the physicochemical properties of biomolecules without major heat production, hence conserving the heat-sensitive compounds (Rostamabadi et al., 2023). More specifically, high pressure leads to changes such as denaturing of proteins and breaking down of cell walls, which in turn allow the solvent to penetrate better and thus give a higher yield and more efficient extraction (Chen et al., 2023). Besides that, HHPE has the ability to change the polysaccharides' structure and nutritional characteristics in such a way that their functional properties of emulsification and viscosity are enhanced (Duan et al., 2022). The application areas of HHPE are diverse, such as isolation of pectin from peels of fruit with a concomitant increase in yield and quality; besides the recovery of bioactive compounds from plants like saffron, which is already a demonstration of the potential of HHPE in the food, pharmaceutical, and nutraceutical industries (Bakshi et al., 2023; Duan et al., 2022). The less extraction times, less solvent usage, and the preservation of bioactivity are some of the pros of this method which, when taken together, make it a great eco-friendly and sustainable substitution to traditional extraction techniques (Tepsongkroh et al., 2023).

3.9 Instant Controlled Pressure Drop (ICPD)

Instant Controlled Pressure Drop (ICPD) is a newer, eco-friendly, and innovative technology that mainly extracts and texturizes food and plant compounds. The process includes treating the material with high-pressure saturated steam for a very short time, then quickly dropping the pressure to a vacuum. This leads to the instantaneous auto-vaporization of the water inside the cells (Usman et al., 2022). The technique used is based on the hydro-thermo-mechanical phenomena where the rapid dropping of pressure tears the cell walls, opens the cell more, and so facilitates the release of intracellular compounds (Herzyk et al., 2024). The whole thing is based on the fast changing of the pressure, which not only helps to retain the heat-sensitive bioactive molecules but also makes the mass-transfer better thus drying or extracting processes become more efficient (Usman et al., 2022). The food industry is the one where ICPD is widely used, e.g., for drying of fruits and vegetables, for the extraction of polyphenols and antioxidants, and so on, but still the quality of nutrients and sensory properties is excellent compared to conventional methods (Raghunath et al., 2023). Besides, it claims to be energy-efficient, reduce processing time, and have the capacity to keep the most precious compounds intact; thus, it is viewed as a sustainable method for food and nutraceuticals (Usman et al., 2022).

3.10 Pulsed Electric Field (PEF) Extraction

Pulsed Electric Field (PEF) extraction is presented as a non-thermal method that applies high-voltage electric fields of very brief durations to increase the extraction of valuable compounds from living sources (Naliyadhara et al., 2022). The procedure consists of sending electric pulses between the electrodes leading to electroporation, whereby the cell membranes get irreversible pores formed, thus being made more permeable (Ranjha et al., 2021). The aforementioned process allows the intracellular compounds like bioactive phytochemicals to come out more easily than traditional methods (Bocker & Silva 2022). The PEF machines are made to control the disruptions of the cells effectively by high field strengths, pulse durations, and energy input. PEF extraction is helpful for the recovery of natural colorants, proteins, essential oils, and other bioactive compounds from plant tissues and food by-products (Castro et al., 2023). The method is being applied in the food and nutraceutical sectors for different purposes including boosting extraction yields, minimizing solvent and energy usage, and retaining the nutritional and organoleptic properties of the products (Naliyadhara et al., 2022). The technology is also marked as green since it has low thermal effects and that the operational costs are lower compared to other methods (Ranjha et al., 2021). Besides, it plays the role of a pretreatment process, which offers higher efficiency for the extraction processes that follow (Bocker & Silva 2022). PEF-assisted extraction has been applied successfully to fruits, vegetables, and agro-industrial wastes, thus playing its part in the sustainability of food production (Castro et al., 2023).

3.11 Ohmic Heating Extraction (OHE)

Ohmic Heating Extraction (OHE) is a new technique of electrowave and thermal power that operates by allowing the fully active alternating electric current to pass in a direct line through the food matrix, thus causing very fast and uniform heating throughout (Joule effect) (Ferreira-Santos et al., 2024). The core concept is the direct and complete heating of the sample via electrical energy transformation, allowing accurate control of the temperature and reducing the thermal gradients to a minimum (Torgbo et al., 2022). At the same time, OHE works on a "two-way street" heating, whereby the material is subjected to electroporation and electropermeabilization of the cell membranes and hence the diffusion of intracellular compounds into the solvent is facilitated (Ferreira-Santos et al., 2024). This technology's capability influenced by such parameters as the electric field strength, current intensity, and processing time (Cilingir et al., 2021). OHE is noted for the quantative isolation of different bioactive compounds, like phenolics, pectin, and pigments, from plant materials, which is usually accompanied by increased extraction rates and improved selectivity compared to the conventional methods (Shao et al., 2021). The processes are prevalent in the food, nutraceutical, and pharmaceutical industries, e.g. recovery of antioxidants from grape pomace, pectin from citrus peels, and natural colorants from vegetables (Ferreira-Santos et al., 2024). Torgbo et al. (2022) not only proved that OHE is associated with less energy and shorter processing time, but also that it is an efficient and sustainable production method. The new technology can process a great diversity of food products, but it can also be applied with other green extraction methods for better processing (Shao et al., 2021). Although the process is non-invasive and the health-benefiting and sensory properties of the extracts remain unchanged, it is still possible due to its gentle and controlled heating (Cilingir et al., 2021).

3.12 High Voltage Electrical Discharge (HVED)

High Voltage Electrical Discharge (HVED) is an innovative, non-thermal isolation method that generates electric fields (usually between 20 and 60 kV) across electrodes that are submerged in water, thus, causing the electrical dissipation of the water and the forming of plasma channels (Sridhar et al., 2021). The mechanism is actually a combination of two phases: a prebreak down phase with formation of shock waves and bubbles, followed by a breakdown phase where the plasma discharge results in very strong turbulence and cell disruption (Gil-Martin et al., 2022). In mechanistic point, HVED is a multi-faceted process that integrates electroporation, shock waves, cavitation, and reactive species formation, eventually causing cell wall and membrane rupture that facilitate intracellular bioactive compounds liberation (Pattnaik et al., 2021). Among the process parameters, the electrode distance, voltage, and treatment time are very crucial for achieving effectiveness of extraction and reducing the degradation of desired molecules to the lowest level (Bocker& Silva., 2022). The HVED technology has become a widespread practice for extracting polyphenols, antioxidants, and other valuable phytochemicals from plant-based food waste and by-products (Sridhar et al., 2021). It is indeed a favorable choice based on the advantages it offers, such as the elevation of the extraction yields, reduction of the solvent and energy consumption, and completely the favorable condition for the heat-sensitive compounds (Gil-Martin et al., 2022). Conversely, the uncontrolled bursting of the cellular materials could lead to a more complicated subsequent purification process (Pattnaik et al., 2021). In this regard, the development of functional foods and nutraceuticals from grape seeds, orange peels, and pomegranate peels are some of the proposed application areas (Bocker& Silva., 2022).

3.13 Enzyme-Assisted Extraction (EAE)

Enzyme-Assisted Extraction (EAE) is the method that employs the use of a specific group of hydrolytic enzymes in cell wall disruption and other structural features breaking up thus, purifying the bioactive materials from the plant, fungal, or animal sources (Gonzalez et al., 2022). Since the EAE process is based on the fact that polysaccharides and proteins are being hydrolyzed by cellulases, pectinases, and proteases, this leads to better penetration by the solvent and, consequently, higher yields of extraction without the use of strong chemicals (Dominguez-Rodriguez et al., 2021). During the extraction process, the enzymes act by weakening the cell walls; hence, polyphenols, polysaccharides, and essential oils among the various intracellular components are made more available, which subsequently results in a higher yield and the activity being better preserved than without the use of enzymes (Syrpas et al., 2021). EAE is considered eco-friendly and economical as it not only lessens extraction time and solvent use but also maintains the integrity of the compounds compared to traditional extraction techniques (Das et al., 2021). EAE advantage include the migrate antioxidants from the fruit pomace, the extracted polysaccharides turned out to have higher antioxidant activity, and bioactive compounds were secured for nutraceutical and pharmaceutical applications (Lubek-Nguyen et al., 2022; Amulya & Ule 2023). In order to increase the extraction yield and obtain the desired bioactivity, the adjustment of factors like the type of enzyme, its concentration, pH, temperature, and time must be done carefully (Syrpas et al., 2021). The EAE method used with approaches such as ultrasonication or supercritical fluid extraction has a great effect on the extraction process selectivity and efficacy (Patil et al., 2021; Li et al., 2021). To conclude, EAE is not only eco-friendly but also a green and economical way of producing raw natural goods of superior quality with diverse industrial uses (Gonzalez et al., 2022).

3.14 Surfactant-Mediated Extraction (SME)

Surfactant-Mediated Extraction (SME) is an advanced method for isolating the target compounds from complex mixtures through surfactants that enhance solubilization and separation. The fundamental concept of SME is the ability of the surfactants to form micelles or microemulsions that have both the hydrophobic and hydrophilic substances in them, thereby resulting in the extraction process being aided not only by the increase in solubility and selectivity but also by the diminishing use of organic solvents (Vakh & Koronkiewicz 2023). On a molecular basis, surfactants lower the tension at the interface and alter the polarity atmosphere, which subsequently frees and moves the compounds into the extracting solvent; for example, the use of natural surfactants like soapnut saponin in microwave-assisted extraction has enabled the simultaneous high-efficiency extraction of a wide range of phytochemicals (Wang et al., 2022). The use of cutting-edge SME techniques such as temperature-modulated ionic liquid-based surfactant-free microemulsions not only permits the in-situ separation and enhancement of compounds with varying polarities but also such phase changes are governed by temperature (Luo et al., 2023). The advantages associated with SME methods are numerous and cover a wide spectrum from the extraction of phytochemicals through plants to the recovery of oils, which is a major reason why these methods are very flexible in both the analytical and industrial fields since they modify the wettability and lower the interfacial tension in the porous media (Bashir et al., 2022; Chowdhury et al., 2022). Nonetheless, supercritical CO_2 extraction is a method that is environmentally friendly, cost-effective, and can be scaled for large production, the current trend in research being the surfactant types and extraction conditions that are appropriate for different applications (Vakh & Koronkiewicz 2023).

3.15 Natural Deep Eutectic Solvents (NADES)

Natural Deep Eutectic Solvents (NADES) are made from natural hydrogen bond donor (HBD) and acceptor (HBA) mixtures composed of amino acids, sugars, and organic acids, that are mixed together in specific ratios by hydrogen bonding which results in low melting point liquids (Koh et al., 2023). The extraction of NADES is very dependent on their unique physical and chemical properties such as less volatility, high solubility, and biodegradability, that makes the isolation and stabilization of the bioactive compounds from the natural sources very easy while being non-toxic and eco-friendly (Jauregi et al., 2024). At the molecular level, NADES to a certain degree rupture the plant cell walls and simultaneously very strongly bind with the target molecules, which causes the increase of extraction efficiency and permeability; additionally, their viscosity and polarity can be changed by temperature and water content to obtain the best extraction results (Mehariya et al., 2021). Use of NADES extraction is very wide-ranging and involves for example the isolation of phenolic compounds, flavonoids, saponins, and other plant metabolites from plants and algae, which can be used for food, pharmaceutical, nutraceutical, and cosmetic industries because of the extracts' improved solubility, stability, and bioavailability (Hikmawanti et al., 2021; Li 2022; Kaoui et al., 2023). Besides, NADES have been studied in terms of application in cryopreservation, removal of heavy metals from food, and as being green solvents in bio-refinery processes, thus indicating their versatility and sustainability across various domains of extraction and preservation that are not harmful to the environment (Wu et al., 2022; Bragagnolo et al., 2024). The above characteristics indicate that NADES are a very green extraction technology with good potential to fully participate in the green chemistry and sustainability crusade, while the problems of scaling and standardization still exist (Schuh et al., 2023).

Table 2: Comparative Table of Non-Conventional Extraction Methods: Advantages, Disadvantages, and Applications

S.No.	Extraction Method	Advantages	Disadvantages	Applications	Citations
1.	Ultrasound-Assisted Extraction (UAE)	High efficiency, reduced solvent and energy use, short extraction time, preserves thermolabile compounds	Scale-up challenges, equipment cost, possible degradation with excessive sonication	Extraction of polyphenols, lipids, essential oils, pigments, bioactives in food/pharma/cosmetics	Shen et al., 2023; Jha & Sit 2022; Low et al., 2022; Deng et al., 2022; Mehta et al., 2022; Ponphaiboon et al., 2023
2.	Microwave-Assisted Extraction (MAE)	Rapid extraction, high yield, low solvent use, energy efficient, suitable for heat-sensitive compounds	Uneven heating, limited to polar solvents, potential compound degradation at high power	Pigments, polyphenols, essential oils, bioactives from plants, food, and agri-waste	Shen et al., 2023; Bhadange et al., 2024; Nonglait & Gokhale 2024; Zhang et al., 2023; Ponphaiboon et al., 2023
3.	Hydrodynamic Cavitation Extraction (HCE)	Enhanced mass transfer, low solvent use, scalable, energy efficient	Equipment complexity, optimization needed for different matrices	Extraction of bioactives, essential oils, and flavors from plant materials	Ponphaiboon et al., 2023; Low et al., 2022
4.	Mechanochemical-Assisted Extraction (MCAE)	Solvent-free or low-solvent, eco-friendly, can disrupt tough matrices	Limited industrial application, possible contamination from grinding media	Extraction of polysaccharides, phenolics, and other bioactives	Jha & Sit et al., 2022; Alam 2024
5.	Supercritical Fluid Extraction (SFE)	Selective extraction, no solvent residue, tunable parameters, high purity,	High equipment cost, requires high pressure, not suitable for all compounds	Lipids, essential oils, flavors, pharmaceuticals, nutraceuticals	Kant & Kumar 2022., Ferreira et al., 2022., Saini et al., 2021., Quiterio et al., 2022; Bhadange et

		green technology			al., 2024; Pagano et al., 2021; Rani et al., 2021; Picot-Allain et al., 2021; Ponphaiboon et al., 2023
6.	Pressurized Liquid Extraction (PLE)	Fast, efficient, low solvent use, suitable for thermolabile compounds, scalable	High equipment cost, limited to certain solvents, possible degradation at high temp/pressure	Polyphenols, antioxidants, oils, bioactives from food and plant matrices	Tena & Asuero 2022; Quiterio et al., 2022; Raghunath et al., 2023; Alyammahi et al., 2023; Pagano et al., 2021; Mediani et al., 2023; Picot-Allain et al., 2021
7.	Subcritical Water Extraction (SWE)	Uses water as solvent, tunable polarity, green, no toxic residues, high efficiency	High temp/pressure may degrade sensitive compounds, equipment cost	Extraction of alkaloids, polyphenols, glycosides, essential oils	Raspe et al., 2022; Quiterio et al., 2022; Alam et al., 2024; Cheng et al., 2021
8.	High Hydrostatic Pressure Extraction (HHPE)	Preserves bioactivity, low temp, short time, high yield, minimal solvent	High equipment cost, scale-up challenges	Extraction of antioxidants, pigments, bioactives from fruits/vegetables	Jha & Sit 2022; Calderon-Oliver, M., & Ponce-Alquicira 2021; Rifna et al., 2023; Daud et al., 2022
9.	Instant Controlled Pressure Drop (DIC)	Rapid extraction, enhances mass transfer, preserves quality, energy efficient	Specialized equipment, limited industrial adoption	Extraction of flavors, essential oils, bioactives from plant matrices	Jha & Sit 2022; Rifna et al., 2023
10.	Pulsed Electric Field (PEF) Extraction	Non-thermal, high yield, low solvent/energy use, preserves bioactivity	Equipment cost, scale-up and safety concerns	Extraction of phytoconstituents, proteins, pectin, essential oils	Ranjha et al., 2021; Jha & Sit 2022; Raghunath et al., 2023; Calderon-Oliver & Ponce-Alquicira 2021; Rifna et al., 2023; Camara et al., 2022

11.	Ohmic Heating Extraction (OHE)	Uniform heating, rapid, energy efficient, preserves quality	Limited to conductive matrices, equipment cost	Extraction of polyphenols, essential oils, bioactives	Rifna et al., 2023; Camara et al., 2022
12.	High Voltage Electrical Discharge (HVED)	Non-thermal, enhances cell disruption, high yield, low solvent use	Equipment complexity, safety concerns, scale-up issues	Extraction of anthocyanins, polyphenols, bioactives	Tena & Asuero 2022; Carpentieri et al., 2021
13.	Enzyme-Assisted Extraction (EAE)	High selectivity, mild conditions, high yield, eco-friendly	High enzyme cost, possible enzyme inactivation, long extraction time	Extraction of polyphenols, essential oils, pigments, vitamins, bioactives	Tena & Asuero 2022; Das et al., 2021; Ferreira et al., 2022; Quiterio et al., 2022; Raghunath et al., 2023; Calderon-Oliver & Ponce-Alquicira 2021; Pagano et al., 2021; Mediani et al., 2023; Picot-Allain et al., 2021
14.	Surfactant-Mediated Extraction (SME)	Enhances solubility, efficient for hydrophobic compounds, low solvent use	Surfactant removal needed, possible toxicity, regulatory issues	Extraction of hydrophobic bioactives, essential oils, flavors	Jha & Sit 2022; Alam et al., 2024
15.	Natural Deep Eutectic Solvents (NADES)	Green, biodegradable, tunable properties, high extraction efficiency, low toxicity	Viscosity issues, limited industrial data, possible need for downstream purification	Extraction of polyphenols, alkaloids, proteins, bioactives from food and plant matrices	Garcia-Roldan et al., 2023; Yahaya et al., 2024; Geow et al., 2021; Cannavacciuolo et al., 2022; Nakhle et al., 2021; Mansinhos et al., 2021

IV. CONCLUSION

The ongoing transition from traditional to innovative, eco-friendly extraction methodologies is essential for meeting the growing global demand for natural, bioactive-enriched products in a sustainable manner. Future research should prioritize hybrid and integrated strategies, real-time process optimization, life-cycle assessments, and industrial-scale validation to fully realize the potential of plant-derived bioactive in promoting health, circular economy principles, and environmental stewardship. By adopting these innovative advancements, the field can transform abundant plant resources and agri-food by-products into valuable, functional ingredients that benefit both industry and society.

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