

Table S1. Strengths, limitations and applications of the main innovative-green-emerging extraction methods [181–186]. Examples of bioactive compounds extracted from plant by-products applying the mentioned emerging methods.

Method	Description	Advantages/strengths	Disadvantages/limitations	Applications	Examples Bioactive compounds/plant by products
UAE	High-frequency sound waves to enhance the extraction of compounds from solid materials (non-thermal process)	• Faster extraction • Reduced solvent use • Improved extraction yields • Increased bioavailability • Versatility • Preserves heat-sensitive compounds • Cost-Effective • Green Technology • Scalability	• Expensive equipment • Energy efficiency • Potential for degradation (higher ultrasonic intensity or duration may lead to degradation of heat-sensitive compounds) • Scalability challenges due to varying energy inputs • Difficulties for optimizing parameters (time, temperature, solvent, power)	• Extraction of bioactive compounds from plants and algae • Extraction of bioactive compounds from fruit and vegetable processing by-products • Extraction of plant natural products to develop new pharmaceuticals or cosmetic ingredients	Antioxidants/Orange peels [187]
MAE	Microwave energy to heat solvents in contact with a sample in order to partition analytes from the sample	• High speed • High efficiency • High yield and purity • Reduced solvent use	• Reduced efficiency with non-polar or volatile compounds • Inhomogeneous heating • Need for additional processing (sometimes filtration or	• Extraction of bioactive compounds from plants and food samples • Synthesis and analysis of pharmaceutical products	Polyphenols/Pineapple peel [188]

	matrix into the solvent	• More cost-effective (reduced solvent consumption, shorter processing time, potentially lower equipment costs) • Ease use • Suitable for thermolabile compounds (rapid heating)	centrifugation to remove solid residues) • Possible lipid burning • Availability of equipment (relatively inexpensive, but with limited availability and accessibility in certain settings)	• Environmental analysis. Extraction of pollutants from environmental samples • Other applications in animal tissue analysis, pulp and fiber extraction	
SFE	Supercritical fluid to extract a material	• High extraction yields in a short time • Minimal solvent usage • Preservation of thermally labile compounds • Tunable solvent density • Reduced energy consumption • No solvent residue	• High capital cost • High pressure requirements • Complexity of recycling • Limited polar compound extraction • Technical expertise required • Potential for non-reproducibility • May not be suitable for all samples • Moisture requirements (raw material may need freeze-drying)	• Food Industry. Extraction of natural products, bioactive compounds, fats, oils. • Pharmaceutical industry. Extraction of active pharmaceutical ingredients • Other industries. Fractionation of polymeric materials, extraction of environmental pollutants	Polyphenols, anthocyanins/Apple peels [189]
PLE	Elevated temperature and pressure to extract compounds from	• Fast extraction • Reduced solvent consumption	• High equipment cost • Optimization required for each application	• Extraction of bioactive compounds from plants and pharmaceutical samples	Antioxidants/ Pomegranate peel

	solid or semi-solid samples	● Automation (multiple samples with minimal human intervention) ● Improved selectivity (adjusting temperature and pressure, the polarity of the solvent can be altered and therefore enhances the extraction of specific compounds) ● Enhanced recovery of sensitive compounds that may be degraded during conventional extraction ● Versatility	● Potential degradation of thermolabile compounds ● High-moisture samples may require drying before extraction to avoid issues with co-extracted water ● Limited applicability for extracting very polar or ionic compounds ● Waste management (extract may require evaporation thus leading to waste generation)	● Food and beverage industry. Extraction of nutrients and natural products, contaminant removal, food waste valorization [190] ● Chemical manufacturing processes for extraction or purification. ● Environmental monitoring of pollution levels (including emerging contaminants like nitrosamines, alkyl phenols, bisphenol A, and UV filters). Extraction of contaminants (pesticides, heavy metals) from various environmental matrices
PEFAE	High-voltage electric pulses to enhance the extraction of bioactive compounds from biological matrices, including food waste	● Improved extraction efficiency (increased extraction yield, reduced solvents and energy) ● Reduced degradation of heat-sensitive compounds (due to reduced extraction time and temperature) ● Selective extraction of specific compounds	● High initial investment ● Effectiveness dependent on conductivity (high conductivity can affect the electroporation process) ● Temperature management ● Need for optimization for different materials ● Potential for side reactions (At high intensities, PEF can lead to	● Extraction of bioactive compounds, antioxidants, vitamins, pigments from food waste, plant tissues and microbial cells. Food waste valorization. ● Extraction of valuable compounds (proteins, polysaccharides, lipids, and pigments) from algal biomass. Hesperidin/Tangerine peel [191]

		• High quality of the extracted compounds (non-thermal processing) • Potential for Industrial Applications	changes in the extracted compounds) • Electrochemical reactions may impact the food product, produce electrode corrosion, fouling and electrolysis of water	• Food processing to improve the quality and shelf life of food products. • Biotechnology and medicine (cell manipulation and gene therapy) • Enzymatic extraction enhancement • Others: extraction of minerals	
EAE	Enzymes to enhance the release of bioactive compounds from plant and other biological sources	• High specificity • High efficiency and reproducibility • Reduced extraction time • Lower solvent consumption • Improved extraction efficiency • High quality extracts, with fewer impurities • Cost-Effective. Initial cost of enzymes can be high, but the overall process can be more cost-effective due to reduced solvent consumption and time	• High enzyme costs of enzymes for large-scale applications • Environmental conditions. Temperature, pH, and other environmental factors affect enzyme activity • Limited enzyme availability. Finding the right enzyme can be challenging. • Limited enzyme stability under industrial conditions • Potential for degradation of compounds under certain conditions	• Waste and plant by-products utilization for the extraction of valuable and bioactive compounds with potential therapeutic properties for the pharmaceutical and nutraceutical sectors • Valorization of plant by-products for enzyme production, sugar and fiber extraction • Food and Beverage industry. Improved quality of products and enhanced functional properties	Anthocyanins/Eggplant peel [192]

		• Enzymes work under mild conditions, preserving the integrity of extracted compounds • Enzymes can increase the solubility of certain compounds making them easier to extract	• Safety concerns. Some enzymes can cause allergic reactions or skin irritation • Scalability challenges. Some enzymes may be less effective or more expensive at larger scales		
FAE	Fermentation to increase the extraction of bioactive compounds from plant materials	• Economically viable • Improved extraction • Milder extraction conditions minimize the risk of thermal degradation of sensitive compounds • High yield • Reduced solvent use	• Slow process • Lower overall extraction rates in certain situations • Fermentation optimization can be complex • When fermentation processes are batch processes, they become labor-intensive and potentially less scalable • Difficulties for maintaining optima microbial growth in large-scale bioreactors • Dependent on the readily available carbon sources for starting the fermentation and for	• Pharmaceutical industry. Extracts may possess antibacterial, antifungal or anti-inflammatory effects • Food and beverage industry. Production of yogurt, cheese, sauerkraut and alcoholic beverages. Possibility of enhancing the nutritional value and functional properties of these products • Chemical industry. Production of ethanol from various sources • Agricultural Biotechnology. Improved crop yields and enhanced nutritional value of agricultural products	Ellagic acid/ Mexican rambutan peel [193]

			the sustained growth of fermenting microorganisms • Possible presence of unwanted microorganisms which reduce yield and final product quality	• Environmental Technology. Biological wastewater treatment	
SWE	Uses water in its supercritical state (373°C and 220 bars) as a solvent	• Rapid extraction • Increased selective extraction of specific compounds • Reduced solvent and energy used • Environmental friendliness. Supercritical fluids can be non-toxic, non-flammable, and leave no harmful residues • Preservation of labile compounds • Tunable solvent density to optimize extraction	• High equipment and operational costs • Technical complexity • Limitations for extracting highly polar compounds • Cosolvent requirement for certain extractions (thus increasing complexity and cost) • Freeze-drying of raw material for moisture reduction	• Waste management and recycling. Extraction of natural products and lipids from plant materials and other sources • Pharmaceutical industry. Extraction of bioactive compounds from natural sources for drug development • Food and beverage industry • Biotechnology and biomedical engineering. Extraction, purification and formulation of bioactive compounds and biomaterials • Chemical industry. Catalysis, polymerization, and other chemical processes • Energy sector. Extraction of hydrocarbons from natural sources and processing biofuels	Phenolic compounds/Potato peel [194]

				• Materials science. Processing polymers, creating nanoparticles, and developing new materials	
DIC	Thermomechanical process where a material is rapidly exposed to high-pressure saturated steam followed by a quick reduction in pressure towards a vacuum	• Enhanced extraction • Reduced processing time • Improved product quality. Preservation of nutritive value and functional behavior • Energy efficiency • Decontamination of microorganisms (vegetative and spore forms) • Green technology (efficient use of water vapor and reduced solvent consumption) • Versatility. Can be applied to a wide range of materials	• Scalability challenges from laboratory to industrial levels. • Cost considerations • Potential sensory changes • Specific limited applications. Not suitable for all types of materials or applications. Optimization may require specific products	• Food processing (drying, texturing, decontamination, reduced anti-nutritional factors) • Extraction of bioactive compounds (essential oils, phenolics, flavonoids) from various food sources. • Pharmaceutical industry. Pharmaceutical processing and decontamination. • Others: Animal feed processing. Decontamination and preservation of fresh cut fruits and vegetables.	Phenolic compounds/ Pomegranate peel [195]
SFC	Uses a supercritical fluid, like carbon dioxide (CO₂), as the mobile phase	• Fast analysis and high resolution • Environmental friendliness • Minimal sample preparation	• Complexity. Specialized high-pressure equipment required and careful temperature control • Not adequate for highly polar compounds	• Analysis of natural products and plant extracts. Very useful for thermally sensitive compounds • Pharmaceuticals. Drug development and quality control (separation and analysis of drug formulations, chiral separations,	Polymethoxyflavones/Orange peel

		● Cleanliness. Minimal contamination from the mobile phase. ● Compatibility with a wide range of samples ● Sensitivity and reduced matrix interference	● The large volumes of modern SFC systems can affect the use of certain column sizes ● Potential for isobaric interferences due to short run times	impurity detection and lipophilicity determination) [196] ● Food and beverages. Analysis of food contaminants, flavor compounds, and the composition of food products. ● Environmental analysis of pollutants and contaminants in water, soil, and air ● Others: cosmetic product analysis, petrochemical industry, polymer analysis, pesticide analysis, surfactant analysis	
PHWE	Uses hot water under pressure to extract bioactive compounds from various matrices	● Environmental friendliness because it uses water as a solvent ● Fast extraction ● Enhanced solubility due to pressure and heat conditions ● High extraction yields ● Versatile to extract a broad range of bioactive compounds and secondary metabolites	● Potential degradation of thermally labile compounds ● Unwanted reactions (hydrolysis, Maillard reactions, caramelization) leading to undesirable products and erroneous results ● Optimization required to find the optimal conditions (temperature, pressure, time)	● Extraction of natural products ● Food Industry. Extraction of plant bioactive compounds as food additives, nutraceuticals, and ingredients in processed foods. ● Pharmaceutical industry. Extraction of plant bioactive compounds with anti-viral, anti-inflammatory, and antioxidant properties ● Environmental monitoring. Extraction of organic contaminants	Phenolics (eriocitrin and hesperidin)/Lemon peel

		● Reduced cost for its simplicity and the use of water as a solvent ● Can be adapted for both laboratory-scale and industrial-scale applications	● Extraction of non-target compounds and thus the need of further purification steps. ● Complexity. Specialized equipment and expertise required, especially for large-scale applications.	from foodstuff and soil/sediments for analysis [197] ● Biorefinery. Extraction of hemicellulose and others from wood ● Extraction of biopolymers from algae	
DES	Mixtures of two or more solid compounds that form a liquid phase at room temperature	● Environmental friendliness. Most solvents have low toxicity and are biodegradable ● Low cost ● Ease preparation ● Versatile properties	● Potential toxicity in some cases. Incomplete understanding of toxicity. ● High viscosity ● Limited applications when highly polar or highly volatile solvents are required ● Absorption of water, which can affect properties and applications ● Challenges in recycling in some cases to avoid environmental contamination	● Food Science. Extraction of bioactive compounds removing heavy metals. ● Chemistry: ◦ Green Chemistry ◦ Chemical Reactions ◦ Analytical Chemistry ● Biotechnology and bioanalysis. Biotransformations, modification of biopolymers (cellulose, starch), drug delivery ● Metal Processing (electroplating, electro-polishing and metal extraction)	Phenolics/ Orange peel [198]

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- Nanotechnology. Synthesis of nanomaterials. Development of new materials for energy storage
 - Sensors and biosensors
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