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Enzyme-Assisted Extraction of Pectin: A Sustainable Alternative to Conventional Techniques

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Pectin, a versatile biopolymer widely used in the biomedical, food, and pharmaceutical industries, is traditionally extracted using acidic hydrolysis. Although the use of organic and inorganic acids at high temperatures enables achieving high yields, this method presents significant environmental and economic challenges due to its vast waste generation and excessive structural degradation of pectin. In response, research has increasingly focused on more sustainable extraction methods, such as microwave-assisted extraction, ultrasound-assisted extraction, subcritical water extraction, and enzyme-assisted extraction (EAE). Among these, EAE has emerged as one of the most promising methods, offering improved pectin quality and yield, while operating under milder conditions and generating less waste. This mini review provides an overview of pectin extraction via EAE, presenting the extraction procedure and key parameters, including raw material types, operating conditions, and enzymes used. Studies show that an enzyme mixture of cellulase and xylanase can achieve yields up to ~30 % for certain raw materials under optimal conditions (50 °C, pH 4.8) in 4 h. Furthermore, the comparison of pectin extraction methods indicates that EAE is an environmentally friendly process with favorable technical performance. However, it remains economically challenging and not yet well-suited for large-scale industrial implementation. Finally, attention is given to key challenges associated with EAE, such as raw material variability, the high cost and limited reusability of enzymes.

1. Introduction

Biodegradable polymers have gained increasing attention in recent years due to growing environmental concerns and the global push towards sustainable material solutions. Unlike conventional plastics derived from fossil fuels, biodegradable polymers can decompose naturally, mitigating long-term ecological consequences. Among biodegradable polymers, pectin stands out due to its natural abundance, biocompatibility, non-toxicity, and versatile functional properties. Pectin is a complex polysaccharide mainly found in plant cell walls, with citrus peels and apple pomace being particularly rich sources. Valorizing such fruit-processing waste into valuable products contributes to resource efficiency, reduces environmental burden, and supports a circular bioeconomy (Nadar et al., 2022). Owing to its gelling, stabilizing, emulsifying, and binding properties, along with its biocompatibility and non-toxicity, pectin is widely used in the food, pharmaceutical, biomedical, cosmetic, and food packaging industries. In food industry, it is employed in the production of jams and jellies, low-fat yoghurts, bakery products, and acidified milk, while in food packaging, it is used for biodegradable films and edible coatings for food preservation (Chandel et al., 2022). In biomedical and pharmaceutical sectors, pectin is applied in targeted drug delivery systems, as an encapsulating and metal-binding agent, and in formulations designed for glycemic control and drug bioavailability regulation. Given its broad applicability, the demand for high-quality pectin continues to grow, driven not only by industrial requirements but also by the need to enhance the efficiency and functionality of pectin-based products. Accordingly, optimizing both the yield and quality of pectin during extraction has attracted significant attention from both the scientific community and industry.

Several technologies have been explored for pectin extraction, each offering distinct advantages and limitations. Conventional methods (CE) include acid extraction, which is cost-effective but may degrade the pectin structure, and alkaline extraction, which is less common due to potential chemical alterations (Nadar et al., 2022). More recent innovations have led to microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE),

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subcritical water extraction (SWE), and enzyme-assisted extraction (EAE) (Nadar et al., 2022). Figure 1 presents the most frequently used methods for pectin extraction worldwide, as derived from an evaluation of online resources; however, the analysis should be considered representative rather than comprehensive. These advanced techniques aim to optimize yield, preserve pectin integrity, and reduce environmental impact. Among these, EAE has emerged as a particularly promising approach. While it does present some disadvantages, such as higher operational costs and sensitivity to processing conditions, the benefits often outweigh these challenges. EAE usually produces pectin with higher purity and enhanced functional properties, with yields equal to or greater than conventional methods depending on raw material and conditions, making it a sustainable option for high-quality production (Chandel et al., 2022).

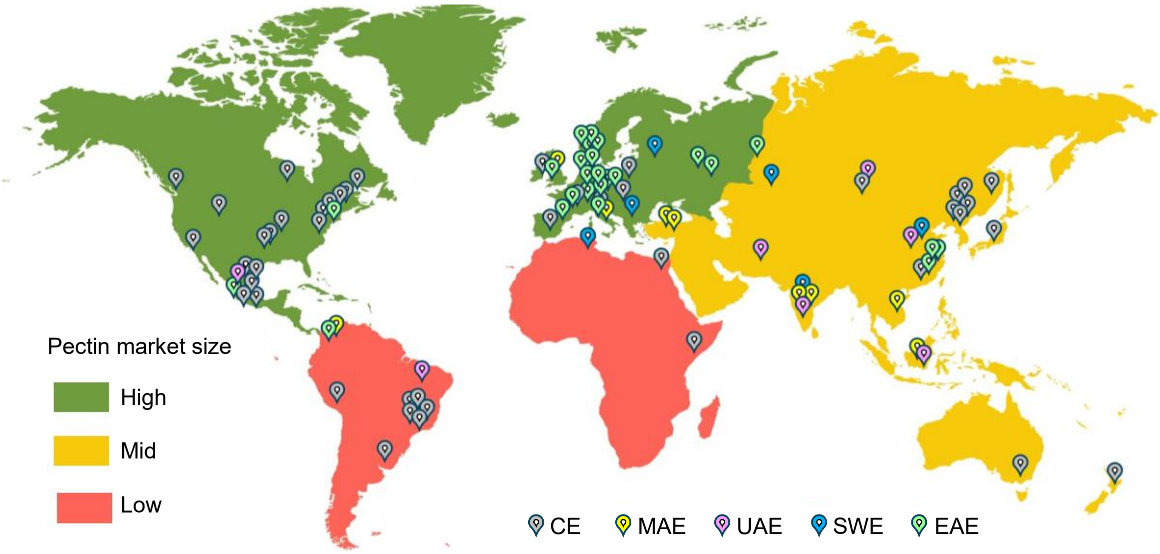

Figure 1: Extraction methods for pectin extraction worldwide

While several review papers have discussed different aspects of pectin extraction, including sustainable extraction methods (Yi et al., 2024), process optimization, applications and challenges (Haque et al., 2025), to the best of the authors' knowledge, a comprehensive and focused mini review article on the throughout exploration of EAE of pectin, has not yet been published. Therefore, this paper provides an overview of EAE of pectin, focusing on the extraction procedure and key parameters such as raw material types, operating conditions, and enzyme selection. In addition, a concise yet insightful comparison between EAE and both conventional and emerging extraction techniques is provided, considering technical performance, economic feasibility, and environmental impact. The review also addresses the key challenges in EAE, including raw material variability and the cost and reusability of enzymes. This mini overview aims to bridge a notable gap in the current literature and offer a valuable foundation for future research and industrial innovation.

2. Enzyme-assisted pectin extraction: A sustainable and selective approach

EAE utilizes enzymes with high specificity and selectivity to efficiently release protopectin from plant cell walls. The process, comprising the sample preparation, extraction, and purification phases and schematically illustrated in Figure 2, has emerged as a promising green technology for improving both the yield and quality of pectin (Dixit et al., 2025). The procedure begins by adjusting the pH of distilled water to below 5.5 using citric acid. Subsequently, the extraction mixture is prepared by incorporating a washed, dried, and ground plant-based pectin source, along with a suitable enzyme preparation. The mixture is homogenized using a magnetic stirrer to ensure uniform consistency. Usually, extraction is conducted at temperatures of up to 60 °C under constant shaking at approximately 200 rpm for up to 24 h. During this period, the enzymes degrade the plant cell walls, releasing the pectin compounds (Nayak et al., 2024). Following extraction, enzymatic activity is terminated by heat inactivation (above 100 °C for 5 min), and the mixture is cooled to room temperature prior to the precipitation and purification steps. Pectin is precipitated by the addition of cold ethanol in excess and recovered by centrifugation at 6,000 rpm for 10 min using a refrigerated centrifuge. The samples are further subjected to mild heat treatment in a water bath, followed by a second cold ethanol treatment to enhance precipitation. The resulting mixture is typically kept at room temperature for up to 24 h before filtration, separation, and washing with ethanol. Finally, the purified pectin is dried in an oven at 50-70 °C or alternatively by freeze-drying.

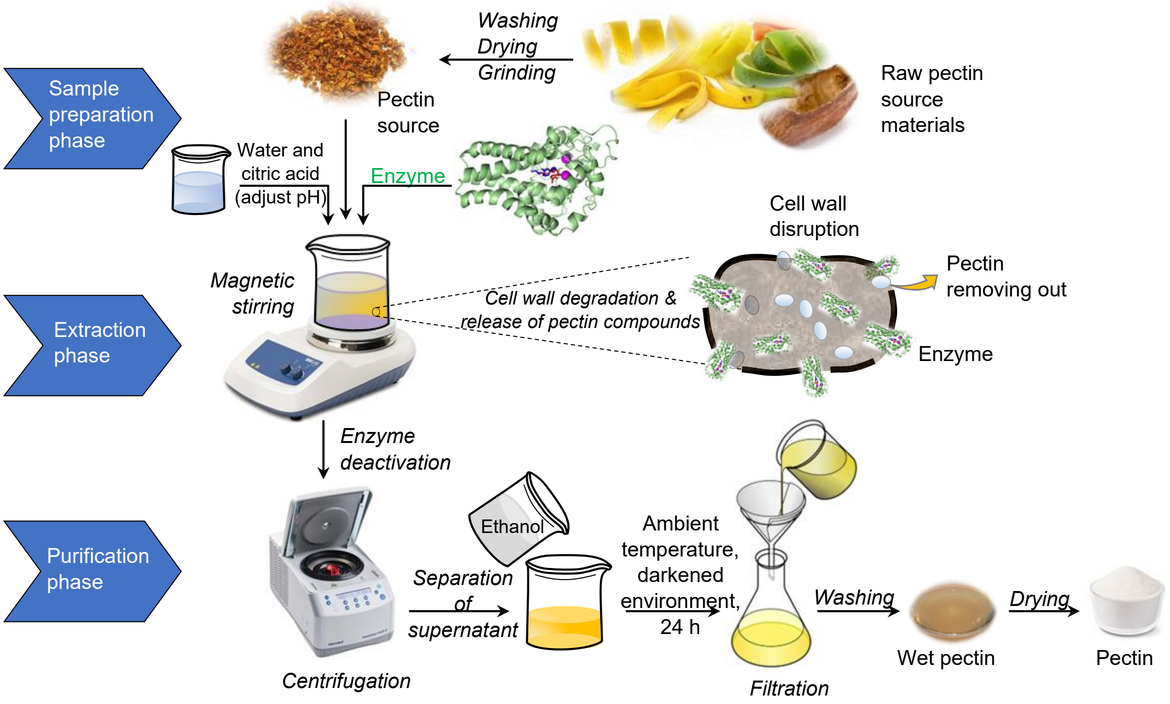

Figure 2: Schematic presentation of enzyme-assisted extraction: from sources to pectin

The quality and quantity of pectin extracted through EAE depend on the raw material, the specific enzyme type and concentration, and extraction conditions such as temperature, pH and duration. EAE of pectin commonly uses raw materials rich in pectin and other pectic substances, as pectin content strongly affects extraction efficiency and economic viability. Beyond pectin content, other selection criteria include moisture content, the presence of potential interfering compounds (e.g. phenolics, proteins, starch), raw material availability and cost, pH value, and the intended application. Additionally, the degree of esterification and molecular weight of pectin in the raw material can influence extraction efficiency and functional properties.

Typically, the raw materials are by-products or waste streams from fruit and vegetable processing, offering cost-effectiveness and environmental benefits through waste valorization. Among the most common pectin sources are apple pomace (Dranca et al., 2020), cocoa pod husk (Hennessey-Ramos et al., 2021), and fruit peels (citrus, pineapple, mango, pumpkin, banana, passion fruit, etc.) (Liu et al., 2023) among others.

Enzymes involved in EAE break down the cell wall matrix to release the pectin. The enzymes best suited for this purpose are pectinase, cellulase, hemicellulase, polygalacturonase, arabinoxylanase, xylanase, pectinesterase, endopolygalacturonase, β-glucosidase, and neutrase (Marić et al., 2018). Auxiliary enzymes such as protease and α-amylase can assist by removing proteins or starch, improving extract clarity and overall yield. While different enzymes serve different purposes, the combination of multiple enzymes can enhance both the extraction rate and overall yield of pectin. For effective pectin extraction, various commercial multi-enzyme blends are available; Celluclast®, rich in cellulase and hemicellulase (Dranca et al., 2020), Viscoferm®, a balanced blend of xylanase, β-glucanase and cellulase (Wikiera et al., 2015), Viscozyme®, containing arabanase, cellulase, β-glucanase, hemicellulase, and xylanase, and FoodPro® which mainly contains cellulase (Zhang et al., 2020).

The selection of enzyme type depends on raw material composition; for example, citrus peels may require stronger pectinase activity, while fibrous materials may benefit from cellulase. Optimization of pH, temperature, enzyme concentration, and extraction duration are essential to enhance enzyme activity and improve both yield and quality of pectin. These parameters are frequently optimized using Response Surface Methodology (RSM), a statistical technique that enables the systematic determination of optimal process conditions while minimizing the number of experimental trials (Hennesey-Ramos et al., 2021).

Table 1 summarizes some of the high-efficiency examples of EAE for pectin extraction, arranged by decreasing pectin yield. The table includes data on the raw material used, the specific enzyme types and their dosages, and the extraction operating conditions (temperature T, pH, and duration t).

Table 1: Overview of pectin extraction via EAE

Yield (%)	Raw material	Enzyme type	Enzyme dosage	*T* (°C)	pH	*t* (h)	Reference
28.8	Sugar beet pulp	Xylanase, cellulase	500 unit/g	50	4.8	4	Abou-Elseoud et al. (2021)
25.6	Lemon peels	Xylanase	45 µg/g	50	5.0	0.5	Liu et al. (2023)
22.9	Butternut squash	Xylanase, cellulase	30 unit/g	50	5.5	2	Milošević and Antov (2022)
18.9	Apple pomace	Celluclast®	50 µg/g	50	4.5	18	Wikiera et al. (2015)
17.9	Apple pomace	Viscoferm®	50 µg/g	55	4.5	18	Wikiera et al. (2015)
15.1	Lime pomace	Polygalacturonase	115 unit/L	20	5.0	2	Bezus et al. (2022)
12.1	Carrot pomace	Cellulase	100 unit/g	50	5.0	24	de Laet et al. (2025)
11.3	Cocoa pod husks	Celluclast®	58 µL/g	50	4.6	20	Hennessesy-Ramos et al. (2021)
10.8	Banana peels	Cellulase, xylanase	65 mL/L	50	5.5	6	Kumoro et al. (2020)
9.4	Sisal waste	Celluclast®	55 µL/g	50	4.0	20	Yang et al. (2018)
9.3	Pineapple guava	Cellulase	10 unit/mg	40	6.5	2	Wang et al. (2024)
8.5	Green tea leaves	Viscozyme®	125 units/L	30	4.5	3	Zhang et al. (2020)
8.4	Sugar beet pulp	Cellulase	200 units/g	50	4.8	4	Abou-Elseoud et al. (2021)
7.2	Apple pomace	Cellulase	4000 unit/g	48	4.5	18	Dranca et al. (2020)
7.0	Sugar beet pulp	Xylanase	150 unit/g	50	4.8	4	Abou-Elseoud et al. (2021)
6.8	Apple pomace	Celluclast®	727 unit/g	48	4.5	18	Dranca et al. (2020)
5.1	Green tea leaves	FoodPro®	750 unit/L	30	4.5	3	Zhang et al. (2020)

As indicated in Table 1, apple pomace is the most commonly utilized raw material for EAE of pectin, followed by citrus peels. Optimal extraction parameters vary depending on the raw material, and enzyme type and dosage, with temperature ranging from 20 °C to 50 °C, pH from 3.5 to 6.5, and extraction times up to 24 h. Although the commercial multi-enzyme blend Celluclast® is commonly used, the highest pectin yield has been achieved using a mixture of xylanase and cellulase in a 1:1.5 ratio (Abou-Elseoud et al., 2021). Furthermore, high pectin yields have also been reported from citrus peels, butternut squash, and various fruit and vegetable pomaces in short extraction times using various enzymes, including cellulase, xylanase, polygalacturonase Viscoferm®, Viscozyme®, and FoodPro® as shown in Table 1.

EAE can be effectively combined with other green extraction methods, such as MAE, UAE and SWE, to improve pectin recovery. For example, sequential treatment of sisal waste with enzyme (Celluclast 1.5 L) followed by UAE attained a much higher pectin yield of 31.1 %, whereas reversing the sequence (UAE followed by EAE) resulted in a lower yield of 14.6 %, which was still 1.5 times higher than EAE alone (Yang et al., 2018).

3. Comparative evaluation of enzyme-assisted pectin extraction methods

To evaluate the EAE method for pectin extraction, a comparison is made between EAE and both CE and emerging extraction methods (MAE, UAE, SWE). The methods are assessed based on technical performance, environmental impact, and economic feasibility (Nadar et al., 2022). The technical criteria considered include pectin quality, yield and extraction efficiency, degree of degradation, processing time, and energy consumption. It can be observed that harsher extraction conditions enhance pectin degradation; however, they compromise structural integrity, leading to reduced functional performance, including lower gel strength and viscosity. Environmental impact is evaluated across the full life cycle of the extraction process, while economic feasibility includes the cost of raw materials, reagents, equipment, processing cost, and process scalability. Table 2 provides a visual comparison using a semaphore color-coding scheme, compiled from multiple references. It shows that sustainable techniques (MAE, UAE, SWE, EAE) demonstrate equal or improved technical and environmental performance compared to CE, but their relatively high cost and limited scalability present significant barriers to industrial implementation. Among the extraction methods considered, EAE generally offers advantages with respect to pectin quality, yield, extraction efficiency, reduced pectin degradation, lower energy consumption, and environmental sustainability (Haque et al., 2025).

The selection of a suitable pectin extraction method depends on several critical factors. First and foremost, the pectin yield must be considered, as higher yields can improve process efficiency and economic viability. Furthermore, preserving the structural integrity of pectin is essential to maintain its desired functionality, which determines its suitability for specific applications in the food, pharmaceutical, cosmetic and other industries. Additionally, environmental sustainability is a growing concern, with preferences given to methods that minimize chemical use, energy consumption, and waste generation.

Table 2: Comparative assessment of pectin extraction methods

Criteria	CE	MAE	UAE	SWE	EAE
Pectin quality	Low quality	High quality	High quality	High quality	High quality
Pectin yield and efficiency	15–25 %	40–60 %	50 %	40–50 %	20–30 %
Pectin degradation	High risk	High/Low risk	High risk	High risk	Low risk
Processing time	1–4 h	2-30 min	10–20 min	1–6 h	6–24 h
Energy consumption	High	Low	Low	Moderate	Low
Environmental impact	High (effluent)	Low	Low	Low	Low
Scalability	High	Moderate	Moderate	Moderate	Moderate
Economic (capital/operational cost)	Low/Moderate	High/Moderate	High/High	High/High	High/High

Green = advantage, yellow = moderate outcome, red = disadvantage

4. Conclusions, challenges and future perspectives

EAE is a promising approach for pectin extraction from various agricultural and food wastes. Despite its technical advantages, no published studies have yet conducted a comprehensive techno-economic assessment of EAE for pectin. Such analyses are essential to evaluate the economic feasibility and scalability of the process and to support its potential adoption in industrial applications. Furthermore, to fully validate the economic and environmental performance from a sustainability perspective, further work is needed, particularly through complete life cycle assessments and continued improvement of the EAE process itself. To enhance both quality and quantity of the extracted pectin, EAE can be combined with other sustainable extraction techniques, such as MAE, UAE, and SWE, depending on the raw material and the desired pectin properties for specific applications. Key challenges for broader commercial use include the inherent variability of raw material composition and the high cost and limited reusability of enzymes. Addressing these issues through improved raw material characterization, enzyme immobilization, and process intensification is critical for enabling the future scale-up of EAE.

4.1 Raw material variability

The physicochemical properties of raw materials used for pectin extraction, such as moisture content, pH, and the presence of interfering compounds, can vary significantly between batches and across growing seasons (Caroço et al., 2019). Unlike controllable process parameters (e.g., temperature or pH), raw material attributes are heavily influenced by external factors, including agricultural practices, harvest timing, and storage conditions, placing them largely beyond the control of manufacturers. This variability remains a major challenge to maintaining consistent extraction efficiency and product quality. As the demand for high-quality, sustainably sourced pectin grows, addressing raw material variability will become increasingly critical for future process reliability. To improve robustness, future extraction systems are likely to adopt statistical and multivariate data analysis to classify raw material lots and predict their impact on processing outcomes. These tools can support smarter decisions on raw material utilization and process adjustments. However, broader adoption is still constrained by the cost, complexity, and time required for detailed analytical testing. As such, the development of rapid, non-destructive, and cost-effective in situ assessment technologies presents a promising path forward. These innovations could enhance process control, reduce variability, and help ensure consistent pectin quality across diverse production scenarios.

4.2 Enzyme cost and reusability

While EAE is widely recognized as an environmentally friendly and effective alternative to CE methods, the high cost of commercial enzymes continues to hinder its large-scale deployment (Subbiah et al., 2025). Currently, enzymes are mostly used in single-use batch operations, which increases operational costs and limits the overall economic feasibility of the process. Furthermore, enzyme activity can be adversely affected by factors such as temperature variations, pH fluctuations, and shear stress, reducing opportunities for reuse and further increasing production costs. Overcoming these challenges will be essential for scaling up EAE in the future, and several promising strategies are emerging to address them. Enzyme immobilization, where enzymes are bound to solid supports, allows for their recovery and reuse across multiple extraction cycles, often with minimal loss of activity. Techniques such as adsorption, covalent binding, entrapment, and encapsulation are being optimised to enhance enzyme stability and enable efficient separation from the reaction medium. In parallel, advances in protein engineering and recombinant DNA technology are paving the way for the development of more robust, cost-efficient enzymes specifically tailored to the conditions of pectin extraction. Looking forward, the integration of these innovations could significantly reduce enzyme consumption and enable the transition toward continuous or semi-continuous EAE systems, thereby improving both economic viability and environmental sustainability.

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