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PECTIN EXTRACTION FROM ORANGE, LEMON AND POMEGRANATE PEELS: CONVENTIONAL, GREEN AND HETEROGENEOUS CATALYTIC APPROACHES FOR SUSTAINABLE WASTE VALORIZATION - A REVIEW

S. P. Babar*

Department of Science & Humanities, Terna Engineering College, Nerul, Navi Mumbai, Maharashtra, India.

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***Corresponding Author**

S. P. Babar

Department of Science & Humanities, Terna Engineering College, Nerul, Navi Mumbai, Maharashtra, India.

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ABSTRACT

Pectin is an important natural polysaccharide widely used in food, pharmaceutical, cosmetic, packaging and biomedical applications. Fruit-processing industries generate large quantities of peel waste, particularly from orange, lemon and pomegranate, which can serve as inexpensive and renewable sources of pectin. Conventional pectin extraction generally involves treatment with mineral acids at elevated temperature, followed by filtration, concentration and alcohol precipitation. Although effective, conventional extraction may require considerable chemical and energy inputs and can generate acidic wastewater and corrosion-related problems. Consequently, recent research has focused on greener extraction approaches including organic acids, ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, pulsed electric field and other intensified technologies. An emerging approach of particular interest is heterogeneous extraction using solid materials such as organic clay. The author's previous studies demonstrated pectin extraction from orange peel using organic clay and from lemon peel using white organic clay, providing examples of clay-assisted green extraction. This review compares conventional and emerging methods for pectin extraction from orange, lemon and pomegranate peels, with particular emphasis on heterogeneous organic-clay-assisted extraction. The influence of extraction conditions on pectin yield and quality, characterization methods, applications and future opportunities for catalyst/material recovery are also discussed. The integration of heterogeneous materials with green extraction technologies may provide a promising route for sustainable production of value-added pectin from fruit-processing residues.

KEYWORDS: Pectin; orange peel; lemon peel; pomegranate peel; organic clay; white organic clay; heterogeneous extraction; green extraction; fruit waste; circular economy.

1. INTRODUCTION

The food-processing industry generates substantial quantities of agricultural and fruit-processing residues, including peels, seeds and pulp. These residues are frequently discarded, burned or utilized in low-value applications. However, fruit-processing wastes contain valuable polysaccharides, phenolic compounds, essential oils, flavonoids and other bioactive constituents. Their conversion into value-added products is therefore an important strategy for waste minimization and circular-economy development.

Pectin is one of the important value-added materials that can be recovered from fruit-processing residues. It is a complex plant-cell-wall polysaccharide consisting predominantly of galacturonic acid-containing structural regions. Because of its gelling, thickening, stabilizing, emulsifying and film-forming properties, pectin is widely used in food products, pharmaceutical formulations, cosmetics, edible coatings and biodegradable materials.[1,2]

Citrus fruits are among the most important commercial sources of pectin. Orange and lemon peels are particularly attractive because they are generated in large quantities by juice-processing industries. Pomegranate peel, although a non-citrus source, is also rich in pectin and contains valuable polyphenols and other bioactive compounds.[7,8] Recent research has increasingly considered fruit peels as feedstocks for integrated biorefineries rather than as waste materials.[7,9]

Traditionally, pectin is extracted by heating fruit peel in an acidic aqueous medium. Acid treatment hydrolyses

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protopectin present in the plant cell wall and releases soluble pectin into the extraction medium. The extracted material is then separated by filtration, concentrated and precipitated, commonly using ethanol. However, conventional mineral-acid extraction may require high temperatures, long extraction periods and corrosive chemicals, while generating acidic effluents.[1,2] Consequently, green extraction technologies such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), enzyme-assisted extraction, pulsed electric field (PEF), high-intensity ultrasound and other process-intensification methods have attracted considerable attention.[1,3,4] A 2025 systematic review emphasized the growing importance of UAE, MAE, PEF and other green technologies for improving extraction efficiency while reducing environmental burdens.[3] An alternative approach is the use of heterogeneous solid materials, particularly organic clay. The author's previous research demonstrated the extraction of pectin from orange peels using organic clay[5], followed by the extraction of pectin from lemon peels using white organic clay as a green approach.[6] These studies provide a useful basis for considering heterogeneous clay-assisted extraction as an alternative to conventional homogeneous mineral-acid treatment. The objective of this short review is therefore to compare pectin extraction from orange, lemon and pomegranate peels, with special emphasis on conventional, green and heterogeneous organic-clay-assisted approaches.

2. Pectin: Structure and Important Properties

Pectin is a heterogeneous polysaccharide present mainly in the primary cell wall and middle lamella of plants. Its major structural component is homogalacturonan, which consists predominantly of α-(1→4)-linked D-galacturonic acid units. Other structural domains, including rhamnogalacturonan-I and rhamnogalacturonan-II, contribute to the structural complexity of pectin. The important parameters used to characterize extracted pectin include: Galacturonic acid content, Degree of esterification (DE), Methoxyl content, Equivalent weight, Molecular weight, Viscosity, Water-holding capacity, Gel-forming ability. The degree of esterification is particularly important because it influences the functional behavior of pectin. Pectin with a degree of esterification above approximately 50% is generally classified as high-methoxyl pectin, whereas pectin with lower esterification is classified as low-methoxyl pectin. Extraction conditions can significantly affect these properties. Severe acidic conditions may increase pectin solubilization but can also cause hydrolysis of the polymer chain and changes in molecular weight and degree of esterification.[1,2] Therefore, an optimum extraction process should consider both yield and quality rather than yield alone.

3. Fruit Peels as Sources of Pectin

3.1 Orange peel

Orange peel (*Citrus sinensis*) is one of the most extensively investigated citrus residues for pectin recovery. It contains pectin along with essential oils, flavonoids, sugars, cellulose and hemicellulose. Orange peel is particularly attractive because it is produced in large quantities by the juice-processing industry. A recent review of fruit-peel pectin extraction reports several conventional and assisted methods for citrus sources, including microwave-assisted extraction and other intensified approaches.[2]

3.2 Lemon peel

Lemon peel (*Citrus limon*) is another important citrus source of pectin. In addition to pectin, it contains essential oils and phenolic compounds. Therefore, lemon peel can be considered a multifunctional feedstock for waste valorization. Recent studies have investigated conventional acid extraction as well as ultrasound- and microwave-assisted methods. Such approaches can improve mass transfer and reduce extraction time.[1,2]

3.3 Pomegranate peel

Pomegranate peel (*Punica granatum*) represents a substantial fraction of the fruit-processing residue. It contains pectin together with polyphenols, flavonoids, tannins and sugars. A recent review of food-processing waste reported that pomegranate peel can contain approximately 20–25% pectin, although the actual value varies with cultivar, maturity and analytical method.[7] Pomegranate peel is particularly interesting for an integrated biorefinery because several valuable components can be recovered sequentially rather than treating the peel as a single-product source.[7,9]

4. Conventional Pectin Extraction

The conventional extraction process can be represented as.

Fruit peel → washing → drying → grinding → acid extraction → filtration → concentration → precipitation → washing → drying → characterization

Mineral acids such as hydrochloric acid, nitric acid and sulfuric acid have traditionally been used. Acid hydrolysis facilitates the conversion of insoluble protopectin into soluble pectin.

The major parameters affecting extraction are: Ph, Temperature, Extraction time, Acid concentration, Solid-to-liquid ratio, Particle size. The conventional method is relatively simple and can provide good extraction efficiency. However, the use of strong mineral acids may cause corrosion and generate acidic wastewater. Long extraction times and high temperatures may also increase energy consumption.[1,2] Recent reviews therefore recommend the development of alternative extraction systems that reduce chemical consumption, extraction time and energy requirements.[1,3,4]

5. Pectin Extraction from Orange Peel

Orange peel is an established raw material for pectin extraction. Conventional acid extraction generally involves heating powdered orange peel in an acidified

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aqueous medium followed by filtration and ethanol precipitation. Recent studies have investigated organic acids and assisted extraction methods as alternatives to conventional mineral-acid extraction. Microwave-assisted extraction is particularly attractive because rapid heating can substantially reduce extraction time.[2]

5.1 Organic-clay-assisted extraction

An important development in this area is the author's study entitled "Pectin Extraction from Orange Peels by Using Organic Clay.**"** S. P. Babar investigated organic clay as an alternative to strong concentrated acid for extracting pectin from orange-peel waste.[5] The study reported that pectin yield was influenced by pH and that the red organic clay at pH 4.3 produced a maximum reported pectin yield of 4%.[5] This result is significant because it demonstrates that organic clay can function as an alternative solid material in the extraction process rather than relying exclusively on conventional strong mineral acids. The study provides an important basis for further development of heterogeneous clay-assisted pectin extraction, particularly with respect to catalyst/material loading, regeneration, reuse and mechanistic studies.

6. Pectin Extraction from Lemon Peel

Lemon peel is an important citrus-processing residue and a promising source of pectin. Conventional extraction generally involves acidified water, heating and subsequent precipitation using ethanol.

Recent literature has demonstrated the potential of ultrasound and microwave-assisted extraction for increasing pectin recovery and reducing extraction time.[2,3] Green extraction technologies have become increasingly important because conventional methods can involve high energy requirements and hazardous or corrosive extraction media.[3,4] The author's subsequent work, "Extraction of Pectin from Lemon Peels by White Organic Clay—Green Approach," extended the organic-clay concept to lemon peel.[6] In this study, lemon peel was used as the raw material and white clay was investigated at pH 4.5 under different extraction temperatures and time periods. The optimum investigated condition was 30 min extraction at 80 °C, and a maximum pectin yield of **1.51%** was reported using ethanol as the precipitating agent.[6] The study is particularly relevant to green extraction because it demonstrates a simple clay-assisted approach for converting lemon-processing waste into a value-added biopolymer.[6] The orange-peel and lemon-peel studies together demonstrate the potential applicability of organic-clay-assisted extraction to different citrus wastes.[5,6]

7. Pectin Extraction from Pomegranate Peel

Pomegranate peel is a promising non-citrus source of pectin. Conventional acid extraction and organic-acid extraction have both been investigated.

Pereira et al. investigated pectin extraction from pomegranate peel using citric acid and studied the effects of pH, temperature and extraction time. The study demonstrated that citric acid can be used as an alternative to strong mineral acids for pectin recovery.[10]

Abid et al. investigated pectins extracted from several pomegranate varieties and reported yields in the range of 6.8–10.1% under their optimized nitric-acid extraction conditions. The extracted pectins were predominantly low-methylated and exhibited useful gelling properties.[11]

Recent research has shifted toward intensified extraction technologies. A 2024 review discussed pulsed electric field, high-intensity ultrasound and microwave heating for pomegranate-peel valorization. These methods can promote cell permeabilization and improve the recovery of pectin and other valuable components.[9]

A broader review of pectin extraction technologies also reports the use of ohmic heating for pomegranate peels, illustrating the movement toward rapid and energy-efficient extraction methods.[1]

8. Green Extraction Technologies

The disadvantages associated with conventional acid extraction have encouraged the development of alternative technologies. Ultrasound produces acoustic cavitation, which can enhance solvent penetration, disrupt plant tissues and improve mass transfer. It can therefore reduce extraction time and improve recovery. Microwave energy produces rapid volumetric heating. It can accelerate cell-wall disruption and pectin solubilization and is particularly useful when short extraction times are desired.[2,3] Enzymes such as cellulases and hemicellulases can modify the plant-cell-wall matrix and facilitate pectin release. The major limitations are enzyme cost and the need for controlled operating conditions. PEF treatment promotes cell permeabilization through electroporation. Recent studies indicate that PEF can be useful in integrated pomegranate-peel valorization processes.[9] Ohmic heating generates heat directly within the extraction medium through electrical resistance. It can provide rapid and relatively uniform heating and has potential for process intensification.[1] Recent reviews have also considered deep eutectic solvents and related alternative solvents for pectin extraction. Their potential advantages include reduced volatility and the possibility of tailoring solvent properties, although recovery, viscosity and economic feasibility remain important considerations.[1,3]

9. Heterogeneous Organic Clay as a Green Extraction Approach

Heterogeneous extraction using solid materials provides a distinct alternative to conventional homogeneous acid extraction. In conventional acid extraction.

Soluble mineral acid + fruit peel + water → soluble pectin

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The acid remains in the extraction medium and requires subsequent neutralization or treatment.

In a heterogeneous approach.

Fruit peel + water + solid organic clay → soluble pectin + solid clay material

The solid material can potentially be separated physically from the extraction medium.

The author's orange-peel study demonstrated the use of organic clay for pectin extraction[5], while the subsequent lemon-peel study demonstrated the use of white organic clay as a green extraction approach.[6] These studies provide a useful foundation for further investigation of clay-based heterogeneous systems.

Potential advantages of organic clay

- Reduced dependence on strong mineral acids
- Simple solid-liquid separation
- Potential material recovery
- Possibility of reuse
- Reduced corrosion potential
- Potential reduction in acidic effluent
- Compatibility with waste-valorization strategies

However, further research is required before the process can be considered fully optimized. Important areas include catalyst/material characterization, loading, regeneration, reusability, extraction kinetics and the effect of clay on pectin molecular structure.

10. Comparison of Pectin Extraction Methods

Table 1: Comparison of conventional, green and heterogeneous approaches.

Method	Major advantage	Major limitation	Potential application
Mineral acid	Simple and effective	Corrosion and acidic wastewater	Orange, lemon, pomegranate
Organic acid	Safer and food-compatible	Requires optimization	Citrus and pomegranate
UAE	Improved mass transfer	Equipment requirement	Fruit peels
MAE	Rapid extraction	Microwave control required	Citrus and other peels
Enzyme-assisted	Mild conditions	Enzyme cost	Fruit wastes
PEF	Cell permeabilization	Scale-up requirements	Pomegranate and other wastes
Ohmic heating	Rapid volumetric heating	Specialized equipment	Emerging
Organic clay	Solid heterogeneous approach	Reuse studies needed	Orange [5]
White organic clay	Simple green clay-assisted approach	Optimization required	Lemon [6]

11. Comparative Evaluation of Orange, Lemon and Pomegranate Peels

Table 2: Comparison of the three fruit-peel sources.

Characteristic	Orange peel	Lemon peel	Pomegranate peel
Botanical source	*Citrus sinensis*	*Citrus limon*	*Punica granatum*
Pectin source	Citrus cell wall	Citrus cell wall	Non-citrus fruit peel
Other valuable components	Essential oils, flavonoids	Essential oils, flavonoids	Polyphenols, flavonoids, tannins
Conventional acid extraction	Widely studied	Widely studied	Widely studied
Organic-acid extraction	Promising	Promising	Demonstrated
UAE/MAE	Widely investigated	Increasingly investigated	Emerging
Organic clay	Demonstrated [5]	Demonstrated [6]	Future research opportunity
Integrated valorization	High	High	Very high

12. Factors Affecting Pectin Extraction

Acidic conditions promote hydrolysis of protopectin and increase pectin solubilization. However, excessively low pH may result in polymer degradation. Increasing temperature generally improves diffusion and hydrolysis. Excessive temperature can adversely affect molecular weight and functional properties. Initially, increasing extraction time improves pectin recovery. Beyond the optimum period, prolonged heating may cause degradation. Reduction in particle size increases surface area and can improve contact between the extraction medium and plant matrix. However, very fine particles may complicate filtration. The ratio affects mass transfer, solvent consumption and concentration requirements. Optimization is therefore necessary for both yield and process economics. For heterogeneous clay-assisted extraction, the amount of clay should be optimized. Excessive clay loading may increase separation requirements without providing proportional improvement in pectin recovery.

13. Characterization of Extracted Pectin

Pectin yield alone is insufficient to evaluate the effectiveness of an extraction method. The quality of the extracted pectin should also be determined. FTIR can identify hydroxyl, carboxyl and ester functional groups and can provide information about esterification. DE is important for classifying pectin and predicting its gelation behavior. Galacturonic acid is commonly used as an indicator of pectin purity. Methoxyl content

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influences the functional and gel-forming properties of pectin. Scanning electron microscopy provides information about surface morphology.

Thermal analysis can be used to determine thermal stability. X-ray diffraction provides information about structural order and crystallinity. ^{1}H and ^{13}C NMR can provide detailed information about molecular structure and esterification. Recent reviews emphasize that structural characterization is essential because extraction conditions can alter molecular weight, functional groups, degree of esterification and rheological properties.[2,3]

14. Applications of Fruit-Peel Pectin

Pectin recovered from fruit waste has potential applications in several sectors. In food industry pectin is used as Gelling agent, Thickener, Stabilizer, Emulsifier, Texture modifier, Edible coating material. In pharmaceutical applications pectin can be incorporated into controlled drug-delivery systems, Encapsulation materials, hydrogels, tablet formulations. In packaging pectin can be used to develop biodegradable and edible films and coatings. Citrus-waste valorization research increasingly consider pectin as a raw material for active and sustainable packaging systems. In biomedical applications pectin-based and modified pectin materials have potential applications in drug delivery, biomaterials and other biomedical systems. Thus, the value of extracted pectin depends not only on yield but also on its functional properties and suitability for a specific application.

15. Circular Economy and Waste Valorization

Pectin extraction provides an opportunity to transform fruit-processing residues into useful materials.
A conventional linear process can be represented as.
Fruit processing → peel waste → disposal
A circular process can instead be represented as.

Fruit processing → peel → recovery of valuable compounds → pectin → value-added products

Orange and lemon peels can potentially provide pectin together with essential oils and phenolic compounds. Pomegranate peel offers even greater opportunities because of its high content of polyphenols and other bioactive constituents.[7,9]

The use of organic clay introduces another potentially sustainable component.
Fruit waste + heterogeneous organic clay → pectin + recoverable solid material
This approach connects **green chemistry, heterogeneous catalysis and circular economy**.

16. Research Gaps and Future Perspectives

Despite significant progress, several areas require further investigation. The possibility of recovering and reusing organic clay should be systematically evaluated. Future work should investigate Surface acidity, Chemical composition, Surface area, Pore structure, Thermal stability, Changes after extraction.

16.3 Mechanism

The interaction between clay surface sites and the plant-cell-wall matrix requires mechanistic investigation In process optimization statistical experimental design can be used to optimize such as Clay loading, pH, Temperature, Extraction time, Particle size, Solid-to-liquid ratio.

16.4 Pectin quality

Future studies should examine the effect of organic clay on.

- Molecular weight
- Degree of esterification
- Galacturonic acid content
- Methoxyl content
- Rheological properties
- Thermal stability.

16.5 Integrated extraction

Future fruit-waste biorefineries should aim to recover several valuable components rather than pectin alone.

16.6 Scale-up and environmental assessment

Pilot-scale investigations, techno-economic analysis and life-cycle assessment are necessary to determine industrial feasibility and actual environmental benefits.

17. CONCLUSION

Orange, lemon and pomegranate peels represent valuable renewable sources of pectin and provide significant opportunities for converting fruit-processing waste into value-added products. Conventional acid extraction remains effective but is associated with limitations including chemical consumption, corrosion, acidic effluent and energy requirements.

Recent developments in UAE, MAE, PEF, ohmic heating and other green technologies demonstrate the possibility of improving extraction efficiency while reducing processing severity. Pomegranate peel is particularly attractive for integrated valorization because pectin can be recovered together with polyphenols and other valuable compounds.

The author's research provides a specific contribution to the development of heterogeneous approaches. Organic clay was successfully investigated for pectin extraction from orange peel, while white organic clay was subsequently investigated for pectin extraction from lemon peel as a green approach. These studies demonstrate the potential of clay-assisted extraction and provide a basis for further research into recyclable heterogeneous materials.

Future research should focus on catalyst/material recovery and reuse, mechanistic studies, process optimization, pectin quality, scale-up and life-cycle

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assessment. The combination of heterogeneous clay-assisted extraction with modern green technologies may provide a promising sustainable route for producing pectin from orange, lemon and pomegranate processing residues.

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