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Review

Recent Advances in the Extraction of Pectin from Various Sources and Industrial Applications

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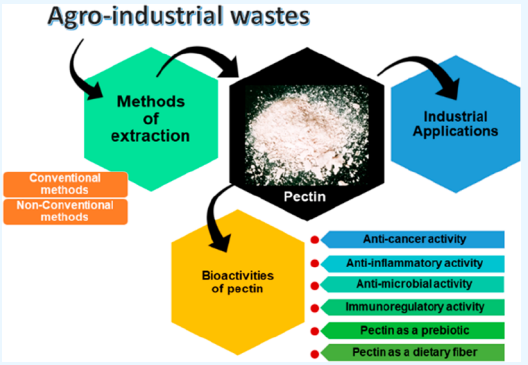
ABSTRACT: Pectin is a structural polysaccharide present in plants that primarily consists of galacturonic acid units. This Review discusses the chemistry of pectin, including its composition and molecular weight. Pectin is conventionally extracted from agricultural waste (fruit and vegetable peels) using an acidic or basic aqueous medium at high temperatures. These processes are time- and energy-consuming and also result in severe environmental problems due to the production of acidic effluents and equipment corrosion. As pectin usage is increasing in food industries for developing different products and it is also used as an excipient in pharmaceutical products, better extraction procedures are required to maximize the yield and purity. The Review encompasses various alternate green approaches for the extraction of pectin, including traditional acid extraction and various emerging technologies such as deep eutectic solvent-based extraction, enzyme-assisted extraction, subcritical fluid extraction, ultrasound-assisted extraction, and microwave-based extraction, and evaluates the yield and physicochemical characteristics of the extracted pectin. This work aims to provide a platform for attracting more thorough research focused on the engineering of novel and more efficient green methods for the extraction of pectin and its utilization for various biotechnological purposes.



1. INTRODUCTION

Pectin is a structural polysaccharide in plants that is mainly composed of galacturonic acid units, which can differ in structure and molecular weight. The primary cell wall contains more pectin, the amount of which gradually decreases toward the plasma membrane. These polymers usually coexist with other cellulose-, hemicellulose-, and lignin-containing elements of the cell walls. The US Food and Drug Administration recognized pectin as "generally recognized as safe". The white layer of the rind in fruits such as oranges and lemons contains roughly 30% pectin.[1] It is a polygalacturonic acid-based dimethyl ester composed of 300−1000 galacturonic acid units that are linked by 1$\alpha \rightarrow 4$ linkages. It contains multiple functional groups that can stimulate various functionalities, and with the proper modifications it has a wide range of applications, mostly because it is considered safe, nontoxic, inexpensive to make, and readily available.[2]

Galacturonic acid is prevalent in pectin; hence, it is also referred to as pectic carbohydrates. Within the pectic category, a number of unique polysaccharides have been identified and characterized. Homogalacturonans are linear strands of D-galacturonic acid, as shown in Figure 1. Pectin contains substituted galacturonans like D-xylose for xylogalacturonan and D-apiose for apiogalacturonan.[3] Many rhamnose residues produce side chains of neutral sugars, with the concentration depending on the source. In pectin, a distinct structural type called rhamnogalacturonan occurs rarely, and it is a complicated highly branched polysaccharide. Plants contain three important pectin domains, namely, homogalacturonan, rhamnogalacturonan I, and rhamnogalacturonan II. In addition to these domains, xylogalacturonan and apiogalacturonan are also considered as pectin because of the presence of homogalacturonan as a backbone. It is also called substituted galacturonan because the backbone is composed of D-galacturonic acid units.[4] Depending on the source and method of separation, the molecular weight ranges between 60 000 and 130 000 g/mol.

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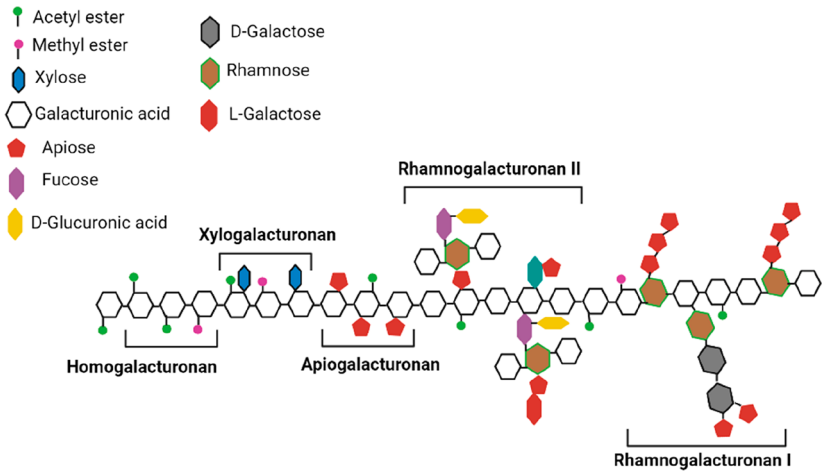

Figure 1. Schematic representation of pectin.

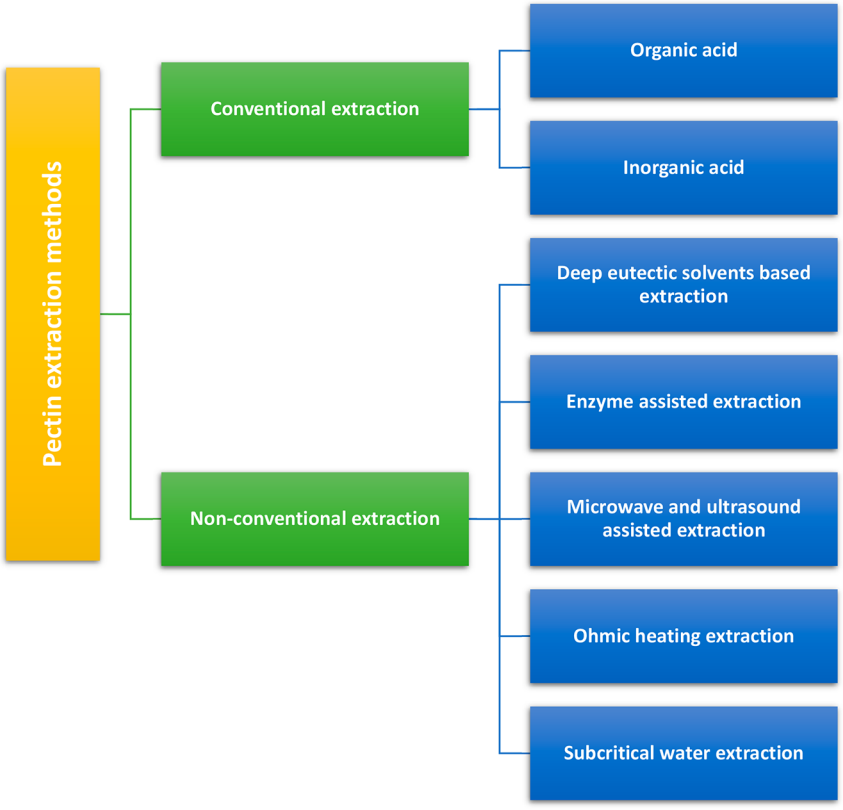

Figure 2. Different extraction methods used for pectin extraction.

Pectin gelling capabilities are affected by the degree of methyl esterification. Pectin with degrees of methyl esterification higher and lower than 50% are classified as high and low methoxyl pectin, respectively.[5] Although most of the plants contain pectin, about 85% of pectin is extracted commercially from citrus peels and apple pomace due to their high pectin content (18−30%) and good availability as industrial wastes.[6] Commercially, pectin is extracted by acid extraction using mineral acids like hydrochloric acid and sulfuric acid. The extracted pectin should contain at least 65% galacturonic acid content and should form a gel under conditions depending on the degree of methyl esterification.[7] In plants, pectin is required for support, and it is one of the high-molecular-weight polysaccharides that can increase the integrity of the cell structure. In food industries, pectin is used as a fat or sugar replacer, and it is also employed to improve the viscosity of juices, jams, and jellies. It is also used for reducing blood cholesterol and treating gastrointestinal disorders in the pharmaceutical industry.[8] It contains water-soluble pectinic acids differing in their sugar and acid content. Pectin is commonly included as a food ingredient due to its gelling ability. Pectin usually contains a natural sugar, rhamnogalacturonan, that causes splitting and kinks in the galacturonic acid chain.[9] Pectin originates from protopectin molecules found in plant cell walls,[10] and the enzyme hydrolysis of protopectin will yield pectinic acid, which leads to the softening and ripening of the fruits.[11] The goal of this Review is to summarize the various conventional and nonconventional extraction methods

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for the extraction of pectin from various sources. This Review also examines the bioactivities and the possible number of applications of pectin in various fields.

2. EXTRACTION METHODS FOR PECTIN

Pectin is a polysaccharide present in almost all plants to maintain the integrity of the cell structure. Protopectin is the insoluble form of pectin present in the cell walls of plants. The extraction at high temperature is initiated by the hydrolysis of the protopectin, followed by the breakage of bonds between sugars and the cell wall, resulting in the release of pectin into the extraction medium. Traditionally, acid extraction was employed to extract insoluble pectin from peels of citrus and apple pomace by heating it in an acidic medium to convert it to a soluble form. For the extraction of pectin from various agro-based industry wastes, various emerging technologies such as deep eutectic solvents, enzyme-assisted extraction, subcritical fluid extraction, ultrasound-assisted extration, and microwave-based extraction, or a combination of one or more methods, are now being used, as shown in Figure 2.[12] The variables generally used during these processes are the solid−liquid ratio, composition of deep eutectic solvents, extraction temperature, pH, duration, pressure, intensity of ultrasound and microwave, and enzyme concentration, or a combination of these variables. A solute is transferred from one phase to another phase to separate contaminants or unreacted substrates during the extraction process. Extraction is also used to separate a solute from a mixture that is difficult to evaporate, like a high boiling point solvent.[13] A solute is transported from a solid to liquid phase and from a liquid to liquid phase in solid−liquid and liquid−liquid extraction, respectively. During acid-based extraction, a solute is transformed into an ionic molecule and transferred from an organic phase to an aqueous phase.

2.1. Conventional Acid-Based Extraction Methods. An inorganic acid (known as a mineral acid) is a type of acid composed of one or more inorganic substances that form hydrogen ions and conjugate base ions upon dissolving in water. Commonly used inorganic acids for pectin extraction are sulfuric acid, hydrochloric acid, and nitric acid. Acid−base extraction comes under liquid−liquid extraction, which separates biomolecules depending on their acid−base properties. The pH shift influences the charge of a solute, whether it is an acid or a base. The majority of organic chemicals are naturally neutral; they tend to be more soluble in organic solvents than in water. However, if the organic molecule takes on an ionic state, then it becomes more water-soluble. An organic acid or base molecule can be transported from an organic phase to an aqueous phase using this method.[13] Acid−base extraction makes use of this property and changes the solute's solubility by transforming the solute into its salt form, which is water-soluble. The organic substance and its salt must have a significant differential in solubility for the approach to work. Another use of acid−base extraction is the separation of two weak bases or weak acids with considerably different pK_a values. A weak base is used to neutralize the relatively stronger acid with a low pK_a value, turning it into a salt. Only the stronger acid is transformed into a salt; the weaker base does not mix with the weaker acid efficiently. The sodium is subsequently eliminated into the aqueous phase during the extraction process. Similarly, with weak bases, a weak acid is utilized to convert a relatively stronger base into a salt.

2.1.1. Apple Pomace. Apple pomace is a rich source of pectin, cellulose, lignin, and hemicellulose in plant cell walls via complex chemical and physical interactions. The pomace used as raw material had a lower yield in the extraction of pectin than apple flour.[14] It is necessary to produce apple flour in the extraction process as an intermediate step to attain a better yield. Performing a citric or nitric acid (6.2%) treatment for 153 min resulted in a maximum yield of 14% with a degree of esterification of 68.84%.

2.1.2. Banana and Orange Peel. Parts of banana plant waste (stem, leaf, and peel) and citrus peel (5 g) were used for pectin extraction with different pH buffers (1−4) containing hydrochloric acid (50 mL), followed by the addition of 5 mL of ethanol for the precipitation of pectin.[15] The extraction of pectin from banana wastes and citrus peel at 60−100 °C and pH 3 for 10−30 min resulted in yields of 1.1−13.6% and 3.8−30.6%, respectively. The equivalent weights of pectin from banana steam, leaf, skin, and orange peel were 250, 166.6, 181.1, and 200, respectively, while the methoxy contents were 31.86, 25.04, 29.76, and 33.108%, respectively. The results of the study demonstrated that a high percentage yield (13.6%) can also be attained from banana peel wastes, which in turn can be employed in industrial pectin production.

2.1.3. Berries. Citric acid extraction was a traditional method for extracting pectin from fruits such as raspberry, blueberry, redcurrant, and strawberry.[16] Conventional citric acid extraction resulted in higher pectin yield (∼8%) compared to enzyme- and ultrasound-assisted extraction, except for raspberry.

2.1.4. Citrange Fruit. Pectin was extracted from citrange using conventional heating and electromagnetic induction at pH 1.2 and 80 °C for 90 min. This electromagnetic induction approach yielded a high pectin yield of 29%, which is comparable to that of conventional heating. Furthermore, the compositional and physicochemical properties of both isolated pectins were similar. Both methods resulted in high yields in a short time without affecting the physiochemical features and composition of the pectin.[17]

2.1.5. Citron Peel. Most plants contain pectin, but citrus fruits, such as oranges, lemons, and citrons, are a rich source of pectin. The acidic treatment for 90 min at 95 °C and pH 1.5 resulted in the maximum pectin yield (28.3%), and the degree of esterification and emulsifying activity were 51.33% and 46.2%, respectively.[18]

2.1.6. Clementine Peel. Citric acid/sodium citrate solutions were utilized as green extracting agents to extract pectin from clementine peel at various pH levels.[19] The pectin extracted using this unique process showed a higher pectin yield (34.94%) and uronic acid content (65.11%), as well as a high degree of esterification (84.71%) at 65 °C for 2 h. The separated pectin exhibited higher molecular weights and less protein in comparison to commercial citrus pectin. pH modification has been proven to be a viable approach for producing pectin with varied esterification levels. Increasing the pH of the extraction medium not only decreases the degree of esterification value but also aids in the elimination of leftover proteins and reducing sugars. Low-methyl-esterified and high-methyl-esterified pectin possessed homogalacturonan and rhamnogalacturonan I-dominated structures, respectively.

2.1.7. Cocoa Pod Husk. Cocoa pod husks are a byproduct of the cocoa industry acquired after the cocoa beans have been removed from the fruit. Pectin was extracted with boiling water and compared with an aqueous nitric acid-based extraction.

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Pectin gels (0.99% galacturonic acid equivalent) formed at pH 2.5 and containing 60% sucrose (w/w) formed the best gels. The apparent viscosities of the materials increased with the decrease in pH. Despite its high acetyl content, the extracted pectin was capable of producing gels at low pH under reduced water activity, indicating its potential usage in acidic goods.[20]

2.1.8. Cubiu (Solanum sessiliflorum D.) Peel. Pectin was extracted from cubiu fruit peel by Colodel and Petkowicz using boiling nitric or citric acid.[13] The pectin with the greatest yield (14.2%), high methyl esterification level (62%), and highest uronic acid content (75.0%) was extracted using nitric acid at pH 1.5 for 2 h.

2.1.9. Gold Kiwi Fruit Pomace. The enzyme-assisted (Celluclast 1.5 L) extraction by Yuliarti et al. resulted in a higher yield (4.5%) than acid or water extraction (3.6−3.8%).[21] Pectin with variable degrees of branching was created using various separation methods involving acid, water, or enzyme. The molecular weight for the pomace pectin that was extracted using enzymes (6.7×10^{5} g/mol) was lower than that of the pomace pectin extracted using water (8.5×10^{5} g/mol) and acid (8.4×10^{5} g/mol).

2.1.10. Jackfruit Seed. Pectin was extracted from the mysterious slimy sheath of the jackfruit seed coat using oxalic acid at a concentration of 0.05 N and 60 min incubation time at 90 °C, with a yield of 35.52%.[22] The extracted pectin had a greater total phenolic concentration and antioxidant activity, with a chemical structure similar to that of pectin from commercial apples and citrus fruits. This study showed that jackfruit-seed-extracted pectin with higher antioxidant activity can be used for various applications in food, health products, medicine, and cosmetics.

2.1.11. Passion Fruit. de Oliveira et al. reported the conventional extraction of direct boiling of yellow passion fruit peel with nitric acid (pH 2) for 2 h.[23] This traditional heating method required a large amount of time and energy to extract pectin, which can result in a pectin breakdown. Furthermore, employing a moderate electric field proved effective, rapid, and ecologically friendly, especially for pectin with a high galacturonic acid content (65%). Passion fruit contains 50−55 g of skin per 100 g of fresh fruit, which is discarded as waste during processing. The peel was water blanched for 5 min, followed by hot air drying at 60 °C for pectin extraction.[24] The methoxyl concentration, galacturonic acid content, and jelly grade were 9.6%, 88.2%, and 200, respectively. Pectin extraction from dried fruit peels may be considered the most efficient use of passion fruit production waste. Pectin was extracted at various pH levels and for varying lengths of time. For the extraction, a randomly selected yellow passion fruit with the same ripeness and peel hue was used. At the lowest pH of 2 for 75 min, the maximum yield of 14.6% was reported by Liew et al.[25] The degree of esterification was 54.78%, indicating it belongs to the high methoxyl pectin category.

2.1.12. Pineapple Peel. Different organic acids (citric, acetic, and oxalic), inorganic acids (hydrochloric acid, sulfuric acid, and nitric acid), and aluminum chloride were used to extract pectin from pineapple peels.[26] Aluminum chloride resulted in a higher yield of pectin (2.4%), followed by nitric (0.8%) and acetic acid (0.3%), compared to other organic and inorganic acids. The degree of methoxylation ranged from 2.4% to 5.6% for inorganic acids and from 2.8% to 3.9% for organic acids and aluminum chloride.

2.1.13. Pomelo Peels. Peels from pomelo are typically discarded as waste, but they can be a reliable source of pectin. Freeze-dried pomelo peels were used for pectin extraction using different organic acids in a ratio of 1:30 (w/v) at pH 3.0. Citric acid had the highest pectin extraction yields (6.5−9.0%) compared with acetic acid (6.2−8.2%) and lactic acid (6.1−8.0%). The extracted pectin belongs to the high methoxyl pectin category because the esterification levels range from 51.6% to 62.7%. The concentration of galacturonic acid in citric acid-extracted pectin was much greater (76.5−85.0%) than that in pectin extracted using acetic acid (65.1−68.2%) and lactic acid (60.4−65.8%). Citric acid- and lactic acid-extracted pectin had much better antioxidant capacities than acetic acid-extracted pectin.[27]

2.1.14. Sugar Beet. The dried sugar beet pulp was used for the pectin extraction using hydrochloric acid at pH 1.5 and 80 °C for 60 min. A sequential ethanol precipitation approach was developed by Guo et al. to isolate pectin as five different fractions using ethanol concentrations from 50% to 80%.[28] The one-step ethanolic precipitation is less selective in terms of pectin structural characteristics and surface qualities but results in a slightly higher yield (9.6%) than sequential ethanol precipitation (9.1%). The reason for the lower yield is the additional washing steps performed in the sequential precipitation. The chemical and macromolecular properties of pectin indicated that it is soluble in a binary mixture of ethanol and water. The increase in the ethanol concentration resulted in the precipitation of neutral sugar-rich fractions because of the enhanced interactions between the solvent molecules and pectin side chains. The various reports on pectin extraction using a conventional acidic medium are discussed in Table 1.

2.2. Nonconventional Methods for Extraction. The corrosive nature, the requirement for longer processing duration, and the temperature in conventional acidic extraction methods result in a high environmental impact and also poor yield. The various green approaches, such as applications of deep eutectic solvent-, enzyme-, microwave-, ultrasound-, ohmic-, and subcritical water-based methods, are considered promising and sustainable approaches for the extraction of pectin.

2.2.1. Deep Eutectic Solvent-Based Extraction. Deep eutectic solvents contain various combinations of hydrogen bond donors, and hydrogen bond acceptors can be employed for improving the extraction efficiency of pectin. A deep eutectic solvent is a fluid made up of a combination of inexpensive and safe components that can self-associate through hydrogen bond interactions to form a eutectic mixture with a melting point lower than the melting point of each individual component. Deep eutectic solvents (DESs) are normally liquid at temperatures less than 100 °C. These DESs have physicochemical qualities similar to typical ionic liquids but are significantly cheaper and less harmful to the environment.[29]

2.2.1.1. Averrhoa bilimbi. The Box−Behnken design was employed to increase the extraction of pectin from *Averrhoa bilimbi* by optimizing the composition of deep eutectic solvents, extraction duration, temperature, and component molar ratio.[30] The following conditions were found to be optimal: 3.74% DES (w/v), an extraction temperature of 80 °C, an extraction period of 2.5 h, and a molar ratio of DES components of 1:1. These optimal conditions resulted in a pectin yield of 14.44%. The primary constituents of pectin are galacturonic acids, arabinoses, and xyloses. Pectin has good functional qualities such as water retention (3.70 g/g), oil

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Table 1. Reports on Conventional and Nonconventional Methods for the Extraction of Pectin from Different Sources

source of pectin	extraction conditions	remarks	refs
conventional acidic extraction			
apple pomace	citric acid and nitric acid were used for extraction at 97 °C for 30 min	citric acid at a concentration of 6.2% resulted in a higher yield of 14% with a degree of esterification of 68.84%	14
banana stem, leaf, peel and orange fruit peel	0.1 N sodium hydroxide was the extraction solvent at an extraction temperature of 85−90 °C for 10−15 min	equivalent weights of 250, 166.6, 181.1, and 200, respectively, for banana stem, leaf, peel, and orange fruit peel; methoxyl contents (%) for the four samples were 31.86, 25.04, 29.76, and 33.108%, and moisture contents were 18%, 10%, 24%, and 28%	15
berries	20% citric acid was used as an extraction solvent at pH 3 for 120 min	pectin yield was ∼8% except for raspberry	16
citrange fruit	1 M H_2SO_4 at pH of 1.2 and 80 °C was used for different extraction durations of 10−90 min	high pectin yield (29%) was obtained at pH 1.2 and 80 °C for 90 min	17
citron peel	citric acid was used at a temperature of 75−95 °C and pH of 1.5−3 for 30−90 min	extraction at 95 °C and pH 1.5 for 90 min resulted in a pectin yield, degree of esterification, and emulsifying activity of 28.3%, 51.33%, and 46.2%, respectively	18
clementine peel	citric acid/sodium citrate was used at an extraction temperature of 65−85 °C with a solvent pH of 2−8, and extraction time of 1−3 h	pectin yield was 20−35% and uronic acid content was 45−65% with a degree of esterification of 11−85%	19
cocoa pod husk	nitric acid extraction for 30 min at pH 3.5 and 100 °C	extraction yield of 10.7% and degrees of methyl esterification and acetylation of 41.0% and 17.6%, respectively.	20
cubiu peel	nitric acid at pH 1, 1.5, and 2 for 2−4 h and citric acid at pH 2 for 1 h	pectin with the greatest yield (14.2%) and uronic acid (75.0%) was extracted using nitric acid at pH 1.5 for 2 h	13
gold kiwi fruit	citric acid-based extraction (50 °C and pH 2.2 for 60 min) and enzyme Celluclast 1.5 L (1.05 mL/kg) at 25 °C for 30 min	pectin extracted using enzymes had a higher yield (4.5%) than acid-extracted pectin (3.6−3.8%)	21
jackfruit seed	0.05 N oxalic acid was used for extraction at 90 °C for 60 min	pectin yield of 35.52%, higher total phenolic content of 65.7 mg GAE/g, and antioxidant activity of 10.4 μM were obtained	22
passion fruit peel	pectin extraction at different pH levels (1, 2 and 5) using nitric acid for 5, 15, 40, and 60 min	yields of pectin at pH 1, 2, and 5 were 4.24, 5.20, and 6.70 g/100 g of peel dry mass, respectively. pectin extracted at pH 2 had the highest galacturonic acid content of 69.21 g/100 g and an esterification degree of 90.68%	23
passion fruit peel	hydrochloric acid was used as an extractant with ratios to dry peel powder maintained at 1:10, 1:15, 1:20, 1:30, and 1:40 (w/v) for an extraction duration of 30−90 min	the methoxyl content of extracted pectin was 9.6%, the galacturonic acid content was 88.2%, and the jelly grade was 200	24
passion fruit peel	0.1 N citric acid at different pH levels of 2, 3.3, and 4.5 at 70 °C for different duration of 30, 75, and 120 min	the pectin yield and degree of esterification varied from 2.25% to 14.60% and from 41.67 to 67.31%, respectively. at pH 2 at 75 min, optimal pectin extraction with a yield of 14.60% was attained	25
pineapple peel	0.5 M aluminum chloride, 0.5 M inorganic acids (HCL, H_2SO_4, and HNO_3), and 0.5 M organic acids (citric, acetic, oxalic) were used as different extraction solvents at pH 4 and 90 °C for 90 min	aluminum chloride resulted in a maximum yield of pectin (2.4%). for the inorganic acids, the degree of methoxylation ranged from 2.4% to 5.6%, whereas for the organic acids and $AlCl_3$ it was 2.8−3.89%.	26
pomelo peel	citric acid, lactic acid, and acetic acid were used for extraction at pH 3 at a ratio of 1:30 (w/v) with an extraction temperature of 90 °C for 90 min	citric acid had the highest pectin extraction yield (6.5−9.0%), followed by acetic acid (6.2−8.2%) and lactic acid (6.1−8.0%) with esterification levels of 51.6−62.7%	27
sugar beet	6 M hydrochloric acid at pH 1.5 and 80 °C under stirring (250 rpm) for 1 h	five fractions were precipitated by gradually increasing the ethanol concentration from 50 to 80%	28
deep eutectic solvents			
pomelo skin	different deep eutectic solvents and molar ratios used for the extraction are lactic acid−glucose−water (6:1:6), lactic acid−glucose−water (5:1:3), lactic acid−glucose (5:1), lactic acid−glycine−water (3:1:3), and lactic acid−glycine (9:1)	the highest yield (23.04%) was achieved by the lactic acid−glucose−water mixture with a molar ratio of 6:1:6, while the lowest yield (7.39%) was achieved by the lactic acid−glucose mixture with a molar ratio of 5:1	29
Averrhoa bilimbi	choline chloride and citric acid monohydrate were combined to make the deep eutectic solvent in different molar ratios (3:1, 2:1, 1:1, 1:2, and 1:3)	a maximum pectin yield of 14.69% was obtained at a molar ratio of 1:1 at an extraction temperature of 80 °C and 2.5 h extraction duration	30
dragon fruit peel	choline chloride−glucose−water at a molar ratio of 5:2:5	the pectin yield was 19.39% at a liquid−solid ratio of 35.25 mL/g and water−NADES ratio of 3.37 mL/mL with microwave irradiation for 14.26 min at 240 W, followed by sonication for 46.07 min	31
guava peel	deep eutectic solvents used at the molar ratio of 1:2 are 10% choline chloride−ethylene glycol and 10% choline chloride−urea	pectin yield from 10% choline chloride−ethylene glycol extraction was larger (37.1%) than the yield from the 10% choline chloride−urea (16.4%)	32

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Table 1. continued

source of pectin	extraction conditions	remarks	refs
mango peel	betaine−citric acid (pH of 0.85, liquid−solid ratio of 27:1, extraction temperature of 80 °C, water content of 70%, and extraction period of 90 min) and choline chloride−malic acid (pH of 0.4, extraction temperature of 85 °C, extraction time of 120 min, water content of 70%, and liquid−solid ratio of 27:1) were the optimized parameters	betaine−citric acid and choline chloride−malic acid combinations resulted in a better yield of pectin (30−38.72%) compared to acid extraction (13.2%)	33
enzyme assisted extraction			
apple pomace	Celluclast 1.5 L (20, 40, and 60 μL/g) at temperatures of 40, 50, and 60 °C for 12, 18, and 24 h	pectin yield was 6.76%, and the degree of esterification was 96%	37
cocoa pod husk	cellulase 1.5 L (40, 58.04, 84.50, 110.96, and 129.00 μL/g)	a yield of 8% with a galacturonic acid content of 43% was obtained	38
mandarin peel	*Aspergillus aculeatus* enzyme at concentrations of 11, 18, and 25 μL/g; extraction times of 18, 24, and 30 h; and solid−liquid ratios of 1:30, 1:35, and 1:40.	the pectin content ranged from 8.7% to 21.3%	39
microwave and ultrasound-assisted extraction			
banana peels	in the continuous process, the extraction parameters are microwave power (300−900 W), time (100−300 s), and pH (1−3). for the intermittent process, the extraction parameters used were microwave power (300−900 W), pulse ratio (0.5−1), and pH (1−3)	continuous and intermittent microwave-assisted extraction resulted in yields of 2.18% and 2.58%, respectively	43
black mulberry	microwave power (300−900 W), irradiation time (10−30 min), and liquid−solid ratio (15−30 mL/g) were the extraction parameters	microwave power of 900 W and a duration of 18.17 min are the ideal extraction condition for maximizing the yield (13.16%) and degree of esterification (55.07%)	44
cocoa peel	various microwave powers (180, 300, 450, and 600 W) were used for extraction using a citric acid solution (pH 1.5) for 10, 15, 20, 25, and 30 min	resulted in a 42.3% pectin yield with galacturonate levels of 58.08% using a microwave power of 180 W for 30 min	45
figure skin	ultrasound-assisted extraction was performed at a solid−liquid ratio of 40 g/600 mL, power of 70 W, and frequency of 24 kHz at 70 °C for 25 min. microwave extraction was performed at 40 g/600 mL, pH 1.4, power of 600 W, and irradiation time of 3.5 min	ultrasound-microwave extraction had the highest extraction yield (11.71%) compared to microwave (9.26%) and ultrasound (8.74%)	46
grape peel	optimized conditions are extraction temperature of 66.71 °C, power intensity of 12.56 W/cm^2, and sonication period of 27.95 min	the experimentally optimized pectin yield was 27.34%	47
grape pomace	optimal conditions of the extraction process were microwave power of 560 W and pH of 1.8 for 120 s	two different cultivars like Feteasc$\breve{a}$ Neagr$\breve{a}$ and Rar$\breve{a}$ Neagr$\breve{a}$ grapes resulted in pectin yields of 9.03% and 11.23%, respectively	48
lemon, mandarin, and kiwi peel	hydrochloric acid and nitric acid were used as the extracting solvents at a microwave power of 360−600 W and irradiation duration of 1, 2, and 3 min for microwave-assisted extraction. ultrasound extraction was performed at 60 and 75 °C for 15, 30, and 45 min	hydrochloric acid-based microwave (360 W for 3 min) and ultrasound (75 °C for 45 min) extraction resulted in pectin yields of 17.97% and 17.30%, respectively	50
mango peel	mango peel powder−citric acid ratio of 1:40 was used at temperatures of 20−80 °C, then it was also treated at 20 kHz and 500 W with pulse durations of 5 s ON time and 5 s OFF time	extraction yields at 80 °C (16.70−17.15%) were found to be around 10× greater than those at 20 °C (1.55−2.09%).	51
orange peel	optimum extraction conditions are 22.5 min of ultrasound, a pH of 1.5, 155 W of ultrasound power, and a liquid−solid ratio of 22.5:1 mL/g	the experimental yield of pectin was 26.87%	52
palm	water−palm ratio (10:1, 20:1, 30:1, 40:1, and 50:1), extraction temperature (30, 60, 80, and 100 °C), pH (2, 4, 6, and 8), and extraction duration (0.5, 1, 2, and 3 h) are the different parameters	extraction at the water−palm ratio of 40:1, pH 4, and 80 °C for 2 h resulted in yield of 25.30%	53
pomelo peel	extraction was done with 10 mM $[HO_3S(CH_2)4mim]HSO_4$ and hydrochloric acid for 5, 10, and 15 min at 230, 385, and 540 W microwave irradiation	galacturonic acid contents extracted with $HO_3S(CH_2)4mim]HSO_4$ and hydrochloric acid were 66.14 and 75.59%, respectively.	54
passion fruit	ultrasound-assisted extraction using HNO_3 at a ratio of 1:30, pH 2, 480 W, and 65 °C for 15 min	ultrasound-assisted extraction resulted in a pectin yield, galacturonic acid concentration, and esterification levels around 12.67, 66.65, and 60.36%, respectively	23
watermelon rinds	microwave powers of 119.7, 199.5, and 279.3 W and durations of 6, 9, and 12 min	pectin yields in the range of 3.925−5.766% and equivalent weights from 1249.702 to 2007.756 were obtained at a microwave power of 279.3 W for 9 and 12 min	55
ohmic heating			
orange juice waste	different variables are solid−liquid ratios (1:10, 1:20, 1:30, and 1:40 g/mL), voltage gradient (5, 10, 15, 20, 25, and 30 V/cm) and pH (1.5, 2, 2.5, and 4)	a voltage gradient of 30 V/cm, pH of 1.5, solid−liquid ratio of 1:20 g/mL and ohmic heating up to 90.8 °C were the best extraction conditions for pectin, resulting in higher yield of pectin with good quality (high degree of esterification and galacturonic acid)	58
pomegranate peels	hydrochloric acid-assisted extraction at pH 1.5 and solid−liquid ratio of 1:40. ohmic heating at a voltage gradient of 10 V/cm for18 min	ohmic heating and HCl-assisted extraction resulted in pectin yields of 8.16 and 8.93%, respectively	59
subcritical water-assisted extraction			
sunflower heads	optimal conditions were a pressure of 8 bar, a temperature of 120 °C, a period of 20 min, and a liquid−solid ratio of 7 mL/g	optimal conditions resulted in a pectin yield, molecular weight, and galacturonic acid content of 6.57, 11.50 kDa, and 82%, respectively	62
apple pomace and citrus peels	extraction was done with solid to liquid ratio of 1:30. the extraction temperatures were 100, 120, and 140 °C, and those for apple pomace pectin extraction were 130, 150, and 170 °C for 5 min	yields of pectin were 69% and 40% for citrus peel and apple pomace, respectively	63

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retention (2.40 g/g), and foaming capability (133.33%). It also has the ability to neutralize free radicals (41.46%) and has a ferric-reducing antioxidant capacity of 1.15 mM.

2.2.1.2. Dragon Fruit Peel. The pectin extracted from the dragon fruit peel using choline chloride−glucose−water (5:2:5) was yellow to brownish in color, while industrial pectin was bright yellow.[31] The extracted pectin belongs to the high methoxyl pectin (59.76%) and pseudoplastic material category, with a high molecular weight (5.05×10^5 Da) and high antioxidant activities (8.14 mg GAE/g).

2.2.1.3. Guava Peel. Yusof et al. compared the deep eutectic solvent-based extraction and citric acid-based extraction of pectin from guava peels.[32] The two different deep eutectic solvents like 10% choline chloride with urea (1:2) and 10% choline chloride with ethylene glycol (1:2) resulted in yields of 16.4% and 37.1%, respectively, while 10% citric acid extraction resulted in a pectin yield of 29.2%. Pectin extracted using choline chloride and ethylene glycol has a higher ability to form a gel because of the high methoxyl content (15.6%) and degree of esterification (98.47%) compared with other extraction mediums. This pectin has less foaming power but still generates a stable foam. Due to the high yield and fast gel formation of the extracted pectin, the combination of choline chloride with ethylene glycol has a significant potential to extract pectin, which will be useful in food preparation as a gelling agent.

2.2.1.4. Mango Peel. Chen et al. reported the extraction of pectin from mango peel using deep eutectic solvents by employing the combination of choline chloride, betaine, and L-proline with organic acids in comparison with conventional acid extraction.[33] Betaine−citric acid and choline chloride−malic acid combinations resulted in better yields of pectin (30−38.72%) compared to acid extraction (13.2%). The application of high-intensity ultrasound power resulted in a higher yield of low-ester pectins but resulted in a lower molecular weight and particle size.

2.2.1.5. Pomelo Skin. The citric acid-based extraction at a pH of 1.8 and 88 °C for 141 min with a liquid−solid ratio of 29:1 mL/g resulted in a pectin yield of 39.72% and a degree of esterification value of 57.56%, indicating it is a slow-setting high methoxyl pectin.[34] The synthesis of distinct pectin functional groups was attained through different structural alterations when the pH was adjusted between 1 and 2. The lactic acid−glucose−water-based deep eutectic solvents resulted in a lower pectin yield of 23.04%. The reports on deep eutectic solvent-based extraction of pectin from various sources have been provided in Table 1.

2.2.2. Enzyme-Assisted Extraction. Different polysaccharides, including pectin, are present as an entangled network in the plant cell walls. The nonpectic components will be hydrolyzed using the cell-wall-degrading enzymes with minimum pectinolytic activity. Enzymes can catalyze reactions, shorten extraction times, use less alcohol during the precipitation process, and increase yield. Protopectinases, which are microbial enzymes capable of solubilizing protopectin, are used as part of popular enzymatic techniques for pectin extraction.[35] However, the application of this technology on a broad scale is dependent on a number of factors like the processing cost, changes in environmental factors like temperature and nutrient supply, and difficulty in the scale-up of the process.[36]

2.2.2.1. Apple Pomace. Pectin was extracted from apple pomace using an enzyme (Celluclast 1.5 L) concentration of 20−60 L/g at different temperatures (40−60 °C) and durations (12−24 h). The optimal extraction conditions are a temperature of 48.3 °C, an extraction period of ∼18 h, and an enzyme concentration of 42.5 L/g of pomace, resulting in a pectin yield, galacturonic acid content, and degree of esterification of 6.76%, 97.46%, and 96%, respectively. The chemical structure of extracted pectin was similar to that of commercial apple and citrus pectin.[37]

2.2.2.2. Cocoa Pod Husk. Cellulases were used in the enzymatic separation of pectin from a cocoa pod husk, and the feedstock concentration, enzyme dose, and time were optimized as 6%, 40 L/g, and 18.54 h, respectively.[38] The chemical extraction procedure with citric acid resulted in an 8% pectin yield and a galacturonic acid concentration of 61%.

Ultrasound-assisted enzyme extraction resulted in a pectin yield of 8.28% and a galacturonic acid concentration of 43%. Enzyme-extracted pectin has similar rheological and physicochemical features to commercial pectin, making it an appealing substitute for the valorization of cocoa husks.

2.2.2.3. Mandarin Peel. A method for extracting pectin from mandarin peels using an *Aspergillus aculeatus* commercial enzyme was optimized by Sousa-Gallagher et al.[39] The response surface approach was utilized to enhance the enzymatic extraction of pectin from mandarin peels. The chosen three-component five-level central composite experimental design investigated the effects of extraction duration, solid−liquid ratio, and enzyme concentration on the pectin yield. The optimized conditions are an enzyme concentration of 18 U, a solid−liquid ratio of 1:35, and a 24 h extraction duration. As a percentage of the dry weight of the polysaccharide, the pectin content in mandarin skin extracts ranged from 8.7% to 21.3% (w/w). The amount of enzyme present had the largest influence on the pectin output from mandarin skins.

The different reports on the extraction of pectin from different sources using enzyme-assisted extraction are discussed in Table 1.

2.2.3. Microwave- and Ultrasound-Assisted Extraction. Microwaves generate heat by interacting with polar substances, such as water and some organic plant matrix ingredients, by ionic conduction and dipole rotation mechanisms. Mass and heat transfers occur in the same direction in microwave heating, resulting in a synergistic effect that accelerates extraction and boosts the extraction yield.[40] Ultrasound is a high-frequency sound wave that exceeds the frequency of 20 kHz. Ultrasonic pulses with frequencies ranging from 20 to 100 kHz are commonly used in extraction. Ultrasound has been widely used in the food industry due to its chemical and/or physical properties.[41] Ultrasound, unlike electromagnetic waves, requires a carrier to go through, where it induces cycles of compression and expansion. If the applied negative pressure is higher than the liquid's local tensile strength, then the expansion cycle creates bubbles or cavities that expand before collapsing. Cavitation, the process of creating, expanding, and collapsing bubbles, is the cornerstone of ultrasound-assisted extraction.

2.2.3.1. Banana Peels. The pH of the extraction solution influenced the extraction of pectin from the banana peels. Due to its chemical conformation, lower pH values degrade the galacturonic acid content of pectin but increase the pectin yield.[42] The continuous and intermittent microwave-assisted extraction of pectin from banana peels showed that it is efficient and capable of producing the best results. Microwave

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power (300−900 W), duration (100−300 s), and pH (1−3) were the extraction parameters used in the continuous process, while microwave power (300−900 W), pulse ratio (0.5−1), and pH (1−3) were used in the intermittent process. The continuous (900 W and pH 3 for 100 s) and pulsed (pulse ratio of 0.5) microwave-assisted extraction resulted in pectin yields of 2.18% and 2.58%, respectively.[43]

2.2.3.2. Black Mulberry. The maximum yield of 13.2% with a degree of esterification of 55% and galacturonic acid content of 37% were attained at a microwave power of 900 W for 18.17 min and a liquid−solid ratio of 15 mL/g.[44] The intrinsic viscosity and molecular weight of pectin were 1.22 dL/g and 32.78 kDa, respectively.

2.2.3.3. Cocoa Peel. Microwave-assisted extraction of pectin from cocoa peel was performed using citric acid at pH 1.5 for 10−30 min at various microwave power levels of 180−600 W. The microwave power of 180 W for 30 min resulted in a higher yield (42.3%), with a methoxy content of 6.51% and galacturonate level of 58.08%.[45]

2.2.3.4. Fig Skin. In the study by Gharibzahedi et al., four extraction methods (hot water, ultrasound, microwave, and ultrasound−microwave) were evaluated for their effectiveness in extracting pectin from the skin of the common fig (*Ficus carica* L.).[46] The ultrasound−microwave-assisted extraction resulted in a yield (12%), higher than those of microwave (9.3%), ultrasound (8.7%), and hot water (6%). Due to the microstreaming caused by the collapse of cavitation bubbles during ultrasound treatment, the mass transfer coefficient of pectin was increased, which in turn improved the yield during the combination approach.

2.2.3.5. Grape Peel. The response surface methodology was used to investigate ultrasound-assisted heating extraction and compare it to conventional acid extraction. The ideal parameters were an extraction temperature of 66.71 °C, power intensity of 12.56 W/cm^2, and sonication period of 27.95 min, resulting in an optimized yield of 27.34%.[47]

2.2.3.6. Grape Pomace. The microwave-assisted extraction of pectin from the grape pomace of Feteasca Neagră and Rară Neagră was optimized using the Box−Behnken design. The optimal conditions for both cultivars are 560 W, a pH of 1.8, and a treatment time of 120 s. The pectin yields for both cultivars are 9% and 11%, and the galacturonic acid contents are 11% and 85%, respectively. These results indicate that grape pomace has the potential to be a promising source of pectin.[48]

2.2.3.7. Lemon, Mandarin, and Kiwi Peel. The optimal conditions for extracting pectin from lemon and mandarin peel is ultrasound-assisted extraction at 75 °C for 45 min using nitric acid and hydrochloric acid, while those for kiwi peel are microwave-assisted extraction at 360 W for 3 min in hydrochloric acid.[49] The degree of esterification was in the range of 50.51−51.63%, indicating high methoxy pectin that could be employed as a gelling agent. Ultrasound-assisted hydrochloric acid extraction of kiwi peel resulted in a 17.3% yield at 75 °C for 45 min, and microwave-assisted extraction resulted in a 17.97% yield at 360 W for 3 min. Microwave- and ultrasound-assisted extraction resulted in almost similar yields (%), indicating that both are efficient techniques for pectin extraction. Both ultrasound and microwave-assisted extracted pectin had a chemical structure similar to high methoxy pectin.[50]

2.2.3.8. Mango Peels. Pectin was isolated from mango peels by Wang et al. using ultrasound-assisted extraction and conventional citric acid-based extraction at two different temperatures (20 and 80 °C).[51] The extracted pectin was compared with laboratory-grade citrus peel pectin (≥74% galacturonic acid content) from Sigma-Aldrich in terms of chemical composition, rheological properties, and emulsification capacities. Mango peel pectin had higher protein contents (4.74−5.94%), methoxylation levels (85.43−88.38%), and average molecular weight (378.4−2858 kDa) than the acid-extracted pectin but a lower galacturonic acid content (52.21−53.35%). The extraction time for ultrasound-assisted extraction at 80 °C is 15 min, which is significantly shorter than conventional acid extraction (80 °C for 2 h) with similar pectin yield (18%). Furthermore, pectin extracted at 80 °C showed higher galacturonic acid and protein contents and higher molecular weight, resulting in higher viscosity, superior emulsifying capability, and greater stability compared to pectin extracted at 20 °C and the acid-extracted pectin. The pectin extracted from mango peel could evolve into a very promising source due to its good thickening and emulsification capabilities.

2.2.3.9. Orange Peel. Pectin was extracted from orange peel using an ultrasound-assisted extraction method and artificial neural network technology. The pH of the extraction medium significantly affected the pectin extraction compared to the ultrasonic power. The best extraction conditions were 22.5 min of irradiation, pH 1.5, 155 W of ultrasound power, and a liquid−solid ratio of 22.5:1 mL/g. The experimental yield of pectin was 26.87% under these conditions, while the response surface and artificial neural network models projected yields of 26.74% and 26.93%, respectively. According to Fourier transform infrared spectroscopy, the recovered pectin is high methoxy pectin because it has a degree of esterification of 63.13%, which is larger than 50%.[52]

2.2.3.10. Palm. The conventional acidic extraction (80 °C at pH 4 and 6) of pectin from matured sugar palm meat and young sugar palm meat resulted in pectin yields of 20% and 8%, respectively. The recommended process to improve the pectin yield (23.5%) is microwave-assisted extraction at 800 W for 3 min at pH 2, followed by ethanol-based precipitation at pH 7.[53]

2.2.3.11. Passion Fruit. The impact of the temperature and ultrasonic power intensity on the extraction of pectin from the skin of the passion fruit was studied using the response surface approach. The extraction was carried out using a desiccated peel−extractant ratio of 1:30 and sonication for 10 min. The highest pectin yield (12.67%), galacturonic acid content (66.65%), and esterification amount (60.36%) were obtained with a power intensity of 644 W/cm^2 and a temperature of 85 °C. The following techniques were utilized to compare the outcomes of ultrasound-assisted extraction to conventional heating (nitric acid, citric acid, and hydrochloric acid) for 10 min at 85 °C with a 1:30 desiccated peel−extractant ratio. The findings demonstrated that, in comparison to the traditional technique, the use of ultrasound promoted a better pectin extraction yield.[23]

2.2.3.12. Pomelo. Liu et al. reported pectin extraction from the albedo portion of pomelo peels using 10 mM 3-methyl-1-(4-sulfonylbutyl)imidazolium hydrogen sulfate for 15 min at 360 W of microwave power, and a liquid−solid ratio of 27 mL/g resulted in a pectin yield of 328.64 mg/g with a slightly lower degree of esterification (56.55%).[54] This yield is higher than conventional techniques using reference solvents (pure water, hydrochloric acid solution, and Na_2SO_4)

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2.2.3.13. Watermelon Rind. The microwave extraction resulted in pectin yields ranging from 3.9% to 5.8% and equivalent weights from 1249.7 to 2007.8 from watermelon rinds. The degree of methylation of extracted pectin ranged from 3.9% to 10.8%. The degree of esterification result showed a comparatively high methoxyl pectin content (>50%) and ranged from 56.86% to 85.76%. The pectin with higher galacturonic acid content was obtained after 12 min of 279.3 W of microwave radiation.[55] Various reports on the ultrasound and microwave-based extraction of pectin from different sources are discussed in Table 1.

2.2.4. Ohmic Heating Extraction. According to Joule's law, heat is produced in the ohmic heating method because of the passage of electric current through the chosen food material. It is one of the most sophisticated thermal processes, and it is fast and consistent in operation. This method has been used to preserve food as well as extract beneficial components from plants.[56] Ohmic heating quickly warms the heterogeneous system via volumetric heating, resulting in proper mass and heat transmission during extraction. This method also reduces processing time and eliminates the variability in pectin characteristics. Through the application of ohmic heating, the grade of pectin can be enhanced.[57]

2.2.4.1. Orange Waste. The optimal extraction conditions for pectin from orange juice wastes during ohmic heating at 90.8 °C are a voltage gradient of 30 V/cm, pH 1.5, a solid−liquid ratio of 1:20 g/mL, a shorter heating time of 15 s, use of a lower content of acid, resulting in a higher pectin yield with a high degree of esterification and galacturonic acid.[58]

2.2.4.2. Pomegranate Peel. The ohmic heating method was used by Sharifi et al. to assess the optimal conditions for extracting pectin from pomegranate peel and compared with hydrochloric acid-based extraction (pH of 1.5 and solid−solvent ratio of 1:40).[59] The voltage gradient (10 V/cm) and extraction time (18 min) during ohmic heating were optimized for the pectin yield and galacturonic acid content using a response surface methodology. The ohmic heating resulted in a galacturonic acid content and pectin yield of 8.2% and 82.9%, respectively, while acid extraction resulted values of 8.9% and 73.8%. The study on varied pomegranate peel sizes demonstrated that the yield remained steady even with greater particle sizes during ohmic heating. Reports on ohmic heating-based extraction of pectin are discussed in Table 1.

2.2.5. Subcritical Water Extraction Technique. In subcritical water extraction, water under increased pressure is heated to a temperature over its normal boiling point without changing the phase. It is also referred to as compressed hot water and superheated water extraction, which is the extraction process that employs water as an extraction solvent.[60] This method has been used in the food and environmental sectors and has been documented under numerous other names.[61] Increasing the water temperature for extraction has several advantages, including low viscosity, low surface tension, an improved mass transfer rate, and great dispersion. As water's dielectric constant decreases from 79 at 25 °C to 33 at 200 °C, extracting both ionic and nonionic components is possible. The subcritical water-based extraction process is generally regarded as safe, hence this technique is suitable for the extraction of various bioactive components used in food and pharmaceutical industries.[56]

2.2.5.1. Sunflower Heads. The processing conditions of fresh sunflower heads (7 mL/g) at 8 bar and 120 °C for 20 min resulted in a maximum pectin yield of 6.57% with strong thermal stability.[61] The degree of esterification value showed that it is low methoxy pectin. Pectin has a molecular weight of 11.50 kDa, 82% galacturonic acid content, and a surface tension of 45.38 mN/m (1.5% w/v).

2.2.5.2. Apple Pomace and Citrus Peel. Pectin was extracted from citrus peel and apple pomace using subcritical water, and the impact of extraction temperature (130−170 °C for apple pomace and 100−140 °C for citrus peel) on the pectin properties was studied by Wang et al.[63] The highest pectin yields from citrus peel and apple pomace were 22% and 17%, respectively, attained at 120 and 150 °C. Differential scanning colorimetry showed that the exothermic property of pectin was controlled by the composition and raw material source, while the endothermic property of pectin was influenced by extraction temperature. The rheological study revealed that pectin solutions exhibited shear-thinning properties and tended to be more elastic ($G' > G''$) with an increase in frequency, which is also reflected in the hydrogel analysis. In vitro studies indicated that both pectin eliminated more than 60% of DPPH radicals and 80% of ABTS radicals. The citrus peel and apple pomace pectin inhibited colon cancer cell HT-29 proliferation at rates of 76.45% and 45.23%, respectively. The reports on subcritical water extraction have been summarized in Table 1.

2.3. Advantages and Disadvantages of Extraction Methods. The conventional acid-based extraction processes are time- and energy-intensive and also result in serious environmental problems due to the production of acidic wastewater and equipment corrosion. Hence, there is increasing interest in the application of alternative green approaches, such as using ultrasound, microwave, enzymes, supercritical water, ohmic heating, and deep eutectic solvents for facilitating the extraction process. Microwave-assisted extraction provides numerous advantages, including increased extract yield, less thermal degradation, and selective heating of the material. Due to the less solvent consumption during extraction, it is also refered to as a green technique.[64] Due to their permanent dipole moment, polar molecules like polyphenols and ionic solutions powerfully absorb microwave energy, causing a rapid temperature increase, and the extraction can be completed quickly.[65] The need for special equipment, lower selectivity, and undesirable reactions at high temperatures are considered the drawbacks of the microwave-assisted extraction process.[66] Ultrasound-based extraction has several advantages, including reduced extraction time, equipment size, energy consumption, lower solvent use, and improved extraction yield, and it is also considered more environmentally friendly than conventional acid extraction techniques.[67] However, the drawbacks are the positioning of the container inside the equipment containing the extraction medium and samples because the extraction efficiency varies with respect to the position of the container.[68] The degradation of extracted compounds during conventional acidic water extraction can be avoided in subcritical water extraction, as it can increase mass transfer and optimal temperature can be maintained.[69] This technique has many advantages, including a quick extraction process and the exclusion of organic solvents, and high-quality products can be obtained. In ohmic heating, rapid and uniform heating, lower energy consumption, lower maintenance costs, and reduction of the fouling risks in heat transfer areas are the advantages.

The narrow frequency band and difficulty in monitoring and controlling the extraction process are the few disadvantages of

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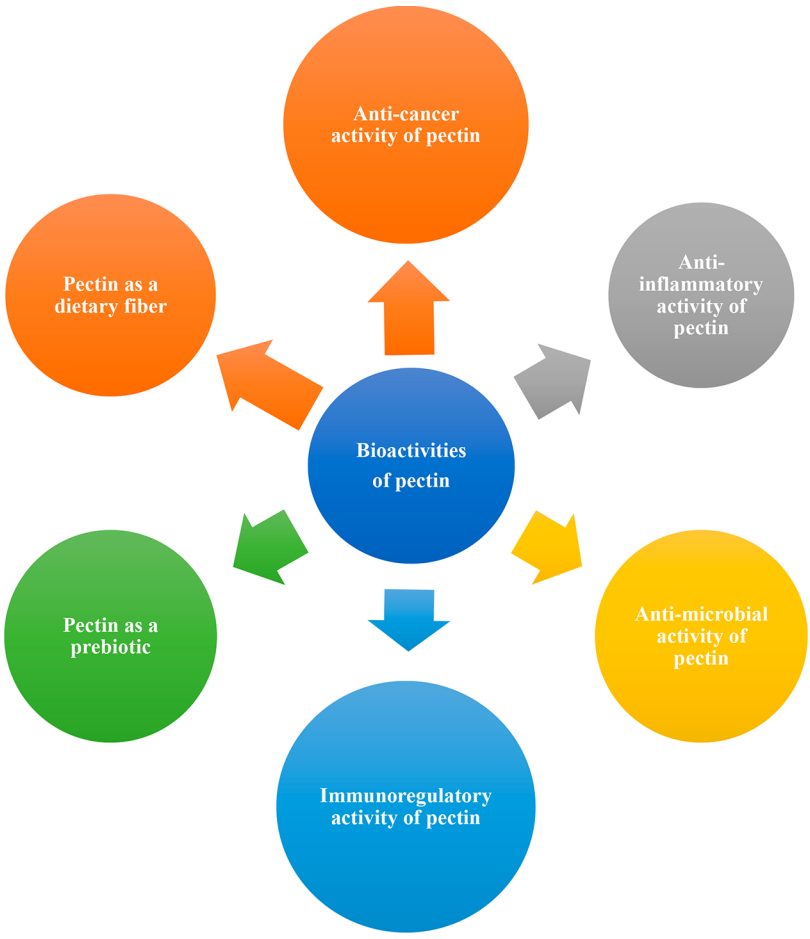

Figure 3. Schematic diagram representing the bioactivities of pectin.

the ohmic heating-based extraction process.[70] The application of water in subcritical water extraction is nontoxic, hence waste disposal problems are nullified while plumbing blockage; hoever, caution to be taken to ensure safe operation because of the usage of high pressure and high temperature.[71] The enzyme-assisted extraction process results in a high extraction yield and does not require complex processing conditions.[72] The high cost of enzymes, longer processing time, lack of complete hydrolysis of plant cell walls, and difficulties in the scale-up of the processes are considered a few disadvantages of the enzyme-assisted extraction process.[73] The lack of toxicity, biodegradability, lack of volatility, lower production cost, and higher extraction yield are the few advantages of deep eutectic solvents, while the high viscosity is considered a bottleneck for industrial applications.[74]

3. BIOACTIVITIES OF PECTIN

The bioactivities of pectin are associated with their structural characteristics, such as rhamnogalacturonan and arabinogalactan side chains, the composition of rhamnogalacturonan and homogalacturonan backbones, the nature of substituent groups, and their synergistic effects.[75] Pectin presents a wide range of bioactivities, including antimicrobial, anticancer, immunoregulatory, and anti-inflammatory activities (Figure 3). It also plays an important role as a prebiotic and dietary fiber.

3.1. Anticancer Activity of Pectin. Numerous *in vitro* and *in vivo* studies of the anticancer effect of native and modified pectin have revealed that it inhibits cell adhesion and proliferation while increasing cell migration and apoptosis.[76] Colon cancer cells were highly inhibited from proliferating when exposed to sugar beet pectin extracts with a variety of pectin structures. Because apoptosis was encouraged by the alkali treatment, sugar beet pectin's anticancer activity increased.[77] Apple pectic polysaccharide has the ability to stimulate cancer cell death and suppress tumor development *in vivo*.[78]

Pectic acid possesses apoptotic properties and can inhibit the proliferation of breast cancer cells *in vivo*. The native pectin did not exhibit the same level of cell antiproliferation as sonicated pectin extracted from sweet potato. Overall, sonication increased pectin's ability to fight cancer, and it may provide the pharmaceutical industry with a reliable, low-cost, and easily scaled method of producing biofunctional pectin.[79] Citrus pectin was proven to trigger cell death in human hepatocarcinoma and human lung carcinoma cell lines after heat treatment at 123 °C and a pressure of 21.7 psi for 60 min.[76] Due to the lack of DNA cleavage, induced cell death was clearly different from classical apoptosis. The apple pomace pectin from hot compressed water-assisted extraction exhibits a high amount of free radical scavenging activity and inhibits colon cancer cells compared to commercial pectin.[80]

3.2. Anti-Inflammatory Activity of Pectin. Amorim et al. studied the *in vitro* activities of acetylated, de-esterified, and deacetylated pectin from cocoa pod husks and commercial homogalacturonan on peritoneal macrophages in mice.[81] The

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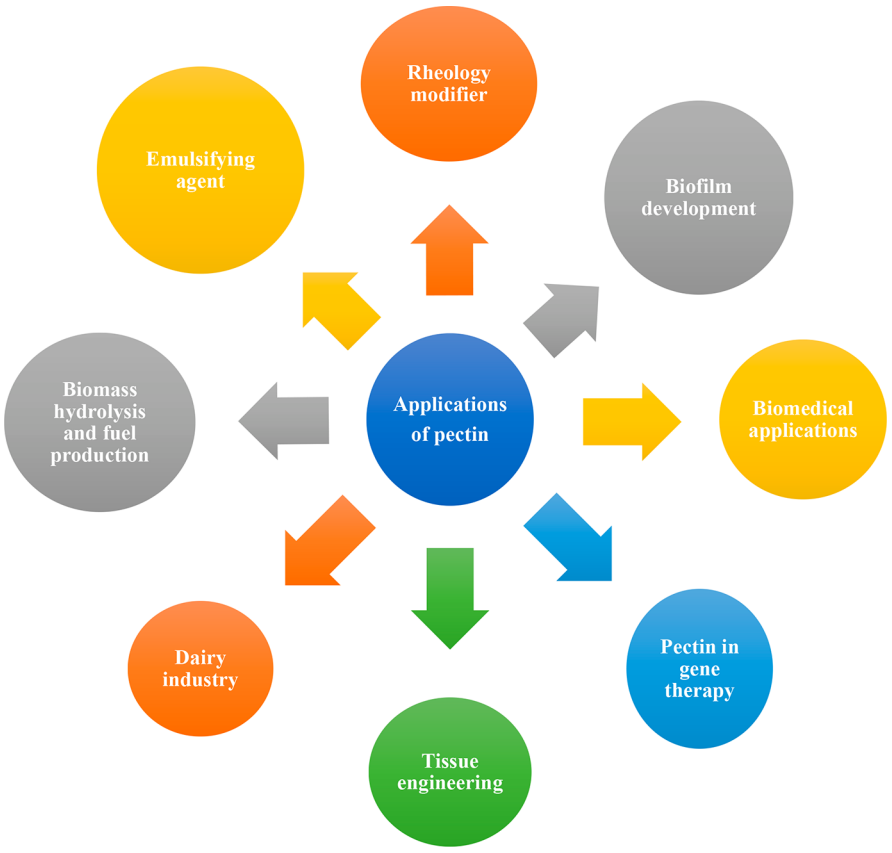

Figure 4. Applications of pectin in various fields.

modified pectin (deacetylated and de-esterified forms) had a better capacity to activate macrophages against a cytotoxic phenotype and reduce the susceptibility toward microbial infection compared to the native pectin form. Popov et al. reported the anti-inflammatory activity of citrus pectin *in vivo* after oral administration in mice.[82] The low methyl esterified citrus pectin inhibits local and systemic inflammation, while pectin with a higher degree of esterification can inhibit intestinal inflammation. These results explain the importance of the presence of low methyl esterified pectin chains to provide wholesome qualities of the diet.

3.3. Antimicrobial Activity of Pectin. Much emphasis has been placed in recent years on the use of natural antibacterial systems in the manufacture of safe and healthy food. Citrus pectin has been found to be a straightforward, environmentally friendly way to reduce and cap Ag nanoparticles (NPs). The Ag NPs possess antibacterial activity toward *Staphylococcus aureus* and *Escherichia coli*, which shows Ag NPs have the potential to function as antibacterial agents. Biodegradable polymers based on pectin along with oleate, linoleate, and palmitate were discovered to have antibacterial activity against a variety of bacterial species, including *S. aureus* and *E. coli*. Both linoleate and oleate along with pectin showed a strong ability to restrict 50−70% growth of the above-mentioned microorganisms. They exhibited superior antibacterial activity toward *S. aureus*. A biobased material for novel uses, such as the secure packaging of active food products, was developed by chemically modifying pectin to boost water resistance and the protective qualities of the polysaccharide.[83]

A stomatological bandage with longer retention in the excised alveolar socket has been designed as an industrial sample of antimicrobial methods without antiseptic drugs and antibiotics. It has been demonstrated that 1% solutions of various pectin concentrations proved to be more effective at inhibiting the growth of *Staphylococci* and *Streptococci*, as well as the development of biofilms containing these cultures.[84]

3.4. Immunoregulatory Activity of Pectin. The composition of pectin plays an important role in determining the immunosuppressive activity, and the presence of more than 80% galacturonic acid residues inhibits the macrophage activity and delayed-type hypersensitivity. The oligomer fractions obtained by the enzymatic digestion of pectin possess immunomodulatory activity that in turn shows the important role of the backbone of pectin. The branched region of pectin stimulates phagocytosis and also increases the production of antibodies.[85] The effect of pectin extracted from lemons with different degrees of methyl esterification (30%, 56%, and 74%) on the activation of Toll-like receptors was studied *in vitro*.[86] The degree of methyl esterification and extent of polymerization influences the immunomodulatory activities of pectin, and these factors can be considered while utilizing it to enhance the immune status.[87]

3.5. Pectin as Dietary Fiber. Pectin is a soluble dietary fiber that lowers blood cholesterol levels in the body.[88] Consuming pectin causes the gastrointestinal tract to become viscous, which reduces cholesterol absorption from food. Microorganisms in the large intestine and colon are responsible for the pectin breakdown resulting in the release of short-chain fatty acids, which is beneficial to human health.

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3.6. Role of Pectin as a Prebiotic. Prebiotics are fermented foods that allow for a noticeable alteration in the composition of the gut microbiota and other actions that strengthen the host immune system. Pectin-derived oligosaccharides and pectin are emerging as superior runners in the new generation of prebiotics. Gut bacteria digest methylated pectin to produce the short-chain fatty acids acetate, propionate, and butyrate, which have a beneficial effect on the body. Pectin is generally used to create functional food ingredients and nutraceuticals and to boost the antioxidant capacity of foods. It is a naturally occurring preventative chemical that serves as a detoxifying agent, which is useful for personnel exposed to toxic cations, including mercury, cadmium, lead, and arsenic.[89] These toxic cations pose major issues when they enter the digestive and respiratory systems.

4. APPLICATION OF PECTIN

The application of pectin as a thickening agent and edible coating or film development is becoming popular. This is also used in several biomedical applications, gene therapy, and tissue engineering. The several applications of pectin (Figure 4) in various fields are discussed below.

4.1. Biomass Hydrolysis and Biofuel Production. Sugar beetroot pulp, citrus peel scraps, and apple pomace containing high pectin contents are promising resources that can be used as bioethanol feedstocks. Notably, these bioenergy feedstocks will necessitate saccharification and fermentation procedures that are adapted or developed for the variety of sugars they contain. Customized or engineered *E. coli* can exploit the pectin-rich waste products for the manufacture of bioethanol.[90] It requires enzymatic hydrolysis of the feedstock, where the contribution of pectin-degrading enzymes is crucial.[91] Although pectin only makes up a small portion of cellulosic biomass, a recent study found that adding pectate lyases to the cellulase enzyme combination reduced the enzyme loading by about 25−30%.[92]

4.2. Biomedical Applications of Pectin. Due to their biocompatibility and inert nature, natural polymers are now chosen over other types in biomedical applications, particularly when it comes to drug delivery systems. Pectin has recently been used for applications in drug administration due to its ability to form a gel in acidic conditions, stick to mucous membranes, and dissolve in basic environments.[93] The mucoadhesiveness of pectin aids in drug targeting and regulation, particularly in the nasal and gastric environments, while its ability to dissolve in basic conditions aids in the release of colon-related medications and the gel-forming ability aids in extending drug contact time in gastric conditions. The efficiency of low methoxy pectin for nasal medicine distribution was established due to its mucoadhesive qualities, having a proclivity to adhere to the mucin with the help of hydrogen bonds. The application of pectin in the formulation of the painkiller fentanyl, which requires rapid drug release, has also been shown to help in the quick relief of cancer pain. Nicotine-containing nasal pectin is considered an option for quitting smoking. Due to the resistance of pectin to proteases and amylases, pectin has been widely used as an encapsulating nanoparticle for drug administration. Most of the proteins are quickly broken down by our digestive enzymes, hence it is preferable to use pectin as an outer coating for the colon and oral drugs to prevent disintegration in the gastrointestinal tract.[94] Pectin has been shown in animal studies to suppress cancer metastasis and original tumor growth. Pectin has the ability to detect Gal-3 components, which is one of the major mechanisms governing cancer growth and metastasis. Citrus pectin was employed to target Gal3, which successfully inhibited metastatic growth.[95]

4.3. Pectin as a Rheology Modifier. Pectin, gelatin, and 3-glycidyloxypropyl trimethoxy silane (cross-linking agent) were used to develop a suitable method for bioprinting.[96] The cross-linking agent requires an additional freeze-drying step to complete the cross-linking reaction. In case of a lower-viscosity solution, pectin is essential to increase the viscosity and yield stress. The 3D water-stable and self-supporting scaffolds, with both micrometer and microporous structures, respectively, can be prepared by combining extrusion and freeze-drying.[97]

4.4. Pectin as an Emulsifying Agent. The high molecular weight, ferulic acid content, acetyl group, and degree of esterification of pectin promote the emulsification properties. Pectin containing a high protein content possesses a good emulsification capacity. Chen et al. reported that increasing the protein content (0.5−3%) of pectin stabilized the beetroot pulp-based emulsion by decreasing the droplet size (4.12−1.5 mm).[98] Emulsified pectin oils act as a fat substitute to develop products of superior nutritional quality by reducing the fat and salt content. It is used in the production of low-fat mayonnaise, dairy products, ice cream, and meat products.[99,100]

4.5. Pectin in Biofilm Development. The combination of synthetic and natural polymers to develop new polymeric materials that increase durability and resistance is the most promising field of study. Polymer films are used to create materials such as hydrogels and medicine capsules, among others. The combination of natural and synthetic polymers results in novel polymeric materials with improved durability and resilience, making this one of the most promising areas of development.[101] This movement is primarily motivated by environmental issues and worries about the widespread use of plastic. Pectin films were made with glycerol and lactic acid to provide antifungal activity to the laminated films. Pectin films had a substantial glass transition at 50 °C indicating moderately flexible at ambient temperature.[102]

The pectin, soybean flour protein, and fish skin gelatin were used to develop a composite film with higher stiffness and strength and a lower water vapor transmission rate. Cross-linking agents like methanol and glutaraldehyde are used to improve the tensile strength.[103] In order to regenerate tissue, bioreactive was created using a substance made of a pectin matrix. This material proved that pectin can transmit signals to molecules, and pectin aids in cell adhesion and proliferation indicating it can be used as a wound dressing material.[104]

4.6. Pectin in Gene Therapy. Gene therapy is a term used to describe the process of treating genetic disorders, since it targets the defective genes that cause the disorders. These defective genes can be replaced, their expression can be silenced, or missing genes can be filled in using viral or nonviral vectors. Nonviral vectors are chosen over viral ones for a variety of reasons, including biocompatibility, low toxicity, and immune system reactions. These nonviral vectors are constructed from pectin, chitosan, or polycationic polymers.[105] Products mediated by carbohydrates have superior binding capacity, facilitating easier uptake by the target cell.

The creation of pectin nanoparticles aids in entrapping DNA for transfection. By adding three different amine groups to pectin, it was able to be modified and was made it bind to plasmid DNA. It was found that the modified pectin has a

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promising role in gene delivery by comparing the effectiveness of its transfection or its potential as a nonviral gene delivery carrier. Pectin−chitosan-based nanoparticles have also been employed as a material for wound dressings. They have the capacity to produce an acidic environment that prevents bacterial growth.[10] The pectin-based nanoparticle was created to augment and improve Itraconazole medication solubility.[107]

4.7. Pectin in Tissue Engineering. Scaffolds are 3D biomaterials with pores that are designed to be used in a variety of sectors. A few of their primary purposes include promoting cell adhesion, allowing for adequate nutrition and gas movement, and primarily for tissue creation.[106] Biocompatible scaffolds in tissue engineering primarily serve as a support matrix or a substrate for the delivery of particular chemicals. A lot of research is being done to support tissue reconstructions in order to use pectin-based scaffolds for bone tissue engineering Pectin can also be used as an injectable biomaterial for bone tissue engineering.[92] Pectin was also suggested as the optimal polymeric matrix for tissue engineering, since it was able to create biopolymer scaffolds utilizing the lyophilization procedure.[108]

4.8. Pectin in the Dairy Industry. The application of pectin in dairy products mainly maintains casein stability in acidified milk to prevent syneresis. The interaction between casein and polysaccharides and the quantity of pectin in milk have a significant effect on the stability of dairy products.[109] Depletion interactions may lead to milk instability, and as a result a phase separation above a particular pectin content can occur. The interaction of calcium ions with pectin can disturb the compact para-casein matrix, and low methoxy pectin in milk at a concentration of 0.2% (w/w) was efficiently used to increase moisture retention and improve the texture of low-fat Mexican manchego cheese. Low-pH dairy drinks respond well to the stabilizing effect of high methoxy pectin. Low methoxy pectins are used to improve the stability of yogurt, fruit recipes of yogurt, and dairy creams.[110] The hardness was dramatically reduced in cheeses with pectin supplements, particularly amidated reduced-fat cheeses. It did not affect the whiteness of cheese compared to reduced fat control. These findings imply that the application of pectin may be a valuable tactic for altering the composition and texture of cheeses.

5. CONCLUSION

There are various methods used for extracting pectin from plant material, including conventional acid-, enzymatic-, microwave-, ultrasound-, subcritical water-, and deep eutectic solvent-based extraction. Each method has its advantages and disadvantages, and the choice of method depends on factors such as the source of the plant material, the desired yield, and the environmental impact. Ultrasound and microwave-assisted extraction drastically improved the pectin yield; therefore, sequential application of ultrasound and microwave treatment can be used for further improving the extraction yield. There are only a few reports available on alternative green approaches such as deep eutectic solvents and subcritical water extraction. Hence, more research related to combined or sequential extraction using emerging technologies can be focused on in the future. Further research is needed to determine the scalability and cost-effectiveness of these methods and to optimize the extraction conditions for different sources of pectin. The utilization of various agroindustrial wastes such as peels and pomace is important for waste management in order to encourage sustainable production in the food and pharmaceutical industries. Comprehensive studies on pectin extraction and the simultaneous application of pectin to various products are needed to ensure sustainability and industrial exploitation.

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Notes

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