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Review Article

Sustainable Extraction and Purification of Phytochemicals: A Review of Green Solvents and Techniques

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ABSTRACT

The importance of phytochemicals in medicine, nutraceuticals, and cosmetics has recently drawn considerable attention toward their sustainable extraction and purification. This review presents the progress in green solvents and methodologies underlined by the drawbacks associated with conventional methods. Phytochemicals are bioactive substances derived from plants that are important for medicinal and commercial purposes. However, most classical methods of extraction and purification involve hazardous solvents and energy-intensive operations, raising environmental and safety concerns. Green solvents, including ionic liquids, deep eutectic solvents, and bio-based solvents, offer environmentally friendly alternatives with high efficiency and low toxicity. These include Supercritical fluid extraction (SFE), Ultrasound-Assisted Extraction (UAE), Microwave-Assisted Extraction (MAE), Pressurized liquid extraction (PLE), and Enzyme-Assisted Extraction (EAE), all of which are advanced green extraction methodologies. These methods afford higher extraction yields while simultaneously reducing the energy consumption and waste generation. Sophisticated purification strategies, including chromatographic techniques, membrane-based purification, and adsorption-desorption procedures, were evaluated for their compatibility with eco-friendly extraction processes. A comparison of the various techniques shows their efficacy, cost, and environmental friendliness. The discussion covers future perspectives, which pinpoint that the development of green solvent formulations, integration of extraction and purification systems, and overcoming of regulatory and scalability challenges are highly needed. This study will be able presents a comprehensive review of sustainable methodologies for the extraction and purification of phytochemicals, which would further help in devising greener, safer, and more efficient approaches in natural product research.

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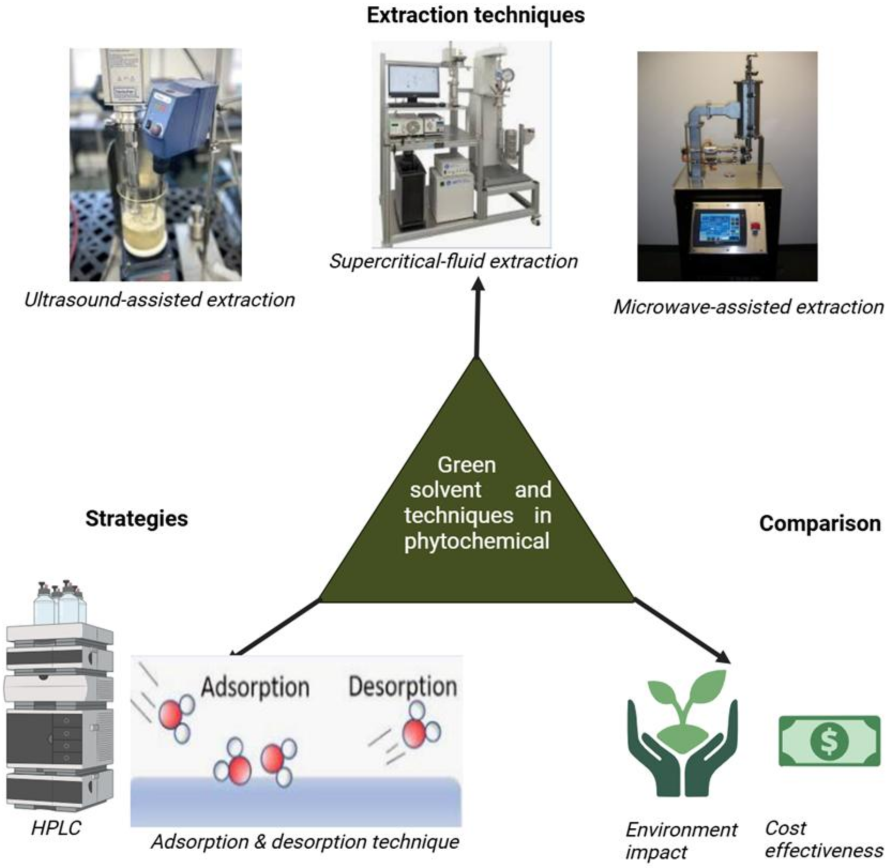
GRAPHICALABSTRACT



Introduction

The increasing focus on natural products derived from medicinal plants, especially botanical and herbal preparations, is attributed to their chemical diversity and potential as sources for new drug development. This review examines the analytical methodologies employed for the extraction, isolation, and characterization of the active ingredients in these plants. The analysis of bioactive compounds in plant extracts is discussed, employing phytochemical chromatographic techniques, such as High-Performance Liquid Chromatography (HPLC) [1]. Secondary metabolites in plants, including terpenoids, flavanols, and flavones, are potential bio-pesticides for sustainable agriculture. Stress-inducible phytochemicals are essential for the development of immune responses in plants. Transcription factors enable plants to respond to challenging environments by regulating their gene expression. Nonetheless, there is a limited understanding of their interactions with pathogens and the mechanisms that contribute to plant immunity. This appraisal examines the role of plant secondary metabolites in pathogens, innate immunity, mechanisms of action, and regulation of transcription factors for sustainable disease management [2]. Secondary metabolites are compounds that aid plants in thriving within competitive environments and are not essential for their typical developmental processes. Over 2,140,000 secondary metabolites have been recorded in the plant kingdom and classified based on their biosynthetic origin, function, and structure. Plants produce secondary metabolites in response to biotic stress using biotic stressors as elicitors to enhance production [3]. Green extraction techniques encompass methods such as supercritical fluid extraction, subcritical water extraction, ultrasound-assisted extraction, and Microwave-Assisted Extraction (MAE). These innovative approaches signify a shift in natural product extraction, prioritizing sustainability, environmental consciousness, and enhanced efficiency. These approaches mitigate the shortcomings of conventional extraction techniques, including low yields and solvent use, while safeguarding the essential bioactive chemicals [4]. Innovative extraction strategies are being devised to obtain bioactive molecules from diverse biomass and natural sources with the objective of enhancing ecological sustainability. Phytochemicals, which are plant-derived bioactive molecules, have substantial health advantages and industrial uses. Innovative methods, such as supercritical fluid extraction, MAE, and ultrasound-assisted extraction, have increased yields, minimized solvent use, and bolstered sustainability. Recent breakthroughs in phytochemical extraction have emphasized their influence on human health, environmental sustainability, and industrial uses [5]. Natural deep eutectic solvents (NADES) serve as eco-friendly solvents for enhancing the extraction efficiency of plant metabolites. This study examines the NADES potential in the creation of pharmaceutical formulations, encompassing plant metabolite-based nutraceuticals, and their capacity to enhance solubility, stability, and bioavailability [6]. The extraction of bioactive and phytochemical substances from plants is essential for medicinal and functional use in the food and pharmaceutical sectors. Effective methods for the isolation of pure bioactive chemicals with increased yields are crucial. Factors influencing the extraction process include the source/raw material, solvent/technique, duration, and temperature. The emphasis has transitioned to green technologies such as ultrasound, supercritical fluid extraction, and subcritical extraction, in contrast to traditional methods such as Soxhlet extraction, hydro distillation, and maceration [7].

Concerns over synthetic phenolic antioxidants such as BHT and BHA have prompted a suggestion for the extraction of antioxidants from fruits and vegetables. Researchers have employed many methodologies to extract, quantify, and characterize bioactive chemicals, including their antioxidant, antibacterial, and anticancer characteristics, from an extensive array of fruits and vegetables [8].

Green Solvents in Phytochemical Extraction

Extraction of bioactive and phytochemical substances from plants is crucial because of their medicinal and functional uses in the food and pharmaceutical sectors. Consequently, effective methods for extracting pure bioactive chemicals with high yields are essential. Green solvents such as subcritical water and supercritical CO_2, bio-based solvents such as ethanol and glycerol, neoteric solvents including ionic liquids and NADES, deep eutectic solvents (DES), and supramolecular solvents have been proposed as alternatives to conventional solvents. Different types and overview of Green Solvents used in Phytochemical Extraction are shown in Figure 1 and Table 1.

Green solvents enhance the extraction of bioactive carbohydrates and phytochemicals from by-products, including grape pomace, skin, and pomegranate peel [7]. Industrial operations frequently utilize volatile and flammable organic solvents, which affect both the environmental and economic performance. Green technologies are being explored to provide ecologically sustainable and adjustable solvents that satisfy both technological and economic requirements. This review presents an overview of suggested green solvents, encompassing supercritical and subcritical fluids, as well as natural deep eutectic solvents, with an emphasis on the environmentally friendly extraction of biologically active molecules from plants [9]. NADES are environmentally benign solvents that improve the extraction efficacy of plant metabolites. NADES are essential for the development of selective and effective methods for separating target compounds from plant matrices [10]. Their solubility, stability, and bioavailability are crucial to their pharmacological properties and bioactive constituents. This study investigated the NADES potential in the development of pharmaceutical formulations, including nutraceuticals sourced from plant metabolites [6].

Types of Green Solvents

Ionic Liquids

Ionic liquids have emerged as prominent green solvents because of their distinctive features that differentiate them from conventional organic solvents.

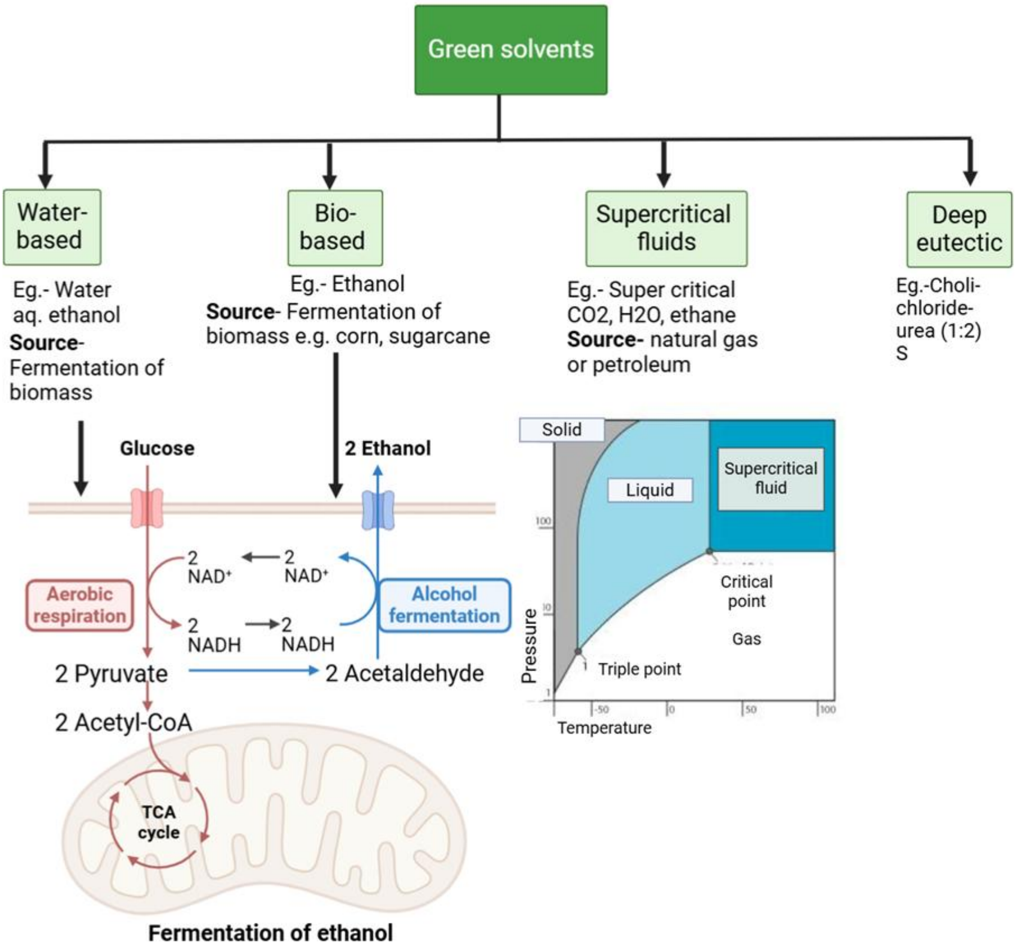


Figure 1: Different types of green solvents in phytochemical extraction

Table 1: Overview of green solvents used in phytochemical extraction

Solvent	Source	Properties	Advantages	Applications	Ref.
Water	Renewable	Non-toxic, inexpensive, universal solvent	Eco-friendly, high polarity, enhanced by techniques like superheated water extraction	Extraction of phenolics, flavonoids, and alkaloids	[11]
Ethanol	Biomass (*e.g.*, corn and sugarcane)	Biodegradabl, polar, and miscible with water	Low toxicity, renewable, effective for polyphenols and flavonoid extraction	Widely used for alkaloids, flavonoids, and saponins	[12]

Solvent	Source	Properties	Advantages	Applications	Ref.
Methanol (Bio-based)	Biomass (*e.g.*, lignocellulosic material)	High polarity, miscible with water	Renewable, efficient for polar compounds	Extraction of alkaloids, tannins, and glycosides	[13]
Ionic Liquids	Synthetic/Customizable	Wide range of polarities, low vapour pressure, and reusable	Selective extraction, reduced solvent loss, customizable for specific applications	Extraction of essential oils, phenolics, and alkaloids	[14]
Deep Eutectic Solvents	Natural components (*e.g.*, choline chloride, and sugars)	Low toxicity, tunable properties	Biodegradabl, highly selective, and low cost	Extraction of flavonoids, alkaloids, and terpenoids	[15]
Supercritical CO_2	Atmospheric CO_2	Non-toxic, non-flammable, and tunable solvating power	No solvent residue, ideal for heat-sensitive compounds, and recyclable	Extraction of essential oils, lipids, and terpenes	[16]
Glycerol	Biodiesel byproduct	Non-volatile, high boiling point, and biodegradable	Low toxicity, cost-effective, effective for polar compounds	Extraction of phenolics and polyphenols	[17]
Ethyl Lactate	Corn-derived	Biodegradabl, non-toxic, miscible with water and organic solvents	Renewable, effective for medium-polarity compounds	Extraction of terpenoids, alkaloids, and phenolics	[18]
Limonene	Citrus fruit waste	Biodegradabl, hydrophobic, and low toxicity	Renewable, ideal for hydrophobic compound extraction	Extraction of essential oils and terpenoids	[19]
Plant-based Oils	Seeds (e.g., olive and sunflower)	Biodegradabl, hydrophobic, and non-toxic	Safe for food and pharmaceutical applications, ideal for non-polar extractions	Extraction of essential oils, lipids, and hydrophobic phytochemicals	[20]

These salts, which are present in liquid form at or near ambient temperature, demonstrate minimal volatility, good thermal stability, and adjustable physicochemical properties. The use of ionic liquids as eco-friendly solvents is consistent with sustainability principles, providing benefits such as less environmental impact and improved efficiency in several operations [21].

Ionic liquids, recognized as environmentally friendly solvents, are the subject of growing research owing to their characteristics, such as low vapor pressure, extensive range, elevated thermal stability, strong ionic conductivity, and capacity to dissolve molecules with diverse polarities. They are utilized in green chemistry to develop cleaner and more sustainable approaches and are increasingly employed in synthetic and catalytic processes. Ionic liquids consist of anions, cations, and neutral species such as benzene, methanol, chloroform, and water. However, their elevated melting temperatures restrict their use in several contexts [22].

Ionic liquids are intriguing substances proposed as solvents for sustainable chemistry, and ionic liquids are sophisticated engineered solvents tailored for specific applications. An often-proposed benefit of Ionic liquids (ILs) compared to volatile organic compounds (VOCs) as solvents in both synthetic chemistry and electrochemistry is their inherent absence of vapor pressure [23].

This study examined the use of imidazolium ionic liquids for phytochemical extraction from 2013 to 2022. The structural formulae, techniques, and applications of these liquids are analyzed. Strategies for analyzing the extraction procedures, recovery methods, and recyclability are also discussed. The toxicity of the imidazolium ionic liquids was also evaluated. The challenges and prospects related to the extraction of phytochemicals using imidazolium ionic liquids are delineated, providing a reference for researchers [24]. Extracting bioactive components from natural products is important for pharmacological purposes. ILs are used in pharmaceuticals for extraction, purification, and drug delivery. This research highlights the recent progress in understanding hydrogen bonding and the importance of multiple interactions in the extraction of ionic liquids. It also examines contemporary obstacles and prospective advancements in the extraction of bioactive substances using ionic liquids, providing substantial insights for researchers [25].

This study incorporated dual-chain imidazolium-derived ionic liquids, noted for their superior solubility, non-flammability, non-volatility, and reusability as extractants for flavonoid extraction from botanical sources. The ionic liquid [Bmbim]Br, noted for its low viscosity, conductivity, and π*, offers superior extraction efficiency and selectivity for flavonoids. The extraction procedure was optimized using specific parameters, resulting in a total flavonoid content of 41.07 mg/g. A recovery strategy was introduced, which achieved a recovery rate of 73.14%. [26].

Computer-aided molecular design (CAMD) is employed for solvent formulation, namely, in the creation of ionic liquid solvents for phytochemical extraction. Ionic liquids serve several purposes, including carbon capture and azeotropic separation. A framework for the design of ionic liquids for phytochemical extraction encompassing the prediction of extraction yield by microwave-assisted methods. The framework was built over many phases, encompassing user requirements, database creation, and algorithm formulation. The yield forecast relies on thermodynamic solid-liquid equilibria and experimental optimization. The framework can determine the optimal ionic liquid for the extraction process [27].

This study examined the ILs application for the extraction of isoimperatorin, a bioactive furanocoumarin, from the roots of Ostericum koreanum. The ideal extraction conditions were refined, yielding 97.17 ± 1.84% and a recovery of 87.73 ± 2.37%. This method markedly improved the purity of isoimperatorin, surpassing the constraints of traditional separation techniques and facilitating its purification. This validates the ILs potential as viable media for phytochemical separation [28].

DES

DESs are contemporary solvents that serve as effective alternatives to conventional solvents for various industrial applications. Diverse categories, synthesis methods, and advantages over industrial solvents and ILs are available. DESs are liquid mixtures made by mixing solid parts together, which lowers melting points by a large amount. They exhibit similar characteristics to ILs but offer advantages such as reduced volatility, non-toxicity, biodegradability, non-flammability, and enhanced chemical stability relative to conventional solvents and ILs [29]. The DESs efficacy was examined in the extraction of bioactive chemicals from biomass. Five Chinese herbal remedies were chosen for evaluation of their efficacy in extracting alkaloids, flavonoids, saponins, anthraquinones, and phenolic acids. Forty-three DESs with varying characteristics were evaluated and alkaloids were identified as the most effective. Research has indicated that DESs are appropriate for the selective and efficient extraction of bioactive chemicals from biomaterials [30].

Green chemistry has enabled the DES development as alternatives to toxic organic solvents for phenolic compound extraction. DES offer biodegradability, ease of handling, and low toxicity. Nevertheless, recovery from DES is challenging owing to the presence of hydrogen-bond networks. Diethyl succinate (DS) can be used for solvent extraction and formulation in cosmetics, pharmaceuticals, and food applications [31].

DESs have significantly increased in popularity owing to their distinctive properties and notable advantages, such as ease of synthesis, cost-effectiveness, low toxicity, and biodegradability [32]. DESs are a category of engineered solvents characterized by low volatility and flammability and are capable of retaining chemically inert liquids throughout an extensive temperature spectrum. Recent advancements in DESs have demonstrated their significant potential as environmentally friendly alternatives to commercially accessible hazardous organic solvents. Nonetheless, the non-cytotoxic, biodegradable, and biocompatible characteristics of these solvents are frequently overstated and require further evaluation [33].

This study employed DESs were used for the extraction of phenolic compounds from virgin olive oil (VOO). Phytochemical Structures of Compounds Extracted Using DESs are presented in Table 2. DESs comprising choline chloride were combined with different sugars, alcohols, organic acids, and urea. The yields were evaluated against a methanol/water standard. DES exhibited favorable solubility for phenolic compounds with varying polarities. The extraction of oleacein and oleocanthal demonstrated enhancements of 20-33% and 67.9-68.3%, respectively, compared to traditional extraction methods. DESs provide an efficient, safe, ecological, and cost-effective alternative to methanol [34].

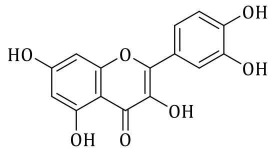
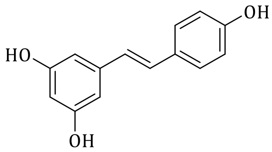
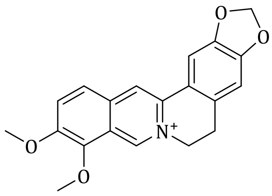
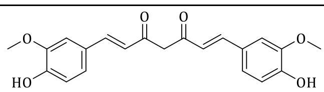
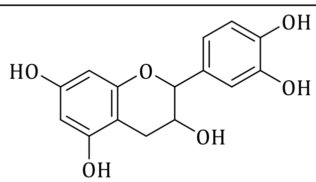
This study investigated the application of NADES to improve the extraction efficiency of bioactive compounds from hop cones through ultrasonic irradiation. Three NADES were synthesized and analyzed using FTIR and Raman spectroscopy. The phytochemical composition of the green extracts was assessed by spectrophotometric assays and HPLC-DAD analysis. The findings demonstrated that NADES displayed the maximum extraction efficiency for hop bitter acids, enhanced extraction of polyphenols, and the most significant antiradical potential against bacteria [35].

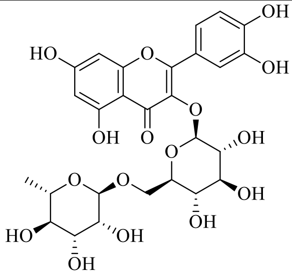
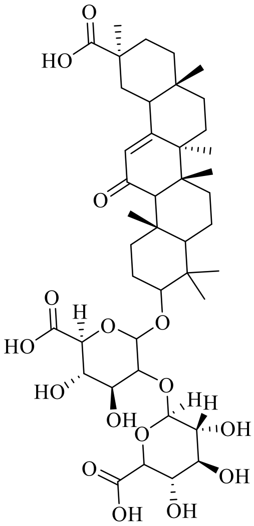
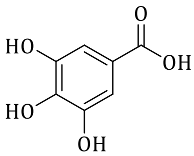
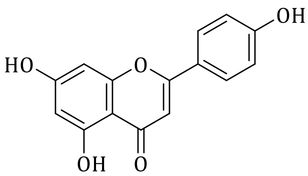
Bio-Based Solvents

The principles of green solvents, their characteristics and attributes, and the potential for synthesizing solvents from biomass as alternatives to traditional methods in the petrochemical industry were examined. The emergence of Green Chemistry has prompted concerns regarding the environmental effects of solvents, implications for human health, and reliance on non-renewable resources [45].

Biomass and waste can substitute fossil resources in chemical synthesis, with bio-based derivatives being utilized as environmentally friendly solvents or components for innovative, less hazardous, and more biocompatible solvents. This study examines the history, classification, and recent advancements in new media, as well as their environmental sustainability, benefits, and constraints across various fields, including organic synthesis, catalysis, biotransformation, and separation [46]. This study investigated the use of sustainable bio-based solvents for the extraction of microalgal lipids, focusing on *Chlorella vulgaris* and *Nannochloropsis sp.* Conventional extraction methods depend on detrimental petroleum-derived volatile organic molecules such as hexane. These findings indicate that all bio-based solvents exceed hexane in extraction efficiency, producing lipid extractions that are two to three times more effective. This facilitates a bio-economy dependent on renewable resources, improving biodiesel production [47].

Table 2: Phytochemical structures of compounds extracted using Deep Eutectic Solvents (DES)

Compound	Class of Phytochemical	Source Plant	Structure	Type of DES Used	Yield/ Recovery	Extraction Conditions	Ref.
Quercetin	Flavonoid	*Sophora japonica*		Choline chloride + Urea	High	Temperature: 60 °C, Time: 90 min Solid-to-liquid ratio: 1:20 g/mL	[36]
Resveratrol	Stilbene	*Polygonum cuspidatum*		Choline chloride + Lactic acid	Moderate	Ultrasonic extraction at 50 °C, Time: 30 min	[37]
Berberine	Alkaloid	*Berberis aristata*		Choline chloride + Malic acid	High	Temperature: 70 °C, Time: 120 min, Solid-to-liquid ratio: 1:15 g/mL	[38]
Curcumin	Polyphenol	*Curcuma longa*		Betaine + Glycerol	High	Temperature: 80 °C, MAE, Time: 10 min	[39]
Catechin	Flavan-3-ol	*Camellia sinensis*		Choline chloride + Citric acid	Moderate	Temperature: 40 °C, Time: 60 min, pH-adjusted DES solution	[40]

Compound	Class of Phytochemical	Source Plant	Structure	Type of DES Used	Yield/ Recovery	Extraction Conditions	Ref.
Rutin	Flavonoid	*Sophora japonica*		Choline chloride + Ethylene glycol	High	Temperature: 50 °C, Time: 75 min, Solid-to-liquid ratio: 1:25 g/mL	[41]
Glycyrrhizin	Saponin	*Glycyrrhiza glabra*		Choline chloride + Propylene glycol	Moderate	Ultrasonic bath at 45 °C, Time: 20 min	[42]
Gallic acid	Phenolic acid	*Terminalia chebula*		Choline chloride + Glycerol	High	Temperature: 50 °C, Time: 90 min, Mild stirring	[43]
Apigenin	Flavone	*Petroselinum crispum*		Betaine + Lactic acid	Moderate	MAE at 70 °C, Time: 15 min	[44]

Advantages of Green Solvents over Conventional Solvents

Green Extraction Techniques

Green Extraction encompasses the creation and implementation of extraction methodologies that reduce energy consumption, allow for the use of alternative solvents and renewable resources, and ensure the production of safe, high-quality extracts or products. The advancement of eco-friendly and sustainable extraction methods for natural resources is now a significant research focus within the multidisciplinary domains of applied chemistry, biology, and technology [48]. Polyphenols, which are beneficial phytochemicals, pose challenges owing to the inherent limitations of traditional extraction techniques. Researchers are currently investigating sustainable, efficient, and economical green extraction methods. Contemporary green extraction methodologies, such as supercritical fluid extraction, ultrasound-assisted extraction, MAE, pressurized liquid extraction (PLE), and pressurized hot water extraction, provide benefits such as diminished solvent utilization, decreased time and energy expenditure, and enhanced recovery rates. These strategies have the potential to address the constraints in the utilization of polyphenols as bioactive substances and for investigating industrial and burgeoning global markets [49].

Table 3: Green extraction techniques principle and purified phytochemicals example

Extraction Technique	Principle	Key Advantages	Disadvantages	Examples of Phytochemicals Purified	Ref.
SFE	Uses supercritical CO_2 as a solvent to extract target compounds under specific temperatures and pressure.	Environmentally friendly, non-toxic solvent (CO_2), high selectivity, low solvent residue.	High initial cost, complex optimization of pressure and temperature.	Polyphenols, alkaloids, carotenoids, and essential oils.	[51,52]
Ultrasound-Assisted Extraction (UAE)	Ultrasonic waves create cavitation bubbles, enhancing solvent penetration and mass transfer.	Faster extraction, lower energy use, minimal solvent consumption, and better yield.	Limited scalability, possible degradation of heat-sensitive compounds.	Flavonoids, terpenoids, and saponins.	[53]
MAE	Microwaves heat the solvent and plant matrix, breaking cell walls and releasing phytochemicals.	Rapid extraction, reduced solvent and energy usage, high efficiency.	Uneven heating, potential degradation of sensitive compounds.	Phenolics, alkaloids, and glycosides.	[54]
PLE	Enhances the solubility of compounds by employing solvents at moderate temperatures and high pressure.	Reduced solvent use, faster process, and compatibility with green solvents.	Equipment cost, not ideal for thermolabile compounds.	Polyphenols, alkaloids, and steroids.	[55]
Enzyme-Assisted Extraction (EAE)	Enzymes break down plant cell walls to release phytochemicals into the solvent.	Mild conditions, improved yield, selective targeting of bioactive compounds.	Cost of enzymes, long reaction time, and enzyme specificity issues.	Polysaccharides, phenolic acids, and flavonoids.	[56]
Natural Deep Eutectic Solvents (NaDES)	Uses green solvents derived from natural compounds (e.g., sugars, amino acids) for extraction.	Biodegradable, non-toxic, customizable solvent properties, and sustainable.	Limited industrial application, solvent recovery challenges.	Phenolics, flavonoids, and alkaloids.	[57]

Effective use and enhancement of mandarin peels using eco-friendly extraction methods. The extraction techniques included supercritical CO2 extraction, volatile compound analysis using GC-MS, and subcritical water extraction to procure bioflavonoids. HPLC revealed that hesperidin was the predominant flavanone, with several polyphenolic chemicals. 5-hydroxymethylfurfural and chlorogenic acid were also identified. Antiradical activity and total phenolic content were assessed using spectrophotometric techniques [50]. Green Extraction techniques principle and Purified phytochemicals example are tabulated in Table 3.

SFE

Supercritical fluid extraction utilizes supercritical fluids that exhibit both liquid and gaseous characteristics at temperatures and pressures exceeding the critical point. The comparatively low viscosity and elevated diffusivity of supercritical fluids improve the diffusion and mass transfer, thereby decreasing the extraction time. Supercritical fluids exhibit densities similar to those of liquids, demonstrating comparable solvation capabilities. Supercritical carbon dioxide is the predominant supercritical fluid used for food preparation. Temperatures above 70 °C have been used for supercritical fluid extraction. Utilizing elevated temperatures in supercritical fluid extraction reduces the solvent density and solvation capacity while augmenting the solute vapor pressure, thereby boosting the extraction yield. Supercritical fluid extraction has been widely employed for oil extraction [58]. Supercritical fluid extraction (SFE) is an eco-friendly and sustainable technique for extracting physiologically active compounds from plant wastes, such as pomace, seeds, and skin. SFE selectively extracts and recovers health-enhancing substances such as polyphenols, essential oils, vitamins, and antioxidants. It employs supercritical carbon dioxide as a solvent, obviating the need for toxic organic solvents and safeguarding heat-sensitive bioactive molecules. SFE facilitates waste valorization by transforming plant wastes into value-added extracts that are applicable in the food, pharmaceutical, and cosmetic sectors [59]. Supercritical fluid CO_2 extraction (SFE) is an innovative technique for the isolation of bioactive chemicals and elimination of environmental contaminants. Temperature and pressure govern the solvent density, influencing the yield, selectivity, and characteristics. This review examines recent studies on the SFE of bioactive plant phytochemicals exhibiting significant antioxidant, antibacterial, antimalarial, and anti-inflammatory properties. It also addresses ecotoxicology and applications of toxic metal recovery. The nonpolar characteristics of Sc-CO_2 confer significant solvent strength, rendering it an effective substitute for the traditional solvent-based treatment techniques. The review enhances SFE-based research investigations and underscores the limitations and prospects for the future use of SFE [60]. Chañar, a fruit indigenous to South America, is utilized to create arrope, a syrup like honey in sweetness. Chañar almonds with elevated oil content were eliminated during arrope manufacturing. The extraction of chañar almond oil was assessed using supercritical fluid extraction to analyze the effects of temperature and pressure. The ideal parameters for extracting chañar almond oil were 60 °C and 40 MPa, resulting in an oil yield of 40 ± 1%, with the highest concentrations of monounsaturated and polyunsaturated fatty acids. The physicochemical properties of chañar almond oil conformed to the criteria for edible oils [61]. The impact of the three extraction procedures on the production of pumpkin seed oil, its physicochemical characteristics, presence of bioactive components, and antioxidant capabilities. The results indicate that SFE produces the largest quantity of unsaturated fatty acids, followed by MP and CP. MP-PSO had the highest acid and saponification values, whereas SFE-PSO had the highest moisture content, peroxide value, and iodine value. MP-PSO had higher antioxidant capabilities than CP and SFE across many assessments. Research further revealed that some bioactive substances, such as β-sitosterol and γ-tocopherol, have a strong correlation with antioxidant activities [62]. Over the last 20 years, the separation of phenolic chemicals using SFE has been thoroughly investigated. SFE has demonstrated efficacy in isolating these chemicals, facilitating the use of plant waste materials, and mitigating environmental impacts. This study aimed to compile and organize current data on the separation of phenolic compounds and assess the most effective supercritical fluid extraction technique for these chemicals [63].

Ultrasound-Assisted Extraction (UAE)

UAE is an environmentally sustainable and effective extraction method that minimizes reliance on organic solvents while increasing the yield of bioactive compounds (Figure 2).

Its applications span multiple fields, such as medical testing, nondestructive testing, distance measurement, welding, cleaning, and food technology. Ultrasonic technology is classified into two categories: low-intensity ultrasonics, characterized by high frequencies and low power levels, and high-intensity ultrasonics, which functions at low frequencies and high-power levels. Low-intensity ultrasonics are suitable for the testing and characterization of diverse substances, whereas high-intensity ultrasonics function at elevated frequencies and power levels [64]. UAE uses ultrasonic energy and solvents to extract compounds from diverse plant matrices. Ultrasound consists of mechanical waves with frequencies higher than 20 kHz, beyond the human hearing frequency range of 20 Hz-20 kHz. These waves consist of cycles of compression and rarefaction that may travel through solid, liquid, or gaseous media, causing displacement and dislodgement of molecules from their original positions [65].

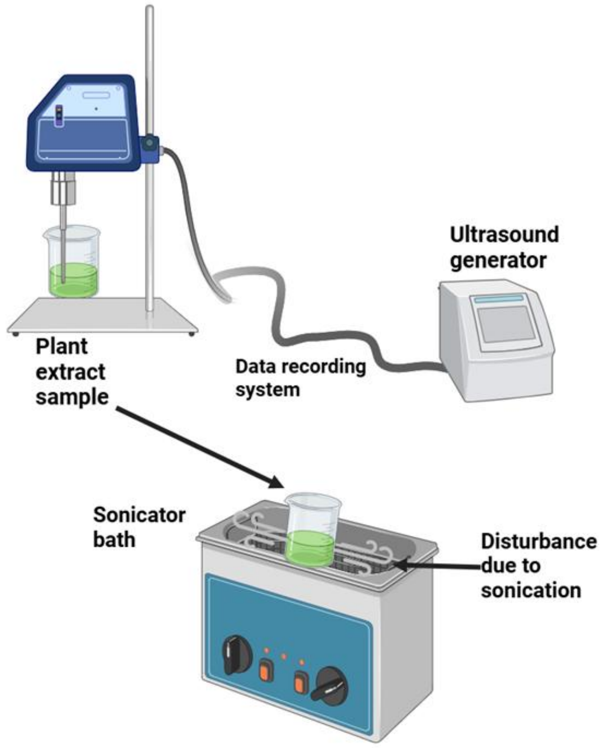


Figure 2: Ultrasound-assisted extraction methodology for phytochemicals

The UAE method was used to extract phytochemicals from dragon fruit peel. The process was enhanced using artificial neural networks (ANN) and genetic algorithms. This study examined the impact of ultrasonic temperature, solvent-to-solid ratio, solvent concentration, and treatment duration on total polyphenolic content, antioxidant activity, and betacyanin levels. The ANN model demonstrated a substantial association with the experimental data, and the output was used for optimization using a genetic algorithm. The optimal parameters for UAE were the temperature of 60 °C, a solvent-to-solid ratio of 25:1 mL/g, a solvent concentration of 60%, and treatment duration of 20 min using ultrasonic methods. The extraction kinetics and thermodynamic analyses were conducted using several extraction combinations [66]. Influence of process variables on the extraction mass yield (EMY) and phenolic compound yield (PCY) of a phytochemical extract derived from jambolan leaves. The extraction solvents AE (absolute ethanol), 75E (75% v·v^{-1} ethanol), and 50E (50% v·v^{-1}) were assessed for their chemical characterization, antidiabetic, and antibacterial characteristics, and impact on cell viability. The peak values of the process variables yielded maximum response variables, with 50E exhibiting the highest concentration of phenolic compounds and flavonoids, thereby enhancing antioxidant potential, antibacterial activity, and α-amylase inhibition. AE led to elevated concentrations of squalene, α-tocopherol, β-sitosterol, and friedelin. The extracts were deemed non-toxic at a concentration of 100 μg/mg [67].

UAE of antioxidants, total phenolics, and soluble proteins from *Momordica charantia*. Two sonication modes, normal and pulsed, were evaluated, and the response variables were examined using a response surface methodology (RSM)-based design. The results indicate a nonlinear relationship between the response variables and control factors. Pulsed-mode sonication exhibited enhanced efficacy relative to traditional sonication, yielding a slightly reduced vegetable-to-solvent ratio and an elevated bioactive content. These findings indicate that pulsed-mode ultrasonication may be used to generate aqueous extracts of bitter gourd for medicinal and functional food applications [68]. This study explored the use of UAE for soluble polyphenols from *Psidium cattleianum* leaves. The UAE method showed 1.71 times greater efficacy than the AOE method for total phenolic extraction, requiring 96.66% less time. The extracts showed enhanced antioxidant properties and identified gallic, protocatechuic, chlorogenic, caffeic, coumaric, trans-cinnamic, 4-hydroxybenzoic, syringic acid, and kaempferol in the PC leaves. These extracts are used for medicinal and industrial purposes, making UAE an efficient method for increasing phytochemical production [69]. UAE is the most efficient technique for extracting phytochemicals and antioxidants from brown macroalgae, demonstrating the highest DPPH activity. The study revealed that UAE and UMAE had the highest DPPH and FRAP activities among macroalgae, along with the highest yields of total phenolic compounds, phlorotannins, flavonoids, and tannins. Nonetheless, no distinct pattern was observed for the FRAP activity. The study indicated that further storage after extraction did not enhance the phytochemical yields or antioxidant characteristics [70].

MAE

MAE utilizes microwave radiation to heat solvents that interact with a sample, facilitating the partitioning of analytes from the sample matrix into the solvent. The capacity of the sample solvent combination for fast heating is intrinsic to MAE and is the primary benefit of this approach. The use of closed containers enables extraction at high temperatures, thereby enhancing the mass transfer of the target chemicals from the sample matrix. The average extraction technique requires 15-30 minutes and utilizes minimal solvent quantities of 10-30 ml. These quantities are approximately tenfold lower than those utilized in traditional extraction methods [71]. MAE is a method that uses microwaves to induce the motion of liquid molecules, thereby facilitating the effective extraction of desired components. It provides advantages, such as diminished extraction duration, lowered solvent expenses, and enhanced automation. MAE uniformly warms both the solvent and the material, leading to an increased yield of the extracted chemicals. It is relevant to diverse botanical substances including essential oils, flavonoids, terpenes, phenols, alkaloids, and glucosides [72]. MAE is a technique for extracting polyphenols from peppermint leaves with optimal results at an irradiation power of 665 W. This method is essential for digesting botanical materials and for generating superior extracts. The research indicated that the irradiation power markedly affected k, with the maximum empirically measured k (2.28 min-1) occurring at 600 W, while the ideal irradiation power forecasted the greatest k (2.36 min^{-1}) at 665 W [73]. MAE at 86

°C using water as a solvent significantly enhanced the total phenolic compound content and antioxidant activity in olive leaves, offering potential advantages as a precursor to ultrasound-assisted extraction. Influence of extraction parameters on total phenolic compounds and antioxidant activity from olive leaves using MAE, ultrasound-assisted extraction, and maceration. Olive leaves have been identified as a substantial source of phenolic compounds with significant antioxidant activities. MAE at 86 °C demonstrated superior efficiency in total phenolic yield and extraction duration, although employing water as a solvent augmented the total phenolic output by 82% relative to maceration [74]. MAE is a technique that efficiently extracts bioactive chemicals from Ficus racemosa fruits, which are an underappreciated source of polyphenols. This study identified ideal conditions for the extraction of components such as ascorbic acid, total phenols, flavonoids, tannins, and antioxidant activity. The HPLC-DAD study detected and quantified several phytochemicals, demonstrating that F. racemosa is suitable for phytochemical extraction in the food and medicinal sectors [75].

PLE

PLE, which was established in the mid-1990s, is a method that enhances efficiency and minimizes solvent usage compared to the conventional extraction methods. It is commonly used for solid and semi-solid materials, employing solvent extraction at temperatures and pressures less than the critical points. The physicochemical characteristics of the extraction solvent are altered by specific pressure and temperature conditions, allowing deeper penetration into the matrix to be extracted [76]. PLE is an environment-friendly method that uses elevated heat and pressure to remove constituents from a solid matrix. To enhance efficiency, factors such as solvent, temperature, pressure, extraction duration, and cycle count must be optimized. PLE settings provide rapid extraction of target analytes using reduced solvent volumes, while preserving excellent yields [76].

PLE, or accelerated solvent extraction, is a process that utilizes elevated pressure and temperature to extract organic molecules. This technology preserves thermally sensitive chemicals because of its significantly shorter extraction duration compared to standard procedures, such as percolation or Soxhlet extractions. Numerous studies have indicated that the PLE approach is more efficient owing to the lower solvent usage and extraction duration [77]. This study investigated the PLE application to obtain bioactive components from pomegranate peel using a mixture of pressurized water and ethanol. The ideal conditions were determined to be 200 °C and 77% ethanol. These findings indicated that PLE was successful in the recovery of TPC, but not in the punicalagin recovery. The antimicrobial activity against S. aureus was 14 mm, necessitating additional investigation to assess its potential for the development of novel food additives [78]. This study examined the bioactive constituents of Carao tree seeds and their prospective application as functional additives. The researchers employed PLE to obtain phytochemicals, which were further characterized using reversed-phase HPLC combined with electrospray ionization time-of-flight mass spectrometry. These findings indicate that Carao tree seeds may serve as a viable source of bioactive chemicals, and that PLE extracts may function as functional components. This study underscores the significance of phenolic compounds in nutrition [79].

The rising demand for nutritious meals has resulted in the proliferation of eco-technologies designed to extract bioactive components from food sources, such as PLE and SFE. These methods provide several benefits, such as the extraction of antioxidant, antibacterial, antiviral, and antifungal chemicals from plant matrices and industrial biowastes. Research has resulted in novel technical advances and commercial applications, facilitating the precise recovery of bioactive compounds from plant and marine food matrices. These sustainable approaches possess prospective uses in biowaste valorization and can facilitate a circular economy model within the food business [80].

PLE can be used to extract bioactive compounds from agricultural food byproducts, possibly facilitating the establishment of biorefineries with health advantages. PLE is an eco-friendly method that uses pressurized liquids at elevated temperatures to obtain bioactive compounds from agri-food leftovers. The objective was to produce biorefineries. The present challenge is to scale PLE to an industrial level to produce cleaner and more efficient processes, with the aim of acquiring bioactive extracts with antioxidant, antiproliferative, anti-inflammatory, antidiabetic, and antibacterial properties [81].

Enzyme-Assisted Extraction (EAE)

EAE can be used to extract pectins from waste and by-products by enhancing the permeability of the plant cell walls. Enzymes are used to extract various phenolic compounds such as flavonoids and anthocyanidins. The enzyme activity, treatment duration, substrate ratio, and particle size are crucial for achieving optimal enzymatic treatment efficiency. Enzymes were used to augment the output yield through moderate and nonhazardous treatments. The enzyme specificity, activity, plant origin and features, ratio, and extraction conditions varied according to the objective. Consequently, researchers have been interested in the capacity of enzymes to break particular bonds of macroelements and release bioactive chemicals, thereby improving the value and generating new derivatives in plant extracts [82].

EAE is a technique that utilizes specialized enzymes to catalyze the destruction or alteration of cellular walls, thereby promoting the release of intracellular chemicals, especially phenolic compounds. EAE has great benefits as a mild technique that generally eliminates the need for chemical solvents, excessive energy use, prolonged durations, or high temperatures to obtain substantial extraction yields. The benefits linked to the typical circumstances render the produced extracts appropriate for utilization across several sectors, including medicine, pharmacy, and the agri-food business [83].

EAE is an economical and environmentally sustainable technique that employs hydrolytic enzymes to decompose the cell walls and constituents of plant or fungal materials. This mechanism facilitates solvent diffusion, enabling a more efficient elution of metabolites. Electro-assisted extraction (EAE) can function as an independent approach or pretreatment for traditional extraction techniques. Enzymes have excellent specificity for factors such as particle size, duration, pH, and temperature and may operate well at low temperatures and moderate pH levels within a brief timeframe without the need for costly apparatus [84].

Enzyme-assisted supercritical fluid extraction (EASE) efficiently recovers significant bioactive chemicals from plant sources while preserving their structure and function. However, the selection of enzymes, supercritical fluid, and operational parameters affects the overall performance. EASE efficiently extracts bioactive chemicals while preserving the structure and function of target biomolecules. Efficiency is contingent upon the selection of enzymes, type of supercritical fluid, and operating conditions. Further studies might improve the efficiency of EASE by elucidating the mechanism of synergistic effects [85].

This study assessed the effects of EAE and solid-liquid extraction (SLE) on the yield of bioactive chemicals, phytochemical composition, and the antioxidant, antibacterial, and antidiabetic properties of plant leaves. Extracts obtained from EAE using Viscozyme L enzyme (EAE-Visc) had the best yield, antioxidant activity, and total phenolic content. Extracts from sea buckthorn leaves have demonstrated α-glucosidase inhibitory and antibacterial activities against Staphylococcus aureus [86].

In this study, we determined the phenolic compounds extracted from maize tassel using EAE with cellulase, protease, and their combination. The findings indicated that The enzyme-based maize tassel extracts (CTE) exhibited the highest total phenolic content, enhanced antioxidant activity, and superior antibacterial characteristics. CTE exhibited nontoxicity towards normal lung fibroblast cell lines, while demonstrating cytotoxicity against human colorectal and lung cancer cell lines, suggesting potential anticancer capabilities [87].

Purification Strategies for Phytochemicals

Chromatographic Techniques

Chromatography is a method used to separate the components within a mixture. The components of the mixture are distributed within a liquid solution, termed the mobile phase, which interacts with the mixture through a framework made of a distinct substance called the stationary phase. Clear segmentation between the mobile and stationary phases is crucial for component separation. The main objective of chromatography is to isolate and purify specific components of a sample, while its analytical purpose is to ascertain the qualitative and quantitative chemical composition of the sample [88].

The chromatography procedure is founded on three components, according to this method.

1. A "solid" phase or "a layer of a liquid adsorbed on the surface of a solid support" always makes up the stationary phase.
2. Mobile phase: "Liquid" or a "gaseous component" always makes up this phase.
3. Distinct molecules.

The interplay between the stationary and mobile phases in a mixture is essential for the efficient separation of molecules. Partition-based chromatography is good for identifying tiny molecules, such as fatty acids and carbohydrates, but ion-exchange chromatography excels in separating larger macromolecules, including proteins and nucleic acids. Paper chromatography is used for the separation of proteins and analysis of synthesis, whereas gas-liquid chromatography is employed for the separation of alcohols, esters, lipids, and amino groups. Agarose-gel chromatography efficiently isolated RNA, DNA molecules, and viruses [89].

Preparative Chromatography

Preparative chromatography is a prevalent and crucial purification technique used globally in organic chemistry laboratories. A novel methodology for the separation of estragole, ethyl cinnamate, and cinnamyl alcohol using gradient elution and microscale preparative flash column chromatography was developed to enhance the students' proficiency in the process. A chemically impregnated TLC plate was utilized to provide near real-time elution data throughout the chromatographic purification process, emulating the function of a UV detector. This straightforward yet efficient method eliminates misunderstandings and errors, conveys critical information on the present elution process, and greatly aids in the visualisation process [90].

Preparative chromatography, an essential separation technology, may markedly enhance the cost efficiency of chemical processes, particularly for small-molecule active medicinal components. Notwithstanding technical developments, this potent activity is frequently underutilized in the pharmaceutical sector. Notwithstanding its potential for cost reduction, it has been effectively employed in extensive molasses purification and the petroleum sector, underscoring its significance in attaining purity [91].

HPLC

HPLC is a chromatographic technology used for the separation and identification of biologically active substances, such as amino acids, carbohydrates, lipids, nucleic acids, proteins, and steroids (Figure 3).

This allows for swift examination of compound structure and function, as well as their purification. The mobile phase moves through columns at a speed of 0.1-5 cm/sec and experiences pressures between 10 and 400 atm, improving separation efficiency and speeding up analysis. The HPLC equipment includes a solvent reservoir, high-pressure pump, column, detector, and recorder [89]. The applications of HPLC are demonstrated in Figure 4.

The peak area approach in HPLC effectively separates, identifies, and quantifies the phytochemical components in Moringa oleifera leaves. The study involved the extraction of leaves from five distinct areas and their subsequent analysis by HPLC. These findings indicated that chlorogenic acid, rutin, ferulic acid, luteolin, apigenin, and kaempferol were effectively separated, identified, and measured. Methanol has superior efficacy for highly polar molecules, with peak areas 74% to over 1100% greater than those of ethanol [92].

Types of High-Performance Liquid Chromatography

Normal-phase Chromatography: Normal-phase chromatography (NP-HPLC) is a HPLC technique that separates analytes based on their affinity for polar stationary phases, such as silica. This classification is based on the ability of an analyte to interact polarally with the sorbent surface. NP-HPLC effectively separates analytes that dissolve in non-polar solvents using a non-polar mobile phase such as chloroform, with the adsorption strength increasing with the analyte's polarity [93].

Two HPLC methodologies are described: a rapid normal-phase isocratic technique for retinol and retinoic acid analysis using a 3 µm silica column and a reversed-phase gradient method for simultaneous analysis of retinoids and carotenoids on a 3 µm C18 column. The isocratic normal-phase HPLC method is suitable for routine retinol analysis in serum after retinoic acid administration, while the reversed-phase gradient technique allows simultaneous measurement in human blood and plant and animal tissues [94].

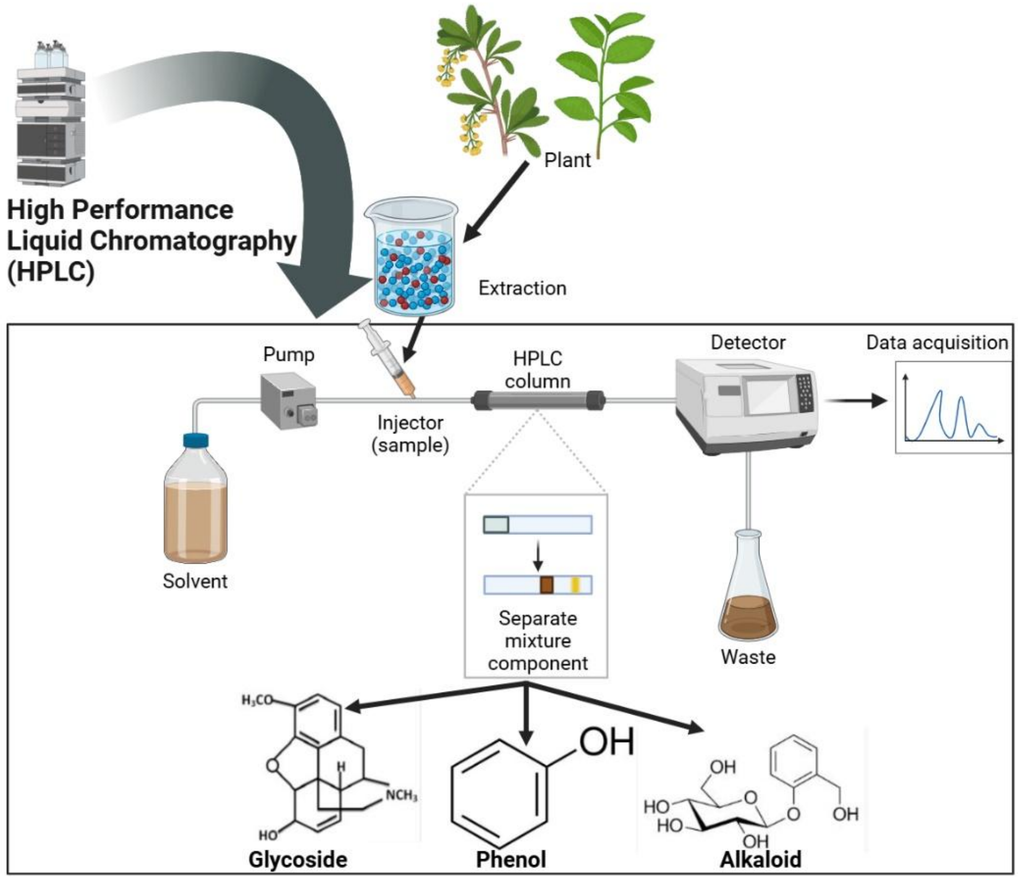


Figure 3: Separation of phytochemical components using HPLC

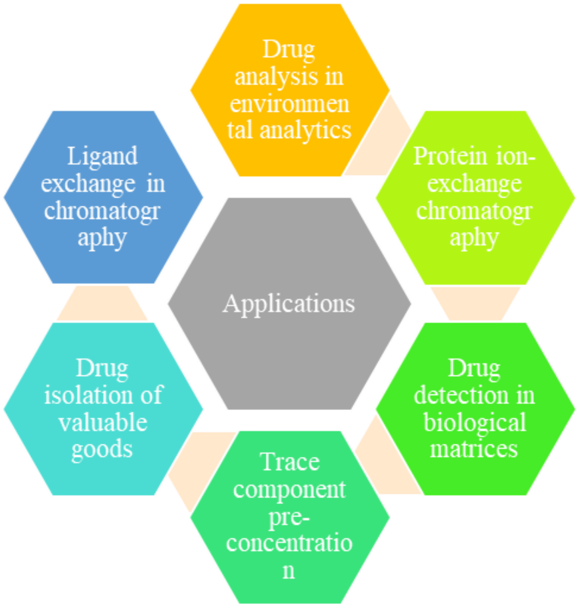


Figure 4: HPLC applications

Reversed-phase Chromatography

Reversed-phase HPLC (RP-HPLC) is a method used to measure the interaction forces between an analyte and stationary phase. It involves a moderately polar mobile phase and non-polar stationary phase, such as a silica surface modified with RMe2SiCl. The hydrophobic interaction theory, which is based on the high symmetry of the dipolar water structure, is used to measure the degree of analyte attachment to the stationary phase [95].

RP-HPLC has been used to quantify the phytochemical markers andrographolide, eugenol, and zingerone in nilaveembu kudineer, a Siddha polyherbal formulation. This method is a quality control tool for traditional remedies as it simultaneously assesses these elements within herbal combinations. The optimized chromatographic conditions included a C18 column, mobile phase with acetonitrile and orthophosphoric acid, defined flow rate, and ultraviolet detector. The method successfully measured these signals in the NK formulation, making it a highly effective quality control tool [96].

Membrane-Based Purification

Membrane-based purification is a process of separating phytochemicals (plant compounds) according to their size and charge using a semi-permeable membrane. Common techniques include reverse osmosis, nanofiltration, and ultrafiltration, all of which use varying pore sizes to filter out particular molecules within a mixture [97].

Affinity chromatography, a novel membrane technique, has demonstrated capacity, effectiveness, and durability over time for high-resolution protein separation and analysis. Biomolecule separation and purification have already benefited significantly from this technique. To perform membrane chromatography, ligands were grafted onto the pore surface of the membrane. Target biomolecules are then adsorbed onto these ligands when convective flow passes through the membrane pores. Protein molecules may more easily reach the binding sites on the pore wall with a larger pore size in membranes, which would drastically reduce the processing time and pressure drop. This method is based on reversible biospecific interactions between a protein and a particular ligand that alters the protein's characteristics and allows it to be isolated from mixtures of complex biomolecules. Purification by affinity chromatography is made possible by the ligand, which binds reversibly to a particular molecule or collection of molecules [98].

Polyphenols, a category of plant secondary metabolites, have garnered interest owing to their bioactive properties. Membrane methods are the premier technologies for the extraction and separation of these chemicals from agro-food sources. This study explored the principles and applications of pressure-driven membrane processes and membrane contactors in the separation, purification, and concentration of polyphenols from agro-food items and by-products [99].

The hydroalcoholic extract of moist olive pomace was purified and concentrated using an integrated membrane method. The extract was tested using the UF010104 and UP005 membranes for ultrafiltration, with UP005 selected for its superior selectivity. The permeate stream exhibited elevated amounts of useful simple phenols and phenolic acids, although sugars and macromolecules were retained. The ultrafiltration permeate was further processed via a nanofiltration phase with an NF270 membrane for enhanced purity and fractionation. Hydroxytyrosol and some phenolic acids were extracted and concentrated by reverse osmosis using an NF90 membrane. The concentrated phenolic combination may have potential use as an antioxidant and in the prevention of diabetes and neurological disorders [100].

Adsorption and Desorption Techniques

The most commonly used method is adsorption, because of its affordability and effectiveness. The basic relationships used in the process of adsorption are depicted in Figure 5.

Activated carbon (AC) and other carbon-based adsorbents, such as biochar, polymer materials, zeolite, biofuels, and agricultural waste, are examples of both organic and inorganic adsorbents that can be employed. Furthermore, nanotechnology has been used to address environmental issues such as water pollution. Owing to their large surface area, nanostructured adsorbents treat water and wastewater more effectively and at a faster rate of adsorption [101].

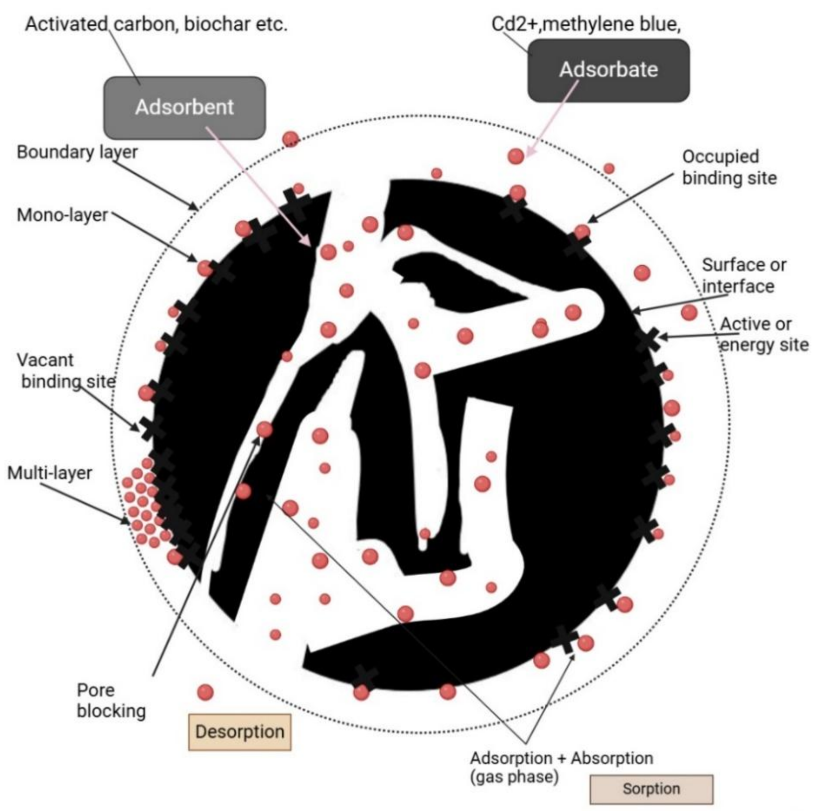


Figure 5: Basic relationships used in the process of adsorption

The following types of adsorbents were reviewed: metallic organic frameworks, aerogels, networking crystalline solids, zeolite nanoparticles, dendrimers, and adsorbents based on natural materials, carbon, waste, biomass, biopolymers, and nanocomposites. In addition, the kinetics, isotherm models, adsorption capacities under various situations, characterization, modification, and manufacture of harmful pollutants are discussed. Adsorption capabilities for varying temperatures, particle sizes, adsorbent dosages, adsorbent concentrations, and pH values [102].

Desorption refers to the transfer of ions or molecules from a solid phase into a liquid phase, which is essential for the recycling and reutilization of solid materials employed in adsorption. It transpires when an adsorbate attaches to a solid surface, resulting in chemical accumulation at the solid-liquid interface. Adsorption and desorption are surface phenomena that involve the adsorbent surface, inhibiting the adsorbate from infiltrating its structure. Desorption and regeneration of adsorbents are crucial for metal recovery from water and wastewater and offer significant insights for economic design. The adsorbents are recyclable and reusable within the same production process, mitigating environmental concerns [103]. The adsorption and desorption ratios of five MPRs were evaluated and compared for selection purposes.

The screening phase utilized 50 mL of N. lotus stamen extract and each MPR in an Erlenmeyer flask. The flasks were incubated for six hours at 25 °C to achieve absorbance equilibrium. The liquid phase was isolated from the MPR by vacuum-assisted filtration, and the total flavonoid content (TFC) was assessed. The absorption ratio was determined using the method A (%) = [(C0 - C1)/C0] × 100. Deionized water was used to cleanse the MPR and eliminate any excess flavonoids. Subsequently, it was desorbed with 50 mL of 95% (v/v) aqueous ethanol solution and incubated at 25 °C in an orbital shaker operating at 120 revolutions per minute. The incubation interval for the screening process was arbitrarily established as six hours to facilitate desorption. The TFC of the generated eluent was then determined. The desorption ratio D was calculated using the following formula: D (%) = [(V2 × C2)/(M × Q)] × 100, where C2 (mg/mL) represents the total flavonoid content of the eluent, V2 (mL) is the volume, and M (g) is the MPR mass. The absorption capacity, Q, is determined as follows: Q is defined as [(C0 − C1)/M] multiplied by V1, where V1 (in mL) represents the initial volume of the extract that interacts with MPR [104].

Comparison of Green Extraction and Purification Techniques

Green extraction focuses on energy conservation, using alternative solvents and renewable resources, and producing high-quality and safe products. The six principles of green extraction should be considered by the industry and science to create eco-friendly labels, charters, and standards (Figure 6).

They drive innovation in SLE and should be considered as a framework for creating innovative and eco-friendly products.

Efficiency Metrics

An essential component for increasing the extraction efficiency is the length of time spent in contact with the raw material and solvents. Additionally, it should be noted that most traditional extraction techniques, such as maceration, include stirring to facilitate mass transfer, which is made possible by the increased extraction efficiency of bioactive compounds. Optimizing the time spent with the extraction efficiency can be enhanced by various factors such as the type of plant, extraction solvent, fresh or dried material, and crushing or pulverization process [105]. Chromatographic methods, namely TLC and HPLC (employing hydroxytyrosol, tyrosol, verbascoside, vanillin, luteolin, coumaric acid, caffeic acid, rutin, and catechol standards), were used to identify and quantify the primary phenolic compounds in the EOP extracts.

The antioxidant activities (ABTS, DPPH, and ORAC) and antibacterial characteristics were used to assess the extraction yield under different circumstances and the bioactivity of the extracts. The antimicrobial testing included *Yersinia enterocolitica*, *Bacillus cereus*, *Listeria monocytogenes*, *Staphylococcus aureus*, *Salmonella enterica*, and *Escherichia coli*. The principles of "green chemistry" and "eco-extraction" seek to establish extraction techniques that are environmentally sustainable, energy-efficient, user-safe, and highly effective [106].

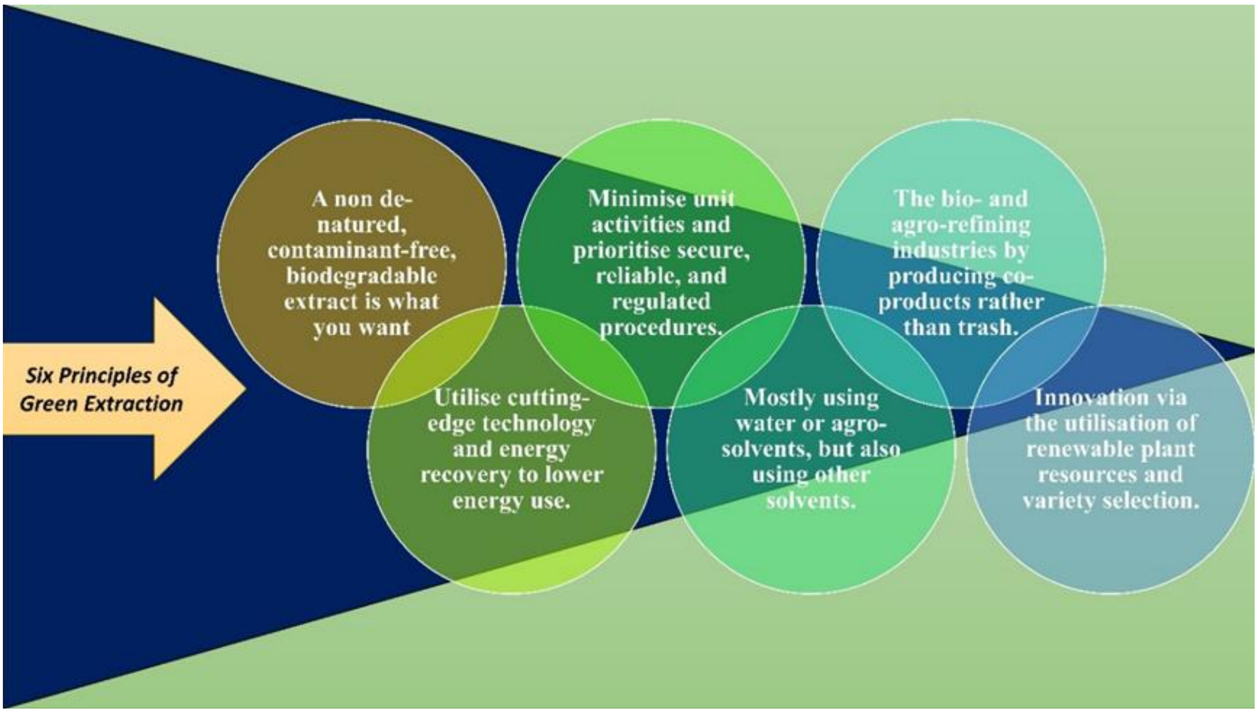


Figure 6: Six principles of green extraction

When compared to other factors, such as extraction temperature, duration, and grinding procedures, it was discovered that the extraction solvent and solid-to-solvent ratio had the greatest effects on extraction efficiency. An increase of up to 50% in the extracted levels of CGAs may be obtained by optimizing these factors, demonstrating the significance of optimizing the extraction technique for precise and reliable findings. Optimized techniques will also aid in reducing the analysis time, effort, and expense, all of which are critical components of a standard analytical procedure [107].

Cost-Effectiveness

Water is regarded as a green solvent because it is inexpensive, nonflammable, nontoxic, and ecologically benign. Polar molecules can be extracted because it is a polar solvent. However, it is not an effective solvent for semi-polar and non-polar substances [108].

Improved extraction yields of non-structurally changed bioactive compounds and shorter extraction periods have been demonstrated using unconventional extraction techniques. These approaches are thought to be economical and environmentally beneficial in the long term. Together with the former, these green alternative methods also demonstrate a reduction in greenhouse gas emissions, resulting in reduced environmental impact [109].

In the early 1990s, the phrase "green chemistry" first surfaced. In addition, it has been embraced globally over the past 20 years. To safeguard employee health, green chemistry aims to reduce environmental pollutants and promote sustainable development principles. Reduced environmental pollution, reduced use of toxic and hazardous chemicals, use of renewable energy sources, energy-saving methods, cost savings, increased security, improved human health, and a higher standard of living are further anticipated outcomes of the application of green chemistry [108].

Environmental Impact

Green extraction techniques have emerged as a new standard for separating active chemicals from natural goods in recent years, particularly with regard to tea plants, as they encourage environmental sustainability [49].

Extraction solvents made from non-renewable resources are hazardous to the environment and, consequently, to human health. A solvent must be evaluated for energy consumption, besides environmental, health, and safety considerations, to be classified as a green solvent. Low toxicity, high solubility, and biodegradability are desirable characteristics of alternative solvents for green extraction. Furthermore, the solvents used should be recyclable and derived from renewable resources; it means that they will have less impact on the environment [110].

The environment and human health are at risk because of the toxicity of some solvents used in the current procedures. Therefore, more ecologically friendly solvents have been developed and used in the past few decades. Designing safer chemicals and more readily degradable products, together with using renewable raw materials, are the main tenets of green chemistry, according to Luczynska *et al.* Low toxicity, rapid mass transfer, and low boiling point are all important factors to consider when choosing extraction solvents [111].

Future Perspectives and Challenges

The most promising approach is sustainable phytochemical extraction and purification using green solvents and techniques. However, a number of challenges and opportunities are yet to be overcome. One major area of future development will be innovating green solvent design for enhanced biodegradability, toxicity profiles, and cost. New ionic liquids, DES, and bio-based solvents are being researched with tailored properties for better extraction efficiency and minimal environmental impact. In addition, there is great opportunity for the integration of advanced extraction and purification systems. Techniques such as UAE coupled with chromatographic or membrane-based purification systems can simplify the processes, reduce energy consumption, and improve yields. In addition, seamless integration faces technical challenges in terms of compatibility and scalability. Another key challenge is the regulatory framework for the use of green solvents and new technologies, especially within the pharmaceutical and food industries. Harmonized guidelines concerning their safety, environmental impact, and industrial applications are required to enable their broad applicability. In addition, there are many challenges in equipment design, process optimization, and cost of translating small-scale laboratory processes to industrial-scale operations. These will have to be developed through interactions between chemists, engineers, and policymakers. Finally, for global translation of green extraction and purification techniques, ensuring that the techniques are economically viable in low- and middle-income countries is an important area. Further research should emphasize the development of low-cost, high-efficiency, and sustainable methods. By tackling these challenges, the field can continue to advance toward a greener and more sustainable future for phytochemical extraction and purification.

Conclusion

This volume and purification technique is expected to replace conventional destructive phytochemical methods to avoid further environmental and health damage in the near future. This review underlines how green solvent-like ionic liquids, deep eutectic solvents, and bio-based solvents will play key roles compared to conventional harmful solvents in terms of safety and low-toxicity characteristics, in addition to being biodegradable. Moreover, advanced green extraction techniques have been developed, such as supercritical fluid extraction, ultrasound-assisted extraction, MAE, PLE, and EAE, which are more efficient and economically effective, with energy use reduction to at least environmental impact. Similarly, a purification approach has been devised to complement such sustainable extraction approaches, which include preparative chromatography, high-performance liquid chromatography, membrane-based purification, and adsorption-desorption techniques. This will enable the integration of phytochemical industries to enhance the yield, purity, and sustainability. In contrast, this comparative analysis showed that these green extraction and purification methods have the potential to outperform conventional techniques in terms of efficiency, cost, and environmental footprint. However, expensive green solvents, the feasibility of scale-up, and regulatory barriers are some of the challenges that need to be met for wider application. Future development involving greener solvents, process integration of extraction with purification systems, and automation will be essential for overcoming many existing limitations. The rapid development toward industrialization of these sustainable extraction and purification techniques should be facilitated through collaborative networking among researchers, industry stakeholders, and regulatory organizations for a greener and more responsible phytochemical industry.

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