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REVIEW ARTICLE

Review of novel techniques for extracting phytochemical compounds from pomegranate (*Punica granatum* L.) peel using a combination of different methods

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Abstract
Pomegranate (*Punica granatum*) belongs to the *Punicacea* family and is usually known for its bioactive and potential health-promoting properties. Bioactive compounds are secondary metabolites derived from plants that contribute to health-promoting factors. Due to its natural health-enhancing properties, it has been popularly utilized in the nutraceutical and functional food industry. Numerous studies have demonstrated the abundance of bioactive chemicals in pomegranate peel. Various extraction methods are employed to separate bioactive compounds from plant material and serve multiple purposes. Prolonged extraction methods result in the loss of polyphenols by ionization, hydrolysis, and oxidation. Emerging technologies such as high hydrostatic pressure, ultrasound-assisted, pulsed electric field, enzyme-assisted supercritical fluid, microwave-assisted, and combinations are progressively supplanting traditional methods. These methods increase extraction efficiency, improve the quality of phenolics extracted, minimize solvent loss, and reduce extraction time, enhancing the final product. These innovative approaches enhance extraction efficiency and decrease energy consumption. However, these methods face limitations, high capital investment, further optimization, and potential scalability issues. Further research and development are required to overcome these obstacles and fully realize their potential. This review highlights the benefits of combining green approaches and solvents to extract bioactive compounds. It also highlights the synergistic effect of various methods, which enhances the different properties of extracts. Using a combined extraction strategy provides an effective solution for using pomegranate peel, waste valorization, and the development of bioactive products.

Keywords Pomegranate peel · Extraction · Solvents · Polyphenols · Bioactive compounds

1 Introduction

Plants are composed of primary and secondary metabolites. Primary metabolites, such as proteins, amino acids, and carbohydrates, are essential for plant growth and development [1]. Secondary metabolites are produced throughout the plant's life cycle to aid in survival and adaptation to environmental challenges [35]. The biosynthesis of both primary and secondary metabolites involves various pathways, with secondary metabolite synthesis occurring at the cellular level (Akhtar et al., 2019; Sreenikethanam et al., 2022). Bioactive compounds in plant products are classified into several categories: terpenoids, alkaloids, nitrogen-containing compounds, organosulfur compounds, and phenolics (Popova et al., 2020). These substances offer specific health benefits, including improved digestion, blood circulation, and anti-inflammatory, anticancer, and antidiabetic properties [2]; [3]. Due to their health-promoting qualities, these bioactive components are commercially extracted and used as functional foods or nutraceuticals [4]. Bioactive compounds are found naturally in plants, animals, microbes, and marine species. Traditional and non-conventional extraction techniques are employed to extract these compounds, with factors such as plant matrix characteristics, extraction solvent, time, temperature, and solubility affecting the extraction process (Chuo et al., 2022). Homogenized

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plant tissues can accelerate the extraction process. The efficacy of the extraction process is influenced by temperature, pressure, time, plant component matrix characteristics, extraction solvent, and extraction method. Over the past 50 years, innovative extraction methods that are more environmentally friendly have emerged, characterized by reduced use of synthetic and organic chemicals, shorter operation times, higher yields, and improved extract quality. There is an increasing trend in adopting novel extraction methods to enhance the specificity and efficiency of extracting bioactive compounds from plant materials (Garavand et al., 2019).

Novel extraction methods have garnered much interest due to their advantages over traditional procedures, such as lower solvent use, increased extraction efficiency, and environmental friendliness. Several novel techniques, including effervescence-assisted microextraction (EAM), cryogenic grinding, enzyme-assisted extraction, deep eutectic solvent (DES) extraction, ultrasonic-assisted extraction, and subcritical water extraction, have emerged as greener alternatives [118]. These methods improve extraction efficiency, preserve thermolabile components, and enhance the techno-functional aspects of isolated compounds [131]. Additionally, hybrid extraction techniques and non-conventional approaches are gaining popularity for extracting bioactive chemicals from natural sources, catering to the functional food industry while maintaining safety and environmental friendliness (Hewage et al., 2022) [5]. investigated the optimal conditions for ultrasound-assisted pressurized liquid extraction of anthocyanins from *Aronia melanocarpa* pomace using an aqueous citric acid solution as the solvent. The optimized conditions are 70 °C, 180 bar, 1.5% wt. citric acid concentration, and a 200-W ultrasound bath—resulting in an 88.0% wt—extraction of anthocyanins in 45 min. A kinetic study further examined the influence of temperature on anthocyanin yield under these optimal conditions.

Developing and implementing these innovative extraction technologies represent a significant advancement in bioactive compound extraction, offering more efficient, sustainable, and effective means of obtaining valuable compounds from varied matrices. This review uniquely focuses on the technology and methods used to extract bioactive compounds from pomegranate peel by leveraging novel and combined extraction technologies, an approach that has not been thoroughly explored or discussed in the literature. The novelty of this research lies in its pioneering integration of multiple advanced extraction techniques, emphasis on green chemistry, the discovery of unique bioactive profiles, technological innovations, comprehensive comparative analysis, interdisciplinary approach, and focus on scalability and industrial potential. This comprehensive exploration sets a new standard for extracting bioactive compounds, particularly from pomegranate peel, highlighting the scientific and practical implications of these novel methods.

1.1 Pomegranate

The Punicaceae family includes the pomegranate (*Punica granatum* L.), primarily grown in tropical and subtropical regions, including China, India, Iran, and the USA. Scientists are gaining attention from pomegranate fruits because of their bioactive components and possible health benefits [6]. Its three components are the fleshy mesocarp, seeds, and outer layer (leathery exocarp). Peels and inner membranes constitute the most significant portion of the fruit [7]. Anthocyanins are pomegranate flavonoids, giving the fruit orange, red, and purple hues. Because of their inherent flavonoid characteristics, these compounds can serve as valuable additives in films by modifying the color of packaging materials to reduce food oxidation. For instance, pomegranate rind extract decreases the transparency of chitosan-starch films [8]. The sensory and textural attributes of prawns improved by adding pomegranate peel extract to the chitosan coating, which prevented melanosis browning [9]. The anthocyanins from pomegranates have great potential as components of intelligent packaging. Anthocyanins can change the color of packing sheets in response to pH variations in the system and reduce the rate of oxidation and respiration. The effectiveness of using pomegranate biowaste as an effective active ingredient in food packaging systems was further supported by several other components that may be found in pomegranate rinds and seeds. These constituents exhibit plasticizing, reinforcing, and prolonging properties towards bioplastics [10].

Pomegranate contains many compounds renowned for their beneficial physiological effects, particularly their antioxidant and anti-inflammatory abilities. Although these advantages are mainly attributed to ellagic acid and ellagitannins, which include punicalagin, penicillins, and gallagic acid, newer studies suggest that anthocyanins and specific fatty acid profiles also play a role. Interestingly, these drugs have synergistic effects that are noticeably stronger when combined than when each component is used alone [11]. Flavonoids are among the secondary metabolites found in pomegranate peels (catechin, gallocatechin, and epicatechin), phenolic acids (gallic, ellagic, and caffeic acids), and hydrolyzable tannins (punicalagin and gallotannins). Punicalagin is one of the most notable of the several phenolic compounds found in pomegranate peels. Punicalagin, known for its diverse biological activities, is a cornerstone in unlocking the therapeutic potential of pomegranate peels. Its antioxidant properties make it invaluable in combating oxidative stress, while its antimicrobial attributes contribute to safeguarding against harmful pathogens. The main class of phytochemicals present in pomegranate peels are phenolic compounds. Punicalagin, the main phenolic component found in pomegranate peels, is well-known for its wide range of biological activities, including its anti-inflammatory, antimicrobial, antioxidant, and anticarcinogenic qualities [12]. These phenolic compounds have been linked to various biological activities and health advantages, including anti-inflammatory, anti-mutagenic, anticarcinogenic, antioxidant, and antihypertensive properties (Morya et al., 2024), according to various in vitro and in vivo studies. Moreover, they have been connected to managing and preventing various chronic illnesses, such as obesity, diabetes, Alzheimer's, and cardiovascular diseases [10, 13].

1.2 Bioactive compounds

A wide range of naturally occurring or synthetically produced chemicals known as "bioactive compounds" have unique physiological impacts on living organisms, often with potential advantages for human health. Among other biological functions, these substances can have antioxidant, anti-inflammatory, antibacterial, and anticancer effects [14]. Some bioactive substances are polyphenols, flavonoids, terpenoids, alkaloids, and peptides [15]. These substances are frequently found in plants and marine life and show therapeutic properties, as mentioned in Table 1. Polyphenols in green tea have shown antioxidative and anti-inflammatory properties that help against chronic diseases [16] and reported that flavonoids such as hesperidin from citrus fruits are involved in improving cardiovascular health. Carotenoids in carrots and other terpenoids have powerful antioxidant

Table 1 Bioactive compounds present in different parts of pomegranate and their functions

SI No	Bioactive compound	Molecular formulae	Molecular weight (g/mol)	Functions	References
1	Anthocyanins	$C_{15}H_{11}O+$	207.25	Combat harmful free radicals, reduce the risk of chronic diseases, and protect cells from inflammatory and oxidative damage	[133]
2	Apigenin	$C_{15}H_{10}O_5$	270.24	Anti-hyperglycemic, anti-inflammatory, anti-apoptotic effects	[134]
3	Chlorogenic acid	$C_{16}H_{18}O_9$	354.31	Antioxidant, antibacterial, antitumor, lipid and glucose metabolism control, anti-inflammatory, and nervous system protective properties	[135]
4	Cinnamic acid	$C_9H_8O_2$	148.16	Exhibit antioxidant, antimicrobial, anticancer, neuroprotective, anti-inflammatory, and antidiabetic properties	[136]
5	Cyanidin	$C_{15}H_{11}O_6+$	287.24	Antioxidant, anti-inflammatory, antitoxin, antidiabetic, cardiovascular, and neuroprotective properties	[137]
6	Catechin	$C_{15}H_{14}O_6$	290.27	Antimicrobial, anticancer, antihypertensive, anticoagulant, and antiulcer effects	[138]
7	Delphinidin	$C_{15}H_{11}O_7$	303.24	Antibiosis, anti-inflammatory, anti-allergenic, and anti-oxygenation activities	[139]
8	Ellagic acid	$C_{10}H_{10}O_4$	302.19	Enhanced effect on cell growth inhibition	[140]
9	Ferulic acid	$C_{10}H_{10}O_4$	194.18	It is an antioxidant that helps protect cells from oxidative damage	[141]
10	Gallic acid	$C_6H_2(OH)_3CO_2H$	170.12	Promote human health by inhibiting or preventing the development of neurological disorders	[142]
11	Genistein	$C_{15}H_{10}O_5$	270.24	Anti-inflammatory, anti-apoptotic, and anti-angiogenic effects in addition to its modulatory effects on steroidal hormone receptors	[143]
12	Punicalagins	$C_{48}H_{28}O_{30}$	1084.7	Antioxidant, hepatoprotective, chemopreventive, anti-atherosclerotic, and antiproliferative properties directed against cancer cells	[144]
13	Pelargonidin	$C_{15}H_{11}O_5^+$	271.24	Antioxidant ability to combat oxidative stress and inflammation	[145]
14	Urolithins	$C_{13}H_8O_4$	228.2	Kidney protecting, neuroprotective, anti-inflammatory, anticancer, anti-obesity, antidiabetic, anti-aging, and cardiovascular protective	[146]
15	Rutin	$C_{27}H_{30}O_{16}$	610.5	Anticancer agent	[147]
16	Quercetin	$C_{15}H_{10}O_7$	302.23	It functions as a medication to treat CVD and reduce coagulation, hyperglycemia, inflammation, and hypertension	[148]; [149]

properties and are linked to a lower incidence of age-related macular degeneration [17]. Alkaloids like berberine, which come from various plant sources, have been studied for their potential to decrease cholesterol and prevent diabetes via altering cellular pathways [18]. Promising antibacterial and immune-modulating properties have been demonstrated by peptides derived from sources such as fish [19].

These compounds may be classified based on their chemical makeup and biological activity [20]. The most well-known substances include alkaloids, flavonoids, terpenoids, polyphenols, and peptides. According to previous research, polyphenols' antioxidant and anti-inflammatory characteristics in foods such as fruits and vegetables may help avoid chronic diseases [21]. According to [9], flavonoids, such as anthocyanins in berries, have cardiovascular and neuroprotective benefits. Like essential oils, terpenoids exhibit antibacterial and anti-anxiety properties, demonstrating their broad therapeutic potential [22]. Alkaloids, like the caffeine in coffee, are widely known for their ability to enhance cognitive performance and stimulant effects on the central nervous system [23]. Collagen peptides are one type of peptide that has drawn attention for its role in supporting joints and maintaining skin health [24]. Exopolysaccharides are an emerging family of compounds produced by microorganisms with prebiotic and immunomodulatory properties that support gut health [25].

1.3 Pigment

Many different fruits, such as pomegranate, plum, and grape pomace, are rich in anthocyanins [26]. In particular, pomegranates are abundant in anthocyanins, which exhibit significant antioxidant capacities [27]. These antioxidants positively impact health and are essential to the human diet. It has been demonstrated that they contain antioxidants and protect cells from oxidative damage. Since anthocyanins are vulnerable compounds that may undergo degradation during commercial processing, it is imperative to safeguard them from external factors [28]. Researchers have looked at various encapsulation technologies, including spray drying, freeze drying, and emulsion procedures, to preserve the stability of anthocyanins. Overall, pomegranate, plum, and grape pomace are valuable sources of anthocyanins that offer potential health benefits [29].

Pomegranate peel has more complex anthocyanin pigments than pomegranate juice. The dark red pomegranate was found to have peonidinhexoside and myricetin-hexoside for the first time [30]. Anthocyanins primarily function as primary antioxidants in the pomegranate, whereas their role as secondary antioxidants has not been definitively determined. The potential antioxidant capabilities of anthocyanins in pomegranate are significantly influenced by various factors, particularly chemical structure and in vitro detection assays [31]. In one of the studies, the anthocyanin and total phenol content extracted from pomegranate peel were highest through microwave extraction and lowest through ultrasound extraction. The microwave extraction resulted in an anthocyanin content of 4 mg CE/g PPP and total phenols of 702.13 mg GAE/100 g. In contrast, the ultrasound extraction yielded an anthocyanin content of 0.35 mg CE/g PPP and total phenols of 232.58 mg GAE/100 g [32]. Similarly, when the freeze-dried passion fruit peel was subjected to solvent extraction, 87.59% of anthocyanin was retrieved [33].

2 Bioactive compound extraction

As extraction affects both the qualitative and quantitative characteristics of the active components in the sample, it is an essential step in producing value-added goods [34]. The identification, isolation, and characterization of bioactive chemicals can only be carried out after extraction. The kind of raw materials used, the extraction techniques used, and the particular extraction solvents used all have a role in the extraction of bioactive chemicals [35] [36]. Pressure, sample particle size, temperature, solution pH, electric field strength and pulse duration for PEF, ultrasonic power and frequency for UAE, and microwave power for MAE are just a few variables that might impact mass transfer and polyphenol solubility. Numerous tests have been conducted to assess the effects of these essential elements [37]. When extracting polyphenols from different sources, particularly plants, one of the most critical considerations is selecting an appropriate solvent before determining the extraction procedure [38]. Da Silva et al. (2022) state that the properties of some bioactive compounds influence solvent selection. Therefore, alternative extraction techniques are needed for other solutes, which may have polar, nonpolar, or even thermally labile chemical properties. Hydrophilic bioactive compounds and polar solvents (ethyl acetate, methanol, or ethanol) are extracted. The polar solvents with lower boiling temperatures can effectively extract phenolic compounds, such as ethanol, acetone, methanol, and acetone, plus water. According to [39], water extraction is primarily suited for removing metals, hydrophobic substances, peptides, carbohydrates, ions, water-soluble amino acids, and nucleotides.

2.1 Conventional technologies

2.1.1 Soxhlet extraction (SE)

One often-used technique to separate compounds from solid materials is Soxhlet extraction. It operates through a continuous process of solvent reflux, where the solid sample is enclosed within a thimble suspended in a boiling flask. The solvent continuously evaporates, condenses, and returns to the thimble, creating a repetitive cycle that effectively extracts the desired compounds [40]. This technique is valuable for isolating nonpolar or semipolar substances from solid matrices [41]. The main benefits of SE are that it is straightforward, has low startup costs, and can be used at high temperatures to enhance process dynamics (Table 2). It does not require filtering, and the solvent and sample are always present during the extraction [42]. It is not necessary to filter the extract. The fact that SE procedures are labor-intensive, heavily solvent-intensive, and have limited extraction efficiency is one of their fundamental problems (Teixeira et al., 2018). Arroy et al. (2017) reported that total anthocyanin extraction from kijit peels was better through Soxhlet extraction (82.2–85.8 mg cyanidin/kg) than ultrasound-assisted extraction (29.6–29.7 mg cyanidin/kg).

2.1.2 Hydrodistillation

Hydrodistillation is the earliest extraction method, and it is still used to remove bioactive compounds and essential oils from plant materials, such as fruits or garbage. In this procedure, dried plant materials are placed into a still compartment, water is added, and the combination is boiled without a solvent [35]. This procedure can be done with steam. Water is used to condense the vapor that is created. The condensed combination is then sent to a separator, which removes the oil and water's bioactive ingredients [43]. Without a solvent, simple separation and quick extraction are the main benefits of this method [44]. Limitations of this method include high heat-sensitive phenolic compounds that cannot be extracted due to high-temperature applications, and combustion of samples may occur [45]. According to [46], hydrodistillation is far better for qualitatively extracting essential oils from *Tamarindus indica* seeds than the Soxhlet apparatus. When pomegranate peel was subjected to hydrodistillation at 60 °C with a water and mixture ratio of 30:1 g/g for 10 min, the yield of anthocyanin was observed to be 40.6 mg/g with a content of 89.1 mg/g and scavenging activity of 31.5 g/g [47].

2.1.3 Decoction

Plant parts such as complex plants' roots, bark and seeds are used in decoctions. Samples (roots, bark, source) were crushed or ground before decoction. A decoction is a preparation in which water extracts active ingredients from medicinal plants [48]. The liquid used in the study was made by boiling the plant material with water. The combination is then boiled at low heat until it reduces to one-eighth of the initial volume for moderately or highly harsh drugs and one-fourth of the initial volume for soft drugs [49]. After the extract cooled and was strained, the filtrate was collected in clean containers. This approach is well-suited for extracting heat-stable compounds and requires less costly equipment. It is straightforward to execute, eliminating the necessity for a trained operator [50]. Unfortunately, the limitations are that heat-sensitive constituents should not be extracted [51]. Water-soluble contaminants are significantly present in the extract due to this approach. It is also inappropriate for extracting volatile or thermolabile components [52]. [53] examined the traditional decoction and its benefits, noting its easy accessibility and ability to produce extracts with elevated levels of EA, TPC, and RSA of pomegranate peel. These extracts demonstrated a TPC of 237 mg gallic acid equivalent (GAE)/g of dried peels (DW), RSA of 472 mg ascorbic acid equivalent (AAE)/g DW, and EA of 94 µg/mL.

2.1.4 Maceration

The maceration extraction method is known for its time-consuming drawbacks and low compound extraction efficiency. However, it has proven helpful for extracting components sensitive to heat [52] [54]. Significant amounts of phenols and anthocyanins were effectively extracted from chokeberry fruit by optimizing parameters such as 50% ethanol, a 1:20 solid-to-solvent ratio, and a 0.75-mm particle size. This demonstrates that the extraction of phenolic components from chokeberry fruit may be achieved effectively through maceration. It is a popular and economical process for turning plant materials into natural goods. Plant materials are soaked in a solvent to extract bioactive components using the maceration extraction technique, which is widely employed in the extraction of natural products. This technique uses the diffusion principle, in which the solvent slowly permeates the plant matrix, dissolves, and removes the desired chemicals. This procedure's simplicity, efficiency, and capacity make it ideal for processing large quantities of raw materials. In particular, delicate chemicals that can harm more aggressive extraction techniques can benefit from maceration. Recent developments have improved this method, including solvent choice, temperature regulation, and process length. To address current environmental problems, research is increasingly concentrating on environmentally friendly and sustainable solvent alternatives (Dias et al., 2022).

2.2 Non-conventional technologies

2.2.1 Microwave-assisted extraction

One popular method well-known for its benefits is microwave-assisted extraction (MAE), which shortens extraction times and uses less solvent [55]. The simultaneous operation

Table 2 Comparison of advantages and limitations of various extraction techniques

Technique	Advantages	Limitations	Recommended compounds	References
Soxhlet	Cost-effectiveness, ease of use, and rapid extraction rate	Lengthy extraction time, high reagent use, and energy expenditure	Lipids, essential oils, and pigments	Sharma, 2023
Maceration	Maceration is a straightforward process that requires essential tools and equipment	It is a drawn-out and time-consuming procedure. There is a greater need for solvent	Polyphenols, flavonoids, alkaloids, and essential oils	[52]
Decoction	It is ideal for obtaining heat-stable compounds. More expensive equipment is not needed for this procedure	Unfortunately, it is not recommended for the extraction of heat-sensitive components	Flavonoids, alkaloids, and polysaccharides	[151]; Zhang et al. 2022
Ionic liquids	Low toxicity and high stability, with adjustable physical and chemical properties	Possibility of pollution during synthesis	Polyphenols, alkaloids, flavonoids, and essential oils	[109]
Microwave-assisted extraction	Reduced equipment capital needed; shorter extraction times; lower energy consumption; higher extraction yields, low solvent consumption	The risk of thermal degradation, uneven heating	Polyphenols, essential oils, alkaloids	da Silva et al., 2022; [152]; [153]
Pressurized liquid extraction (PLE)	High extraction efficiency, reduced solvent usage	High pressure required, limit solvent option	Polyphenols, alkaloids, terpenes	[154]
Supercritical fluid extraction (SFE)	Non-toxic solvents (e.g., CO_2), high selectivity, high purity of extracts	High operational cost, requires specialized equipment	Essential oils, carotenoids, sterols	[155]; [156]
Enzyme-assisted extraction	Pretreatment selective to the substrate can be finished at room temperature and pressure to save energy	Because the cost of preparing enzymes is high, optimizing the conditions to obtain the maximum extraction rate is essential	Bioactive peptides, polyphenols, flavonoids, and proteins	[71]; [157]
Pulsed electric fields	The technique is easy to use, produces no pollution, and processes many samples	Controlling the appropriate electric field strength is essential. A powerful electric field could hinder the extraction process	Flavonoids, alkaloids, and essential oils	[132]
Enzyme-assisted extraction	Mild extraction conditions, increased yield of specific compounds	Cost of enzymes, longer extraction time	Polysaccharides, proteins, phenolics	[72]; [158]
Ultrasound-assisted extraction	High extraction efficiency, reduced extraction time, low solvent consumption	Possible degradation of thermolabile compounds, limited to small-scale applications	Polyphenols, flavonoids, anthocyanins	[158]; [159]
Hydrodynamic cavitation	High extraction efficiency, reduced solvent usage, shorter extraction time, enhanced mass transfer	Equipment cost, scale-up challenges, thermal degradation, limited to liquid phase extraction, cavitation erosion of reactor compounds	Polyphenols, essential oil, carotenoids, flavonoids, anthocyanins	[160]; [161]

of heat gradients and mass gradients, two synergistic transport phenomena, may be the cause of the expedited process and increased extraction yield. MAE, or microwave-assisted extraction, is one of the most widely used techniques [56]. Heat and mass gradients, two transport phenomena that work in concert to accelerate the process and provide a high extraction yield, may be responsible for these results [55]. When employing the microwave-assisted method, the extraction yield was notably higher. In addition, the extraction time was around 60 times shorter than conventional extraction methods [57]. Figure 1 illustrates the effects of solvent type, solvent/solid ratio, and microwave power on the extraction yield of phenolics. The most productive settings were as follows: the power of 600 W, the type of solvent being 50% aqueous ethanol, and the ratio of solvent to solid, 60/1 mL/g. The suggested extraction strategy's efficacy was assessed compared to ultrasound-assisted extraction (Fig. 2), as per Kaderides et al. [12]. Plants with a high water content are very effective at this extraction, but plant parts with a lower water content take more time to heat. Microwave-heated plant material can never be heated over 100 °C, which is the boiling point of water. Although polar, water molecules have unequal charges. There are magnetic and oscillatory fields in microwave radiation. The frequency range of the microwaves employed in a microwave oven must be within the natural frequency range of water molecules [58]. The

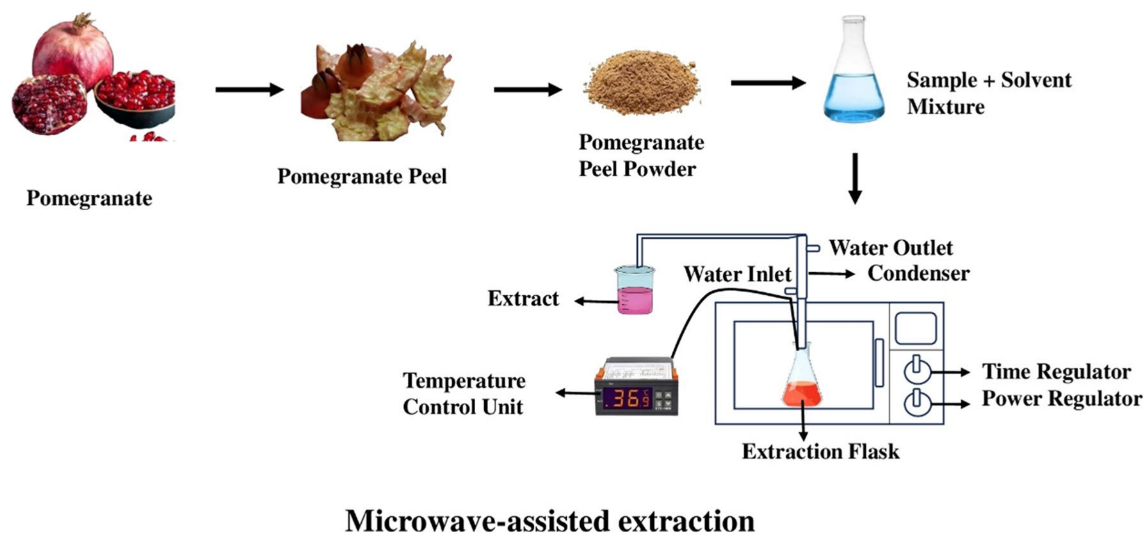

Fig. 1 Microwave-assisted extraction

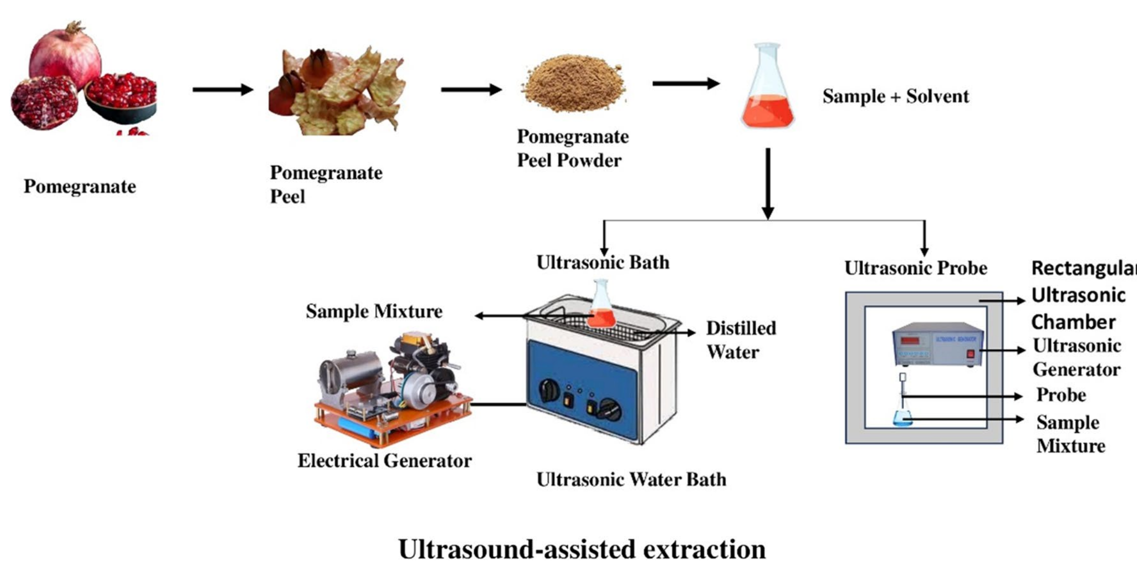

Fig. 2 Ultrasound-assisted extraction

positive and negative sides of a water molecule interact with the positive and negative forces of a moving electric field during the transmission of a microwave. This causes the water molecules to oscillate, which causes the molecules to rub against one another and heat [59]. Microwave-assisted extraction (MAE) has become a promising technique for phyto-bioactive chemical extraction because of its simplicity of use, high extraction efficiency, low solvent need, and comparatively high energy consumption. Limited by the uneven heating of samples can lead to localized overheating and degradation of heat-sensitive compounds. Additionally, the high initial cost of microwave equipment and the necessity for specific solvent conditions [60]. By combining enzymolysis with microwave irradiation, MAE can change the structure of cell walls and increase their permeability [61]. This makes it easier for the target molecules in the matrix cell to be moved into the solvent. Heat-sensitive flavanols are best extracted using the MAE technique. MAE is less environmentally hazardous because of its shorter extraction periods, significant energy savings, and lower atmospheric CO_2 emissions (Cheng et al., 2015).

2.2.2 Ultrasound-assisted extraction (UAE)

Ultrasound-assisted extraction is a sustainable method of extracting phenolic compounds from various sources. This method offers excellent consistency in results, reduces solvent usage, streamlines the process, minimizes wastewater production, and yields purer extracts [62]. Two physical processes are involved in the extraction process: diffusion through cell walls and the flushing of cell contents, which occurs when the walls are broken. By effectively interacting with plant matter, ultrasound waves cause alterations in plants' physical and chemical characteristics. By rupturing the integrity of plant cell walls, the cavitational effects produced by these waves enhance mass transfer and facilitate the release of extractable chemicals. The destructive properties of ultrasonic waves are necessary for ultrasound-assisted extraction. UAE enhances capillary effects, capillary disruption, increased penetration, and mass transfer [63], as shown in Fig. 3. In the UAE, high temperatures improve solubility, diffusivity, and pressure, enabling waves to permeate tissue and transfer contents in organic and inorganic solvents as shown in Fig. 2. By damaging the plant cell walls, the cavitation effects of these waves allow the release of extractable chemicals and improve mass transfer. Increased swelling causes a mass transfer rate to increase, increasing extraction efficiency and shortening extraction time [59]. Ultrasonic-assisted extraction (UAE) devices are critical for extraction because they can identify important design parameters such as acoustic energy density, ultrasound power, ultrasonic volume, and mode of operation [51, 64], limited by the risk of overheating or prolonged sonication degrading sensitive phenolic compounds. Furthermore, the unique characteristics of the plant material and the solubility of the phenolics in the selected solvent may impact the efficacy of UAE [65]. Ultrasound increased the extraction yield to 13.85 g gallic acid equivalent per 100 g of dried pomegranate peels and reduced the extraction time [66]. UA 60% and UET 6.2 min were found to be the most ideal ultrasonic extraction settings after examining individual components and combinations of all operational variables. The pomegranate peel extract (POPx) was projected to have the following maximum values at this ideal state: 42.2 mg GA/g, 88.8%, 1824.6 μmol Fe^{2+}/g, and

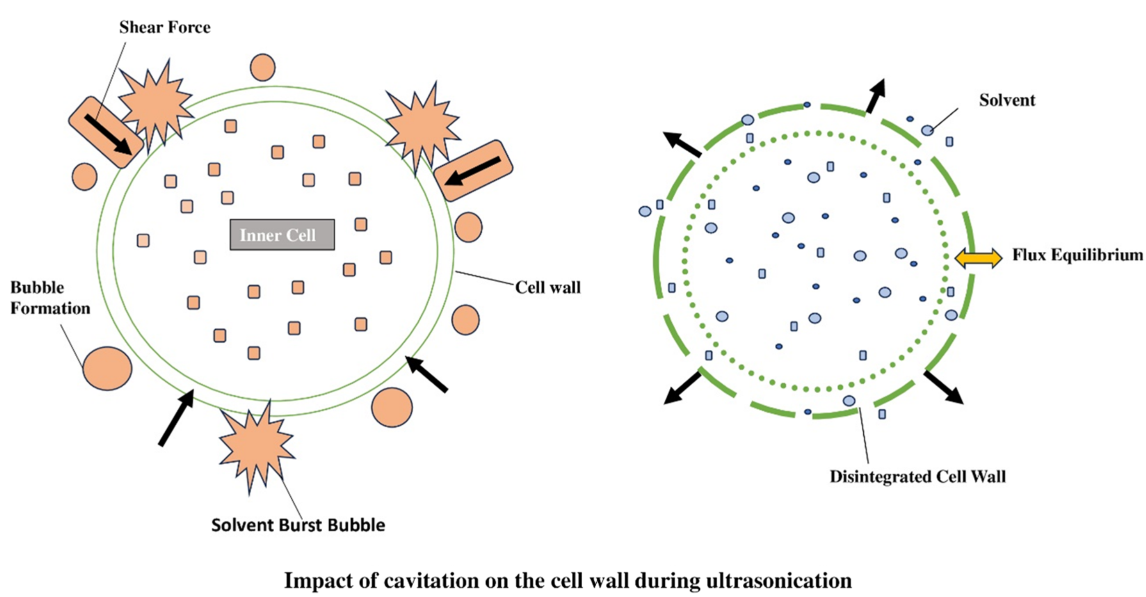

Fig. 3 Impact of cavitation on the cell wall during ultrasonication

0.51 mg/mL for TPC, DPPH, FRAP, and IC50, respectively [67].

2.2.3 Enzyme-assisted extraction (EAE)

The development and study of enzyme-assisted extraction methods for extracting bioactive chemicals from plant materials have been substantial [68]. These techniques break down the source material's cell wall using certain enzymes, increasing the extraction yield [69, 70]. Studies, for example, have demonstrated that the use of cellulases and pectinases, as opposed to conventional methods, enhances yields and preserves antioxidant activity when phenolic compounds are removed from plant materials, for example, it has demonstrated that the use of cellulases and pectinases, as opposed to conventional methods, enhances yields and preserves antioxidant activity when phenolic compounds are removed from plant materials (Li et al., 2020; [135], [2]). Enzyme-assisted extraction (EAE), as opposed to traditional solvent-based extraction, has been used to extract bioactive peptides from marine algae sources, resulting in increased yields and bioactivity preservation. Enzyme-assisted technology (EAE) is a green technique for extracting phenolic chemicals. It involves adding the proper enzyme to increase extraction efficiency [71]. It is limited by the activity and specificity of the enzymes, which might not be suitable for all phenolic chemicals or plant materials. Other factors include the price of enzymes and the requirement for exact control over extraction conditions [72]. The food matrix releases polyphenolic compounds more quickly when enzymes like cellulase or xylanase are added because they facilitate enzymatic hydrolysis, which speeds up the breakdown of cell walls, as shown in Fig. 4. The manipulation of process parameters allows for the controlled release of these valuable polyphenols from food sources [73]. Under optimum enzymolysis settings of 55 °C, pH 5.0, for 88 min, with a water-to-raw material ratio of 22:1 mL/g and a cellulose dose of 0.93%, researchers obtained a yield of 22.31 ± 0.07% for pomegranate peel polysaccharide [74].

2.2.4 Pressurized fluid extraction (PFE)

An improved and effective method for removing bioactive substances from different plant parts, food items, and natural sources is pressurized fluid extraction (PFE). PFE increases the solubility and diffusion of target compounds—usually water or carbon dioxide (CO_2)—into a pressurized solvent by applying high pressure and heating [75]. Because it can produce more bioactive chemicals than more conventional extraction techniques like maceration and Soxhlet extraction, this approach has attracted much interest [76]. Furthermore, PFE is regarded as ecologically benign as it permits the recovery and repurposing of the extraction solvents and lessens the requirement for significant amounts of organic solvents [77]. PFE is limited by the potential for high temperatures and pressures to cause the thermal breakdown of delicate phenolic compounds. Furthermore, the yield and overall efficiency of the extraction process might be impacted by variations in the solubility of certain phenolics in the extraction solvent. High yields of phenolic compounds and anthocyanins show that PLE has excellent promise for extracting beneficial chemicals from grape marc.

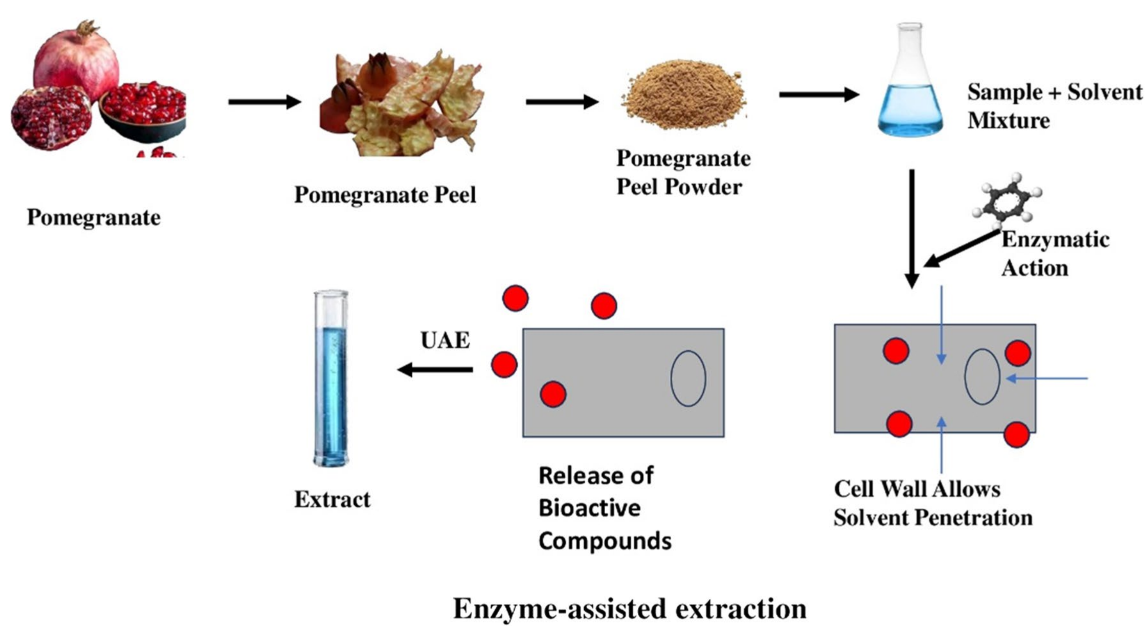

Fig. 4 Enzyme-assisted extraction

The recovery of anthocyanins and phenolics is significantly influenced by the solvent used and the chosen temperature [78]. When PLE worked with water–ethanol combinations at greater temperatures than standard acetone extraction, it produced extracts with enhanced antioxidant ability. It delivered larger polyphenols from local agro-industrial waste, such as Negra Criolla grape pomace. Modifying the PLE solvent's ethanol concentration allows for selective polyphenol recovery [79]. Compared to the other two methods, PLE yielded less effective outcomes, resulting in extracts that had reduced polyphenolic content and weakened antioxidant characteristics [44]. However, no particular pattern was found regarding the impact of acid type, acid concentration, or ultrasonication. Reducing extraction time with PLE could be crucial for refining the process further, reinforcing this technique's potential to establish innovative and sustainable extraction methodologies [80]. Pressurized liquid extraction (PLE) using a mixture of pressurized water and ethanol produces pomegranate peel extract (PPE) under ideal circumstances. This extract has a total phenolic content (TPC) of 164.3 ± 10.7 mg gallic acid equivalents (GAE) per gram of dry weight (DW) and a punicalagin content of 17 ± 3.6 mg per gram of DW, respectively [81].

2.3 Combination of novel extraction technologies

2.3.1 Ultrasound-assisted enzymatic extraction (UAEE)

UAEE is thought to be a blend of two complimentary extraction methods that offer additional benefits. Enzymes in the EAE process assist in the recovery by weakening and rupturing cell walls and membranes. However, it is worth noting that, unlike cell walls, enzymes cannot fully hydrolyze the matrix [82–84]. Figure 5 illustrates how the cavitation caused by ultrasound in the United Arab Emirates can physically constrict and rupture the matrix, facilitating enzymatic reactions and the consequent release of target molecules. Moreover, enzymes alone cannot improve the mass transfer of target materials, solvents, or other enzymes inside or outside the matrix. Additional physical techniques like shaking and agitation are frequently used in EAE to increase mass transfer. UAE is the better choice since it can improve mass transmission within and outside the matrix [85]. More substrates are exposed to the enzymes in the EAE system, and more target molecules are released as a result of the ultrasound intensity in UAE, which increases the matrix's surface area and the area of interaction between phases. According to certain studies, ultrasonication in EAE can accelerate enzymatic reactions by increasing collisions between the substrate and enzyme, which could indicate a greater release rate [82]. Plant tissue bioactive chemical extraction has been accelerated by research into UAEEs. Using UAEE, polysaccharides from various plant sources have been extracted [86, 87]. UAEE is limited by the high cost of the enzymes needed for the procedure and the possibility of phenolic compound degradation as a result of extended ultrasonic exposure. Furthermore, optimizing the combination of ultrasonic conditions and enzyme concentrations might be difficult and time-consuming [88]. This study used a genetic algorithm and response surface approach to optimize the extraction conditions. Pomegranate peels are used with UAEE, a solvent that is water. The

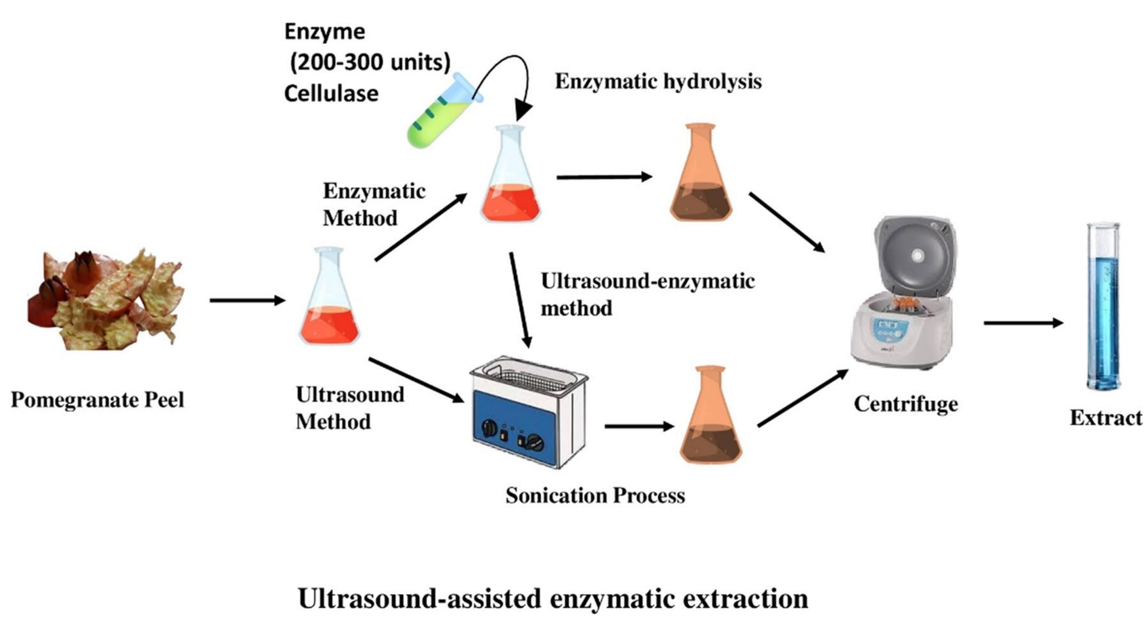

Fig. 5 Ultrasound-assisted enzymatic extraction

ideal conditions for ultrasound and enzyme concentration (1.32 mL/100 mL) were 41.45 min for the TPC (19.77 mg GAE/g), TFC (17.97 mg QE/g), and DPPH (74.213%) [164].

2.3.2 Ultrasonic microwave-assisted extraction (UMAE)

One of the methods with the greatest research and potential for a combination extraction technique is UMAE, which combines UAE and MAE. The UMAE process utilizes ultrasonic waves and microwaves to destroy the cellular structure of the source material, allowing for the release of the desired compounds [89, 90]. Sectional and time-sharing methods optimize the extraction, ensuring even distribution and complete retrieval of the target compounds. After extraction, the filters and evaporation chambers separate the extracted compounds from the biomass. UMAE boasts several benefits, including improved extraction efficiency, shorter operation times, and the efficient utilization of waste materials. Moreover, the nutritional value of the extracted compounds is maintained by minimizing high-temperature exposure [91]. UMAE is limited by the process's high temperatures and pressures, which cause delicate phenolic compounds to degrade. Furthermore, variables, including the matrix of the plant material, the duration of the extraction process, and the solvent selection, might affect the effectiveness of UMAE and lead to variable phenolic yields [92]. By breaking down cell walls and improving solvent penetration into the sample matrix, ultrasound facilitates mass transfer by increasing the contact surface area and encouraging the solvation of soluble substances. Concurrently, the sample is quickly heated by microwave radiation, which raises the solute's mass transfer rate and solubility, speeds up the desorption of pertinent molecules from the sample matrix, and increases extraction efficiency [70]. Compared to standard decoction extraction, ultrasonic and microwave extraction combined produced a considerably larger quantity of bioactive chemicals ($p < 0.001$). Under optimal conditions, microwave-ultrasonic aided extraction (MUAE) using natural deep eutectic solvents effectively extracts anthocyanins from perilla leaves, yielding 619.62 mg/100 g [93].

2.3.3 Microwave-assisted enzymatic extraction (MAEE)

By using high-energy microwaves in conjunction with enzymatic plant cell wall destruction, a process known as microwave-assisted enzymatic extraction (MAEE) enhances the solubility of bioactive components and allows for the extraction of polysaccharides. The adoption of MAEE technology leads to decreased generation of chemical reagent waste compared to conventional extraction methods while also enhancing overall extraction efficiency [94], limited by the high temperatures required, which may cause heat-sensitive phenolic compounds to degrade. Furthermore, the selectivity and activity of the enzymes, which might not be at their best in a microwave environment, can limit the efficacy of MAEE [95]; Zhang et al. [92] extracted polysaccharides from the swollen culm of the mountain *Zizania latifolia* (PMZL) using microwave-assisted enzymatic extraction (MAEE) for the first time, with a noteworthy yield of $60.43 \pm 1.12\%$. Furthermore, microwave-assisted enzymatic extraction has effectively extracted valuable compounds from various sources, such as *Chlorella vulgaris*, *Zizania latifolia*, and *Sagittaria trifolia*. Numerous sectors, including medicines, nutraceuticals, functional foods, cosmetics, and functional materials, might benefit significantly from using this extraction technique [96]. Microwave-assisted enzymatic extraction (MAEE) efficiently extracts phenolics by 0.6% viscozyme and microwave power of 443 W from pomegranate peel, phenolics 305 mg GAE/g [97].

2.3.4 Hydrodynamic cavitation

Hydrodynamic cavitation is an innovative extraction method that employs the formation, growth, and implosive collapse of cavities or bubbles in a liquid, generating localized high temperatures and pressures. This extreme environment facilitates the disruption of plant cell walls, enhancing the release of intracellular phenolic compounds into the solvent [98]. Additionally, the process can be fine-tuned by adjusting parameters like inlet pressure, flow rate, and cavitation device design to optimize phenolic extraction efficiency. Hydrodynamic cavitation thus presents a sustainable and efficient approach for extracting valuable phenolics from plant materials [99].

Hydrodynamic cavitation is a successful and efficient technique for obtaining important chemicals from pomegranate peel, with notable advantages regarding environmental impact and extraction efficiency. Research indicates that hydrodynamic cavitation-based extractions (HC) reliably produce significant concentrations of beneficial substances such as total polyphenols and ellagitannins, particularly at higher frequencies [100]. Moreover, non-edible pomegranate by-products extracted using hydrodynamic cavitation have demonstrated strong anti-inflammatory and anti-fibrotic properties and prospective cardiovascular benefits in vivo that are equivalent to those of standard extractive approaches [101]. Hydrodynamic cavitation (HC) significantly enhanced the extraction efficiency of valuable compounds from pomegranate by-products compared to traditional and non-conventional extraction methods. HC outperformed both ultrasound-assisted extractions (UAE) and microwave-assisted extractions (MAE), achieving extraction yields of around 80% instead of 45% and 57% for UAE and MAE, respectively. Among these innovative approaches, HC has shown great promise, delivering the most favorable outcomes and contributing substantially to the enhancement of bioactive compound yields, limited by the possibility of sensitive phenolic chemicals being destroyed by extreme specific conditions such high pressure and temperature. Furthermore, the particular characteristics of the plant material and the type of solvent employed might have an impact on the extraction's effectiveness [102]. Ballistreri et al. (2024) conducted a study on high-pressure carbonization (HC) at 4 bar pressures, examining treatment durations of 0, 10, 20, 30, 40, 50, 60, and 90 min under low temperatures (42 °C) [103]. The investigation revealed degradation and diminishment of vitamin C and total phenolics in juices subjected to prolonged HC treatment. As a result, it was inferred that HC has the potential to serve as a non-thermal technique for enhancing the stability and physicochemical attributes of Brazilian orange juice [104].

3 Solvents

The extraction solvent significantly impacts the extracted molecules' yield, selectivity, and quality because they are used to isolate bioactive chemicals from various natural sources. Different solvents have unique characteristics that dictate whether or not they are suitable for a given extraction technique. Popular solvents like ethanol and water, nonpolar solvents like hexane, and solvents with intermediate polarity like acetone and methanol are frequently employed for extraction [105]. Due to its safety, affordability, and ability to extract hydrophilic substances such as polyphenols and polysaccharides, water is frequently used as a solvent. Due to its mild polarity, ethanol is preferred because it is good at extracting various chemicals, including flavonoids and alkaloids. Different bioactive chemicals with various solubilities are removed using methanol and acetone, two intermediate polarity solvents [106]. As shown in Table 3, methanol produced the maximum total extract during pomegranate peel extractions carried out with a solvent-to-sample ratio of 15:1 (w/w) at 40 °C for 4 h. Water, ethanol, acetone, and ethyl acetate were the next highest yielding solvents [107]. Recent research has emphasized the optimization of solvent choice depending on certain component classes and target sources. Panja [108] examined the effectiveness of various solvents in isolating polyphenols from apple peels, emphasizing the significance of solvent polarity in achieving high yields [3]. Investigations of the effects of different solvents on the extraction of bioactive chemicals from medicinal plants have focused on the contribution of solvent characteristics to improving extraction selectivity. The former has shown increased yields and efficiency when comparing natural deep eutectic solvents (NADES) and ionic liquids to conventional solvents [109]. It was clarified that a 50% (v/v) ethanol/water solution and water were used to examine the effectiveness of deep eutectic solvents (DES) for polyphenol extraction [110]. Compared to water, which produced 13 mg/100 g of total phenolic content, the DES solvent showed a greater amount of 152 mg/100 g.

3.1 Natural deep eutectic solvent (NADES)

The main components of natural deep eutectic solvents include molecules that can donate hydrogen bonds, like urea, and carboxylic acids, such malic and citric acids, as well as molecules that can absorb hydrogen bonds, including betaine and choline chloride. These ingredients melt at a temperature much lower than the melting temperatures of the individual ingredients when mixed at particular molar ratios, generating a transparent liquid [111] [112]. Natural deep eutectic solvents are mostly composed of organic acids, including citric, lactic, and malic acids, as well as sugars like fructose, sucrose, and glucose. NADESs also include urea and choline chloride, which are found naturally in a variety of cellular and organismic systems [113]. The amount of pectin extracted and the molecular weight of the water-based fractions and NADES both increased when apple pomace was treated with a combination of choline chloride and lactic acid (NADES) for 2 h at 80 °C [112, 114]. After this treatment, the amount of pectin obtained from the water-based fraction was much more significant (six times greater) than that obtained from the NADES. The extraction of GalA, a component of pectin, reached its highest level at 56.1%. This suggests that the choline chloride and lactic acid treatment helped to loosen the structure of the cell walls, making it easier to extract pectin with water. Therefore, using choline chloride and lactic acid followed by water extraction is a very effective and totally environmentally friendly way to obtain pectin from apple pomace [114]. Anthocyanins can be extracted effectively with NADES and ultrasound assistance. The extraction efficiency is determined by the DPPH test, and the findings indicate that the range of cyanidin 3-glucoside/100 g is 81.1 to 327.6 mg eq [115]. This result outperformed the ethanolic solution (3.55 mg EAG mL^{-1}) and the other tested NADES (0.81 to 3.84 mg EAG mL^{-1}) extraction efficiency. Choline chloride and lactic acid (CC-LAC) were shown to be the most effective NADES combination for phenolic extraction from pomegranate peel, yielding 4.14 mg EAG mL^{-1}. This result was greater than the extraction efficiency of the ethanolic solution (3.55 mg EAG mL^{-1}) and other tested NADES (0.81–3.84 mg EAG mL^{-1}) [116].

Table 3 Different types of solvents used in pomegranate peel extraction

SI No	Extraction method	Solvent used	Extraction parameters	Detection method	Findings	References
1	Heat-assisted extraction	SUPRAS (supramolecular solvents)	Boiling for 2 h, Temp—93 °C	The mass and NMR spectrum	The SUPRAS extract was purified with water and ethyl acetate. Pure EA was obtained through antisolvent precipitation with tetrahydrofuran and water. The ellagic content in final product was 95.6% and the yield 75%	[162]
2	Ultrasound-assisted extraction	Natural deep eutectic solvents (NADES)	20 g of NADES solvent ratio, extraction time—25 min, temp—45 °C	Response surface analysis	The CC-LAC solvent has more phenolic recovery by 84.2% than ethanolic extraction. Study shows that NADES solvent is more efficient for extracting pomegranate peel than other harmful solvents	[116]
3	Microwave-assisted Soxhlet extraction (MASE)	Methanol	Microwave power—100–800 W, time—0–35 min, solvent concentration—10–30%	Ultra-high-performance liquid chromatography (UHPLC)	MASE gives extract with high TTC, TFC, and TPC and high antioxidant capacity. 163 mg rutin TFC yield, 323 mg TTC yield, and 376 mg gallic acid TPC yield. The method MASE allowed for the creation of a quick solvent-minimized extraction process and enhanced the amount of extracts from a natural source	[163]
4	Ultrasound-assisted enzymatic extraction	Water	Ultrasound time—41.45 min, enzyme concentraction—1.32 mL/100 mL, and incubation time—1.82 h at 44.85 °C	UV–visible spectrophotometer	UAEE is cost-effective and more recovery of polyphenols and less energy consumed. TPC (19.77 mg GAE/g), TFC (17.97 mg QE/g), and DPPH (74.213%). Ultrasound and enzymes can extract polyphenols from pomegranate peels efficiently, offering a potential solution for utilizing this by-product	[164]
5	Ultrasound-assisted extraction	Ethanol	Extraction time—15.38 min, Temp—55.7 °C, β-cyclodextrin—1.8%	High-performance liquid chromatography (HPLC)	The extraction efficiency of 65.20% and the analysis of HPLC resulted that β-CD solution improved the extraction efficiency. Aqueous β-CD and UAE are beneficial for extracting bioactive compounds from fruit processing by-products for functional foods and nutraceutical applications	[165]

Table 3 (continued)

SI No	Extraction method	Solvent used	Extraction parameters	Detection method	Findings	References
6	Hydrodynamic cavitation	Water	Extraction time—20 min, Temp—39 °C, cavitation number—0.10 to 0.11	High-performance liquid chromatography (HPLC)	Using hydrodynamic cavitation, results showed PPE's efficacy in a hypertensive rat model, similar to whole fruit extract (PFE) from the same technique, with good bioaccessibility after oral administration	[101]

4 Storage conditions and stability

Storage conditions are an important factor in determining the preservation of polyphenols in different food items. The stability and maintenance of these constituents are essential for maintaining the nutritional and health advantages of stored products. Recent investigations have emphasized fine-tuning storage conditions to minimize bioactive component deterioration with time [117]. Higher results were found when the study looked at how storage affected the amount of betalain, flavonoids, total phenol, and antioxidant capacity in beetroot powder [118]. The findings from the storage experiment revealed a notable decrease in all the bioactive constituents within the stored beetroot powder [118]. Various factors influence the stability of phenolic compounds, including pH, temperature, light exposure, water activity, storage conditions, and the processing method employed [119]. Multiple factors influence the stability of anthocyanins post-extraction, with pH playing a crucial role. A pH of 10 signifies greater stability [120]. Temperature affects stability; prolonged exposure and higher temperatures cause anthocyanin degradation [121]. Exposure to light significantly changes stability and degrades anthocyanin extracts. Water activity also affects the stability of anthocyanins when they are present. Furthermore, stability is influenced by the extraction solvent used; for example, acidified ethanol (1%) shows better anthocyanin preservation [122–124]. These compounds are susceptible to deterioration and loss of efficacy due to their inherent instability. Nevertheless, the adoption of innovative technologies, notably nanotechnology, offers the potential to mitigate or prevent the degradation of these compounds. Nanocomposites and nanocarriers can amplify the impact of bioactive compounds, shield them from degradation, enhance their solubility, and enable precise targeting within the body. It is imperative to carefully select the materials used for encapsulation and the techniques employed to encapsulate these compounds to enhance their preservation [125]. It has been found that pomegranate peel extract exhibits good storage stability under various conditions. Research has indicated that the extract exhibits stability over a range of pH values, with acidic pH demonstrating stability while neutral and basic pH exhibits breakdown [126].

5 Future perspectives and challenges

Extraction processes have been pivotal in several sectors, such as food production, environmental management, and medicines. Extraction methods are continually evolving, primarily motivated by the imperative for sustainability, precision, and enhanced efficiency [127]. Prospects on the horizon encompass adopting environmentally responsible practices, precisely targeting specific compounds, managing intricate

Table 4 Extraction of bioactive compounds from pomegranate peel extract using various extraction methods

Extraction method	Conditions	Findings	References
Microwave-assisted method	Solvent/solid ratio, 60/1 mL/g 50% aqueous ethanol/powder, power—600 W	The efficiency of microwave extraction is 1.7 times higher than that of ultrasound extraction in 4 min, while ultrasound takes up to 10 min	[12]
Ultrasound-assisted extraction	Ultrasound power control—60%, extraction time—6.2 min	The extract had antifungal activities against *Aspergillus niger*. TPC—42.2 mg GA/g, DPPH—88.8%, FRAP—1824.6 μmol Fe^{2+}/g	[67]
β-Cyclodextrin-assisted extraction	β-CD solution (1.8%; w/v), sonication at 40 kHz and 100 W for 30 min	After 60-day storage, the anthocyanin degradation indicates 600 mg/L PPE has higher color index than control sample	[166]
Pulsed ultrasound-assisted extraction (PUAE)	S/S ratio—2.17 g/100 mL, sonication power 116 W with 80% duty cycle	Resulted extract yield, TPC, TFC, AOX, and TAC are the following: 0.511 g/g, 182.66 mg GAE/g, 36.69 mg QE/g, 164.82 mg GAEAC/g, and 22.51 mg cyn-3-glc eq/100 g	[167]
High-pressure-assisted enzymatic extraction	Pressure—300 MPa, time 15 min, cellulase and pectinase conc.—4% each	High-pressure extraction (300 MPa) exhibits better extraction yield than enzymatic extraction of punicalagin isomers and bis-hexahydroxydiphenoyl-glucoside	[168]**;** [168]21
Pressurized liquid extraction	Ethanol conc.—77% Process temperature—200 °C	TPC—164.3 ± 10.7 mg GAE/g, punicalagin content—17 ± 3.6 mg/g of pomegranate peel extracted using PLE. And antimicrobial activity is 14 mm	[81]
Hydrodynamic cavitation	Process time—15 min Energy—38 Wh/kg Room temp—30 °C	Lyophilized extract from whole pomegranate fruit obtained using hydrodynamic cavitation is the optimal solution for preserving antioxidants and antiradical properties intact, thanks to its stability without water that causes oxidative reactions leading to degradation of phytochemicals	[169]
Microwave-assisted Soxhlet extraction	Ethanol conc.—30% Time—35 min Power—100–800 W	Total tannin content—323 mg (GAE)/g, TPC—376 mg (GAE)/g, TFC—163 mg rutin content	[163]
Enzyme-assisted supercritical fluid extraction (EASFE)	Enzyme conc. Protease, pectinase, and cellulase in ratio 25:25:50, ethanol 80%, extraction time (30–120 min), temperature—55 °C, pressure—300 bar	Phenolic acids like vanillic, ferulic, and syringic contents are as follows: 108.36 μg/g, 75.19 μg/g, and 88.24 μg/g	[170]

source materials, ensuring compliance with regulations, and integrating diverse technologies. As shown in Table 4, recent developments in extraction techniques—such as solid-phase microextraction, ultrasound, microwaves, supercritical fluids, and other cutting-edge approaches—are revolutionizing the business by making it possible to extract bioactives from pomegranate peel [128]. Innovative technology for extracting anthocyanins from pomegranate peel involves various intricate issues that must be carefully considered. Because anthocyanins have different structures, careful optimisation of extraction parameters, including temperature, pressure, and solvent selection, is required. This process can take a lot of time and resources. Significant challenges include ensuring the purity and selectivity of extracted chemicals, accelerating commercial viability methods, and addressing anthocyanin stability against degradation [129]. Furthermore, careful consideration must be given to the expenses of specialized equipment, environmental effects, regulatory compliance, and the requirement for reproducible extraction processes. To overcome these obstacles and utilize cutting-edge extraction techniques to maximize the potential health benefits of pomegranate peel anthocyanin, interdisciplinary collaboration and targeted research efforts are essential. Emerging trends involve the principles of the circular economy, the exploration of plant-based extraction, the retrieval of nanoparticles, high-throughput methodologies, and the application of biotechnological approaches [130]. Environmentally friendly extraction methods are becoming increasingly popular for isolating bioactive compounds from food sources. Hybrid extraction techniques have proven effective and promising in the functional food market [131]. The future of extraction methods holds excellent promise, presenting numerous possibilities while posing the concurrent challenge of balancing sustainability and optimizing the efficiency of extraction processes [132]. While traditional extraction methods are effective, they come with limitations such as the loss of polyphenols and energy inefficiency. However, emerging technologies and hybrid approaches, including microwave-assisted techniques, supercritical fluid, pulsed electric fields, ultrasound, and high hydrostatic pressure, and their combinations, are increasingly being utilized as alternatives to traditional methods [2]. These innovative techniques offer numerous advantages, including enhanced extraction efficiency, higher yields, reduced impurities, preservation of heat-sensitive compounds, diverse solvents, and decreased energy consumption. The nutraceutical and functional food industries will be able to approach sustainability and health more mindfully and sustainably thanks to these cutting-edge techniques in bioactive component extraction. This review discusses novel microwave, ultrasound, enzymatic, and pressurized fluid extraction methods and their combinations, such as UAEE, MAEE, and UMAE. Their method of extraction, benefits, drawbacks, use of various environmentally friendly solvents, and the usage of cutting-edge discoveries and technology to extract additional bioactive substances. Therefore, these novel extraction technologies provide an efficient extraction process. However, novel and combined extraction technologies are lacking in design and must be improved.

6 Conclusion

While effective, traditional extraction methods have limitations, including the loss of polyphenols and energy inefficiency. However, emerging technologies and hybrid approaches, such as ultrasound, pulsed electric field, supercritical fluid, high hydrostatic pressure, microwave-assisted methods, and their combinations, are increasingly being used as substitutes for traditional methods. These innovative techniques offer numerous advantages, including enhanced extraction efficiency, higher yields, reduced impurities, preservation of heat-sensitive compounds, diverse solvents, and decreased energy consumption. The future of bioactive compound extraction holds great promise, with these innovative methods paving the way for a more sustainable and health-conscious approach to the nutraceutical and functional food industry. This review discussed novel microwave, ultrasound, enzymatic, hydrodynamic cavitation, and pressurized fluid extraction methods and their combinations (UAEE, MAEE, UMAE). Their extraction mechanism, advantages, disadvantages, use of different green solvents, and the extraction of other bioactive compounds using novel technologies and findings. Therefore, these novel extraction technologies provide an efficient extraction process. However, novel and combined extraction technologies are lacking in design and must be improved.

Author contribution YPM: original draft writing, software. SM: writing — review and editing, validation, visualization. MS: conceptualization, project administration, resources, supervision, writing — review and editing.

Data availability Not available.

Declarations

Conflict of interest The authors declare no competing interests.

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