



Revolutionizing pectin extraction from sugar beet pulp: a critical review of green and scalable techniques

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Abstract

This review explores different approaches for extracting low-esterified pectin from sugar beet pulp (SBP), a sustainable and often ignored by-product of sugar industry. Although traditional acid hydrolysis is commonly used, it has disadvantages such as varying yield and environmental concerns. Newer approaches—such as enzyme assisted extraction, ultrasound-assisted extraction, and microwave-assisted extraction—have shown promising results in improving efficiency and preserving pectin quality. Using enzyme, especially when combined with ultrasonic pre-treatment, has demonstrated effective in increasing yield and reducing processing time. SBP-derived pectin has unique structural characteristic, like high acetylation, which can affect its functional properties. Hybrid techniques and eco-friendly solvents are developing as valuable tools to overcome these limitations. This review highlights strengths and challenges of each method, underlining importance of optimizing conditions for industrial use. This review specifically examines SBP, an underexploited source of pectin, highlighting novel green extraction technologies, structural-function relationships, and commercial viability—areas not extensively addressed in prior reviews.

Keywords Sugar beet pulp · Pectin extraction · Green extraction techniques · Sustainable bioprocessing · Industrial feasibility

Introduction

Pectin is a highly marketed renewable biopolymer classified as a water-soluble anionic biopolymer and the global market for this product will likely expand from \$1.25 billion in 2024 to \$2.50 billion by 2033 (Asadi, 2006; Roman-Benn et al., 2023). Plant-based structural polysaccharide functions as a high molecular weight substance in plant cell walls which exhibits hydrogel formation properties (Grassino et al., 2016; Martău et al., 2019; Ngouémazong et al., 2015; Yang et al., 2018) (Fig. 1). In the commercial production of pectin, apples and citrus fruits are the sources of pectin but researchers also explore extraction methods from industrial waste materials (Chandel et al., 2022; Huang et al., 2017; Martău et al., 2019; Sheldon, 2016; Yang et al., 2018). The pectin molecules derived from various sources and extraction procedures exhibit different topological arrangements due to their fundamental composition of homogalacturonan (HG), rhamnogalacturonan I (RG-1), rhamnogalacturonan II (RG-2) and xylogalacturonan (XG) (Ma et al., 2020) (Fig. 1). While the literature on pectin extraction from fruit peels provides general overviews, this review specifically

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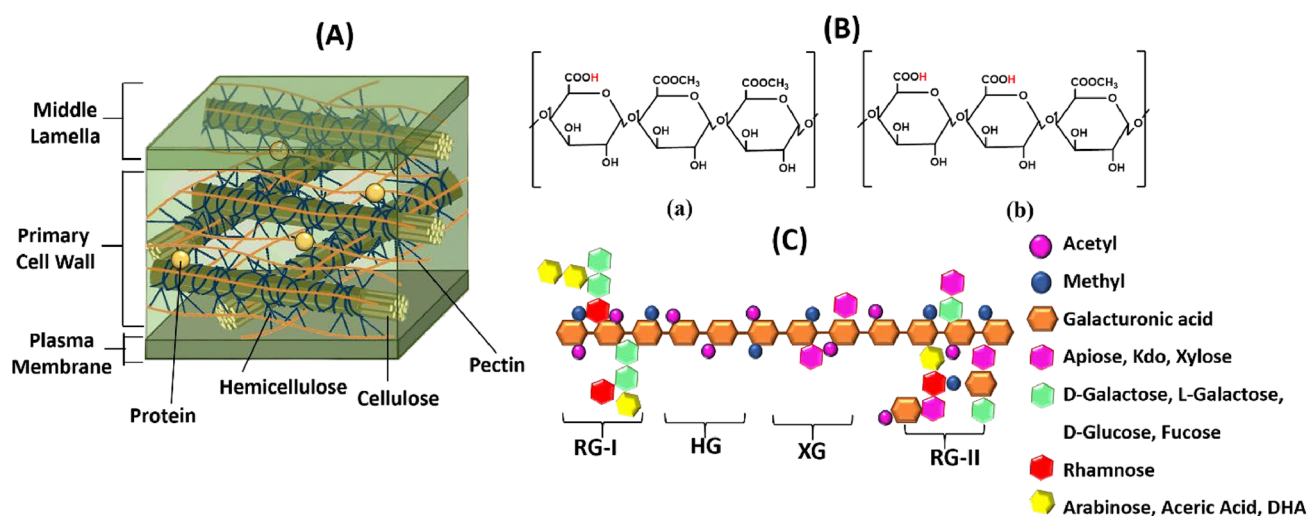


Fig. 1 (A) Structure of primary plant cell wall contain pectin; (B) Structure of the pectin (a) High esterified pectin, (b) Low esterified pectin; (C) Chemical structure of pectin composed of linear galacturonic acid (GaA) chain and complex side-chains including

rhamnogalacturonan I (RGI), homogalacturonan (HG), xylogalacturonan (XG) and rhamnogalacturonan I (RGI). Abbreviations: Dha (3-deoxy-D-lyxo-2-heptulosaric acid); Kdo (ketodeoxyoctonic acid) (Roman-Benn et al., 2023)

focuses on sugar beet pulp (SBP), a low-cost and abundantly available by-product. The study evaluates current and emerging extraction techniques for SBP through an assessment of sustainable methods which align with industrial environmental standards. The structural uniqueness of the SBP-derived pectin, especially its high acetylation, requires a focus on research that has not been adequately addressed in previous studies (Wang et al., 2018).

The studies involving pectin mostly examine its use in food production alongside applications in agriculture as well as medicine. The pharmaceutical industry employs pectin for multiple applications which include using it as edible coatings and bio-based antimicrobial films and nanoparticles that help with cancer treatment and wound healing (Celus et al., 2018; Chaturvedi et al., 2019; Espitia et al., 2014; Gaona-Sánchez et al., 2021; López-Mata et al., 2018; Ma et al., 2020; Munarin et al., 2012; Naqash et al., 2017; Sakoei-Vayghan et al., 2020; Sun et al., 2020; Tian et al., 2020; Zhang et al., 2015). By modifying its structure either individually or combined with other biopolymers new possible functions can be achieved (Chen et al., 2021; Freitas et al., 2020; Muñoz-Almagro et al., 2017; Naqash et al., 2017; Wang et al., 2018; Zhang et al., 2013, 2015). Since pectin has the ability to chelate metal ions, different extraction methods combined with different pectin sources produce distinct antioxidant properties (Wang et al., 2018; Wicker et al., 2014; Zhang et al., 2015). The use of pectin in food-based emulsions serves as an antioxidant which enhances various properties and minimizes artificial additives to create clean label products (Ma et al., 2020; Naqash et al., 2017; Zhang et al., 2015). The edible pectin coatings promote water

retention and inhibit decay in fresh produce which maintains their structure while extending product freshness (Espitia et al., 2014; Sakoei-Vayghan et al., 2020). Researcher are investigating safe sustainable food packaging materials has heightened within the last 10 years due to safety concerns and rising demand for natural ecological technology (Zhang et al., 2015). Due to pectin's permeability properties, the drug delivery system utilizes it which enables colon-specific drug delivery while maintaining resistance to amylases and proteases and allowing metabolic degradation from intestinal bacteria. Research studies show that pectin enhances immune system function while it enhances digestive system metabolic operations (Paharia et al., 2007; Zhang et al., 2015).

Sugar beet serves as a garden vegetable which humans have cultivated for more than 2000 years to produce various food products (Adiletta et al., 2020). The first sugar beet factory was built in Silesia in 1802, and by 1818, world beet sugar production had overtaken that of cane sugar. The European Union is a global leader in sugar production, with beet sugar accounting for almost all sugar production in Europe (Asadi, 2006). Sugar derived from sugar beet is identical to that obtained from sugarcane (Babu and Adeyeye, 2024; Duraisam et al., 2017). A large amount of residue was left behind after the sugar extraction known as sugar beet pulp (SBP) (Kelly, 1983). The sugar industry generates SBP which functions as a main by-product and finds usage in applications beyond its typical role as animal feed (Fig. 2) (Adiletta et al., 2020; Kelly, 1983). SBP contains abundant polysaccharides, including cellulose, along with hemicellulose and pectin which make it an excellent starting material

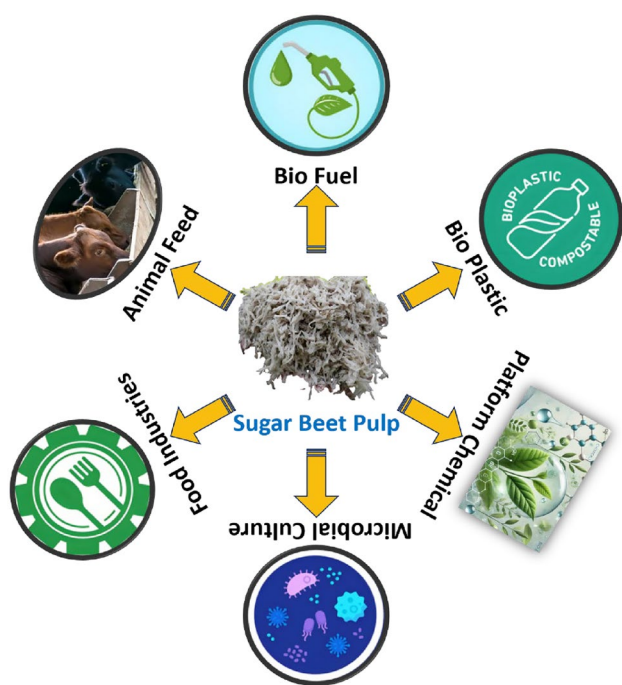


Fig. 2 Schematic Diagram for application of the sugar beet pulp in various Industries

for industrial and biotechnological applications (Peighambardoust et al., 2021) (Fig. 1). SBP valorization has been one of the key targets of research, as it represents a valuable resource for bioplastics and the generation of biochemical products and sustainable biofuels (Aksakal et al., 2021; Ellis et al., 2021; Finkenzstadt et al., 2008; Liu et al., 2018; Muthusamy and Pramasivam, 2019; Tomita et al., 2019). In addition to environmental sustainability benefits, the use of SBP delivers enhanced monetary value through minimizing agricultural waste. Bioethanol production is one of the main research applications for exploring SBP potential (Fig. 2). The microbial hydrolysis of SBP carbohydrates produces fermentable sugars which then ferment into ethanol. The method allows for the replacement of fossil fuels with renewable sustainable energy resources (Berlowska et al., 2017; Igwebuike et al., 2024; Patelski et al., 2024; Usmani et al., 2021). The researchers show that SBP works well as a biogas production material through anaerobic digestion. The high methane content in biogas from SBP makes it an efficient energy source which can power industrial operations through heat and electricity production (Fig. 2). In addition to the increased operational energy efficiency, the strategy for streamlined biofuel production from SBP within existing sugar industrial processes is also expected to be followed, and thus waste management challenges are reduced. SBP also finds a significant use in the production of bioplastics and environmentally friendly materials (Ćirić et al., 2024). Furthermore the structural properties of SBP

contain polysaccharides, particularly cellulose and hemicellulose have value in developing sustainable polymer blend materials for packaging applications. The creation of biodegradable composites demands the unification of SBP with polymer structures to establish sustainable alternatives for petroleum-based polymers which are non-biodegradable. The materials help to reduce plastic waste and promote the selection of renewable resources for industrial manufacturing processes (Fadel et al., 2022; Marzo-Gago et al., 2023; Tsang et al., 2019).

The main purpose of SBP production is to obtain furfural and hydroxymethylfurfural (HMF) which act as essential building blocks for bio-based chemical manufacturing. The extraction process of these chemicals from SBP enables the creation of environmentally friendly chemical methods while decreasing our reliance on petroleum-derived starting materials. SBP contains non-sucrose carbohydrates such as arabinose and galacturonic acid that provide potential for high-value biochemical product synthesis. SBP demonstrates significant economic value and environmental importance because it functions as feedstock for various industrial applications (Usmani et al., 2021).

Pectin is the most valuable component of SBP. Sugar beet pulp-derived pectin possesses distinctive characteristics that differ from pectin extracted from citrus fruits and apples (Table 1). The substances display different properties because their molecular structures and methylation patterns differ from one another. The elevated acetylation level of sugar beet pulp pectin compared to citrus and apple pectins substantially affects its ability to dissolve and form gels. Compared with citrus and apple pectins, which develop stable gels in the presence of acidic conditions and sugar, the acetyl groups in SBP pectin reduce its ability to form strong gels (Table 1). The high acetylation content of SBP pectin creates exceptional emulsifying and stabilizing properties which make it an effective emulsifier and stabilizer for oil–water emulsions and colloidal systems. The degree of esterification in sugar beet pulp pectin stands lower than that of citrus pectin (Table 1) (Adina et al., 2011; Baraiya et al., 2023; Chandel et al., 2022; Oosterveld, 1997; Pacheco et al., 2019).

The modification of SBP pectin through this property enables it to use less calcium ions when forming gels. The substance shows special operational characteristics in environments with minimal sugar levels and acidic conditions which makes it useful for industrial applications (Huang et al., 2017; Mesbahi et al., 2005; Peighambardoust et al., 2021; Rejaei and Salehi, 2016). Due to these neutral sugars, the higher content of arabinose and galactose in SBP pectin enhances its water-retention capacity and solution viscosity (Basak and Annapure, 2022; Tsokri, 2023). The product features are proven to enable successful use in applications that require moisture retention and texture modification. The

Table 1 Comparative analysis of citrus fruit pectin and sugar beet pulp pectin based on chemical composition, functional properties, and extraction yields

Aspect	Citrus Fruit Pectin	Sugar Beet Pulp Pectin	Ref
Galacturonic acid content (%)	65–75%	40–50%	(Chandel et al., 2022b; Pacheco et al., 2019)
Degree of esterification ^a (%)	50–80%	30–50%	(Chandel et al., 2022b; Sun and Hughes, 1998)
Acetylation (%)	< 1%	5–10%	(Pacheco et al., 2019; Sun and Hughes, 1998)
Ferulic acid content (mg/g)	< 0.1 mg/g	2–3 mg/g	(Adina et al., 2011; Sun and Hughes, 1998)
Water-binding capacity (g water/g pectin)	~ 10 g water/g pectin	~ 4–6 g water/g pectin	(Baraiya et al., 2023; Oosterveld, 1997)
Emulsifying activity (%)	~ 20%	~ 60–80%	(Pacheco et al., 2019)
Extraction yield (% of raw material)	20–30%	10–15%	(Chandel et al., 2022b; Pacheco et al., 2019)

a = (> 50% = High Methoxyl) or (< 50% = Low Methoxyl)

main benefit of sugar beet pulp pectin lies in its economic feasibility and wide availability. The extraction of sugar beet pectin from sugar extraction waste produces an economical pectin source that remains less expensive than pectin extracted from conventional fruit processing methods. Pectin extraction from SBP enables better waste reduction and sustainability, as it utilizes a material which otherwise would become waste (Almowallad et al., 2022). The distinctive physical and chemical properties of sugar beet pulp pectin allow it to function perfectly in various industrial formulations because of its enhancement of emulsification and the maintaining of water content while controlling viscosity. The tolerance to pH and ionic conditions of SBP pectin makes it an excellent asset to develop environmentally friendly and innovative solutions.

Different extraction techniques of pectin from SBP receive increased interest because of the growing need for sustainable and economical functional biomaterials. The sugar industry produces large amounts of sugar beet pulp which contains significant pectin content but remains underutilized in comparison to citrus peels and apple pomace. The research needs to explore various extraction methods including acid hydrolysis and enzymatic treatment and subcritical water extraction as green alternatives to enhance both pectin yield and quality and functional properties along with reduced environmental effects. This review provides comprehensive analysis of different extraction approaches by assessing their operational effectiveness and economic viability alongside sustainability aspects. The research focuses on developing environmentally friendly and efficient pectin extraction methods to increase sugar beet pulp value and implement circular economy principles. In this review article, the literatures were systematically collected from a structured search across the major scientific databases such as Web of Science, Scopus, Google Scholar and ScienceDirect. The articles were searched by applying predefined inclusion (such as, article timeframe 2010–2025; extraction of pectin from sugar beet pulp) and exclusion (such as focused solely on apple/citrus pectin) to ensure a

comprehensive and unbiased evaluation of recent advance in pectin extraction from SBP.

Novel approaches for pectin extraction from sugar beet pulp

Mass transfer principles are the basis of the pectin extraction process, because the extraction efficiency relies on protopectin hydrolysis followed by solubilization and the equilibrium point of the extraction solvent. Hydrolysis and solubilization step allow diffusion of dissolved pectin molecules toward the bulk solvent (Adetunji et al., 2017; Minkov et al., 1996; Pinelo et al., 2006). The extraction follows first-order dynamics which allows mathematical models to describe pectin degradation through assessments of molecular weight and intrinsic viscosity (Cho and Hwang, 2000; Minkov et al., 1996). The mathematical expression for protopectin hydrolysis rate inside spherical pectin-bearing particles appears as shown in Eq. 1:

$$\frac{dC}{dt} = kC(1 - \epsilon), \quad (1)$$

where C represents protopectin concentration, k is the hydrolysis rate constant, and ϵ is the porosity of the particle (Minkov et al., 1996). The successful extraction of pectin depends on precise operational parameter control because improper conditions lead to decreased quality of extracted pectin.

The extraction process is largely dependent on pectin diffusion through the solid matrix to the bulk solvent which is controlled by temperature and solid–liquid ratio. The Stokes–Einstein relation shows that diffusivity follows Eq. 2:

$$D \propto \frac{T}{\eta} \quad (2)$$

which relates absolute temperature T to dynamic viscosity coefficient η (Adetunji et al., 2017; Loncin and Merson,

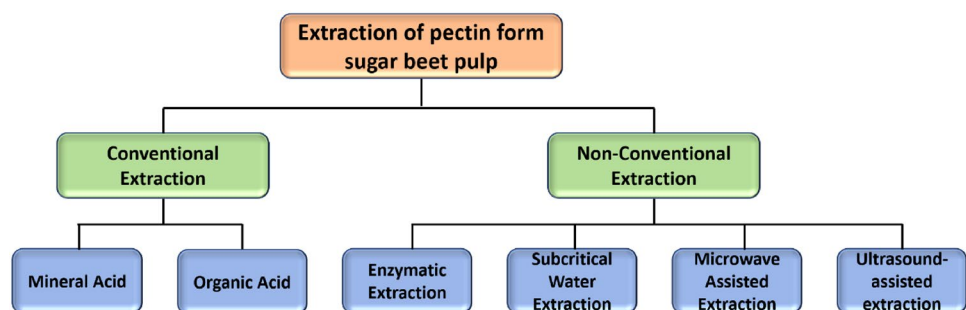
1979). When the solution viscosity increases sufficiently to slow down mass transfer, the extraction process attains an optimal duration, resulting in both dissolution stagnation and accelerated thermal degradation. In particular, the relationship between solid material and extraction solution determines the extraction yield while minimizing solvent consumption (Chen et al., 2015a; Kulkarni and Vijayanand, 2010). The extraction solvent pH controls both pectin quality and yield because acid promotes hydrolysis but alkaline conditions trigger β -elimination degradation (Kratchanova et al., 1994). Since smaller particles produce higher yield through increased surface area yet excessive fineness can reduce solvent, the extraction efficiency of pectin depends on raw material characteristics (El-Nawawi and Shehata, 1987; Huang et al., 2018). Huang et al., 2018 demonstrated that superfine grinding of SBP particles enhanced pectin extraction efficiency and raised the galacturonic acid content. The research confirmed that pectin quality depends on particle size as smaller particles increased yield and larger particles caused higher viscosity (Huang et al., 2018). Alternative extraction methods have been investigated by researchers to enhance both operational efficiency and sustainability which show potential for industrial application. Here, we will discuss about various extraction technique for pectin from sugar beet pulp (Fig. 3).

Enzymatic extraction (EE)

EE is a promising bioengineering technique for solvent-based extraction as it reduces chemical solvent presence in derived products (Puri et al., 2012). The increasing demand for sustainable food and pharmaceutical manufacturing processes has elicited the increasing importance of EE extraction methods due to their minimum solvent requirements. Rhein-Knudsen et al. (2015) examined the moderative effects of EE on seaweed-derived hydrocolloids including carrageenan, alginate, and agar (Rhein-Knudsen et al., 2015). The research results demonstrate that enzymes are critical members in marine polysaccharide modifications which enhance the efficiency and reduce the environmental impact of polysaccharides (Dulanlebit and Hernani, 2023).

Enzymes prove highly useful in extraction processes because they perform specific reaction targeting through precise hydrolysis reactions. Enzymes possess targeted action which allows them to perform chemical solvent reduction and production enhancement through methods that extend past acid-based hydrolysis (Bitwell et al., 2023; Nadar et al., 2018). Multiple polysaccharide networks make up the plant cell wall structure which contains cellulose and hemicellulose (xyloglucan) and pectin with proteins that create complex bonding structures (Broxterman and Schols, 2018; Cosgrove, 2024). The pectin matrix creates a barrier structure that makes extraction operations more difficult because it exists with cellulose and xyloglucan framework. The enzymes cellulases, hemicellulases and proteases are used to degrade single cellular components because they do not break down pectin. The successful implementation of EE requires full comprehension of enzyme operation principles and their best operational parameters (Bitwell et al., 2023; Nadar et al., 2018). Abou-Elseoud et al. studied the EE extraction of the pectin from the SBP (Abou-Elseoud et al., 2021b). The researchers evaluated cellulase and xylanase along with their combined usage which produced superior results compared to single enzyme applications thus achieving higher pectin yields. Researchers achieved higher extraction yields especially when the enzymatic reaction time was limited by using ultrasonic pre-treatment before enzymatic processing. The ultrasound technology speeded up the process yet it maintained the emulsification properties of the pectin. The researchers showed through their study that the combined enzymes create an efficient and sustainable method for pectin extraction (Abou-Elseoud et al., 2021b). Furthermore, Abou-Elseoud et al. The research of 2021 investigated SBP pectin as a corrosion inhibitor for mild steel in acidic solutions. The pectin extraction process using enzymes generated superior corrosion protection results than the extraction methods based on acid. The research investigated the relationship between pectin concentration, temperature conditions and chemical bond formation, on corrosion prevention systems. In addition to the characterization of pectin compounds as mixed-type inhibitors, the pectin compounds functioned as a primary inhibitor of the cathodic reaction, while providing effective steel surface

Fig. 3 Various techniques for the extraction of pectin from the sugar beet pulp



coverage for corrosion reduction. The study shows that pectin obtained from sugar beet pulp functions as an environmentally friendly industrial corrosion protection agent which also preserves its worth for food and pharmaceutical uses (Abou-Elseoud et al., 2021a).

The enzymatic extraction of pectin from SBP functions as an environmentally friendly method instead of acid hydrolysis because it decreases chemical usage and protects equipment from damage and simplifies wastewater management. The extraction process becomes simpler because it omits several pre-treatment procedures (such as big-scale raw material grinding and sugar and color pigment removal which traditional and physical methods need) to reach maximum pectin recovery with natural structure and quality protection (Wikiera et al., 2015). The method needs less solvent to operate which results in lower production expenses that benefit companies adopting green manufacturing practices (Puri et al., 2012). Multiple barriers exist when trying to expand EE applications for industrial use at larger scales. Enzymes face difficulties in industrial applications because their high production costs and environmental sensitivity cause their performance to decrease when scaled up. The acid hydrolysis extraction process for EE extraction operates differently from other extraction methods because it does not enhance extraction rates which could impact industrial production efficiency (Norton et al., 2006; Puri et al., 2012). The method shows potential to become a sustainable production method for high-quality pectin but requires additional development to more cost-effective and scalable.

Acidic extraction (AE)

The industrial pectin extraction through acid extraction followed by alcoholic precipitation remains the dominant method because it provides simple procedures and low energy requirements alongside cost-effectiveness and automation capabilities. Pectin extraction occurs through the thermal degradation of protopectin under acid conditions

at 60–90 °C for 1–6 h using sulfuric, hydrochloric or citric acids before alcohol precipitation. Acid extraction achieves two main objectives through its process which separates neutral sugar side chains and dissociates the rhamnogalacturonan-I (RG-I) region to produce homogalacturonan (HG)-rich pectin (Badaró et al., 2020; Das and Arora, 2021; Dias et al., 2020; Freitas et al., 2020; Sun et al., 2020; Yang et al., 2018). During pectin extraction, the acid type fundamentally influences both extraction yield and structural composition as well as functional properties of the extracted pectin. The researchers studied the efficient protopectin breakdown by using hydrochloric acid (HCl) as extraction acid which produced pectin with over 80% galacturonic acid content (Phatak et al., 1988; Sun and Hughes, 1998). HCl extraction results in pectin chain degradation, which produces lower molecular weight pectin (35,500–91,400 Da) that demonstrates reduced gel-forming capability under high-sugar conditions. (Phatak et al., 1988). The pectin obtained through HCl extraction exhibits high methylation levels above 60% DE enabling its use as thickener or emulsifier rather than gelling agent. (Phatak et al., 1988; Sun and Hughes, 1998). In particular, the implementation of mineral acids presents two major disadvantages in terms of equipment deterioration and waste disposal. Organic acids such as citric acid, lactic acids, malic acids, acetic acids and tartaric acids are currently being explored as potential alternatives to mineral acids (Vriesmann et al., 2012). The organic acids represent a superior choice due to their lower dissociation capacity supporting reduced pectin breakdown. (Freitas et al., 2020). Researcher further found that the extraction process of pectin through organic acids such as citric, malic, and lactic acids produces different results compared to mineral acids. The extraction process using organic acids affects yield and esterification degree (42–71%) and galacturonic acid (GalA) content (60.2–77.8%) through changes in pH and extraction time (Ma et al., 2013) (Table 2).

The use of acidic conditions with long extraction times leads to higher yield but a decrease in esterification levels

Table 2 Summary of extraction parameters, yield, and physicochemical characteristics of pectin isolated from sugar beet pulp using various organic acids and compared the data with mineral acid (HCl) data has been collected from the (Ma et al., 2013)

Acid type	pH	Time (h)	Yield (%)	GalA content (%)	Degree of esterification (DE) $\pm 0.5\%$	Emulsifying activity (%)	Emulsion stability (%)
Citric Acid	1.5	2	17.2	75.8 $\pm$ 1.4	42	40.1	79.4
Citric Acid	2.0	1	13.1	77.8 $\pm$ 1.2	71	38.5	75.2
Malic Acid	1.5	2	16.5	60.8 $\pm$ 2.2	45	37.8	72.3
Malic Acid	2.0	1	14.3	64.3 $\pm$ 1.8	68	36.4	70.1
Lactic Acid	1.5	2	12.7	52.7 $\pm$ 3.5	58	35.2	62.1
Lactic Acid	2.0	1	10.9	56.3 $\pm$ 3.0	66	34.8	65.4
Hydrochloric Acid	1.5	2	19.4	61.2 $\pm$ 1.0	38	39.5	76.8

* refers to data obtained using hydrochloric acid as a reference extraction agent

due to acid hydrolysis oxidation of ester bonds. The extraction of pectin through organic acids preserves rhamnogalacturonan-I (RG-I) groups intact which produces a complex polysaccharide structure (Ma et al., 2013). Organic acid extracted pectin has high emulsifying properties compared with other methods and achieves emulsion activity between 35.2% and 40.1% and stability between 62.1% and 79.4%, respectively (Ma et al., 2013). Organic acids function as environmentally friendly extraction methods which reduce chemical waste output while preserving pectin properties. As the organic acids shows promising sustainable production than the mineral acid, it's requires additional development to more economical viable and scalable.

Subcritical water extraction (SWE)

Subcritical water is defined as liquid high-pressure water, which can reach temperatures exceeding its boiling point but maintains its liquid state. The extraction method employing subcritical water conditions operates under the names subcritical water extraction (SWE) and pressurized hot water extraction (PHWE) and superheated water extraction (SHWE) (Zakaria and Kamal, 2016). The method, also known as accelerated solvent extraction (ASE), becomes known when researchers use any solvent other than water as the subcritical solvent. (Hawthorne et al., 2000; Ibañez et al., 2003). This can explain the use of different names for similar techniques in food and environmental science studies. The increased temperature of subcritical water extraction is a source of enhanced diffusion, reducing surface tension and viscosity and increasing vapor pressure and mass transfer capabilities. Moreover, water properties such as dielectric constant change significantly under these conditions, for example drops from about 79 at 25 °C to 43 at 160 °C and further down to 33 at 200 °C. (Azmir et al., 2013; Zakaria and Kamal, 2016). Water properties are transformed through subcritical conditions which enables better extraction of ionic and non-ionic compounds making it an effective solvent for multiple applications (Brunner, 2009; Chen et al., 2015b; Ueno et al., 2008). Guo et al. (2014) explored innovative techniques for pectin extraction, including SWE. Their findings revealed the smallest particle size of pectin

obtained through SWE and formation of stable emulsions and the intact esterification degree and galacturonic acid content of pectin (Guo et al., 2014). The pectin characteristics undergo significant changes through subcritical water extraction (SWE) affecting yield quantity and purity level and functional properties. In addition to general SWE studies, this research highlights how the chemical composition of SBP influences extraction results. The extraction conditions including temperature and time duration serve as primary factors for producing high-quality final products.

Research has established that performing SWE at 120–130 °C for 20 min produces high pectin yields from the sugar beet pulp while maintaining minimal degradation through an efficient process (Peighambardoust et al., 2021; Piñkowska et al., 2021). The SWE extraction method achieved extraction yields of 20.65%, which matched the conventional extraction method (CE at 20.38%) while requiring only 20 min instead of the standard 4 h extraction time using the SBP (Peighambardoust et al., 2021) (Table 3). The efficiency of SWE demonstrates its potential as an industrial pectin production method which delivers rapid processing alongside superior product quality. Pectin extracted from SWE of SBP contained more galacturonic acid and higher methylation, acetylation and ferulic acid content than CE but lower molecular weight (Peighambardoust et al., 2021). The advanced pectin extraction process produced structural modifications, which resulted in modified characteristics. Consequently, the Newtonian behavior of SWE-derived pectin was also demonstrated at lower concentrations which provided stable viscosity under different conditions thus making it suitable for applications with predictable rheological properties (Peighambardoust et al., 2021). The process affected starch gelatinization by decreasing pasting properties and increasing enthalpy change (ΔH) which offers potential benefits for food product development (Peighambardoust et al., 2021). The SWE treatment of sugar beet pulp at elevated temperatures results in hemicellulose hydrolysis, which produces uronic acids and monosaccharides while preserving most cellulose and lignin and protein structures in the extracted residual material (Piñkowska et al., 2021). The results of the study revealed that SWE extraction techniques produced twice as much output as traditional CE extraction

Table 3 Overview of hydrothermal and high-pressure extraction parameters and their effects on pectin yield from sugar beet pulp.

Extraction method	Extraction temperature (°C)	Pressure (MPa)	Holding time (min)	Acid addition	Pectin yield (%)	Reference
Hydrothermal	120	N/A	20	Yes (HCl)	13.63 ± 0.5	(Piñkowska et al., 2021)
Conventional extraction (CE)	80–90	N/A	180–300	Yes (HCl)	6.43 ± 0.07	(Kaya et al., 2021)
HHPE (with acid)	40, 80–90	250–450	5	Yes (HCl)	12.09 ± 0.11	(Kaya et al., 2021)
HHPE (without acid)	40, 80–90	250–450	5	No	Not specified	(Kaya et al., 2021)

techniques (Kaya et al., 2021) (Table 3). The efficiency of pectin extraction was enhanced by the combination of SWE with acid treatment methods, without major chemical properties change. The extraction process through SWE decreased the degree of esterification while slightly reducing the galacturonic acid content but the extracted pectin maintained food-grade quality (Kaya et al., 2021).

In general, SWE offers innovative and eco-friendly approaches for pectin extraction from sugar beet pulp. The SWE extraction process enables the rapid and efficient production of pectin with better chemical composition with minimal acid chemicals and delivering higher extraction yields without affecting pectin functional properties. The developed methods show promising industrial applications which will lead to sustainable pectin production methods. However, there are some drawbacks to use the SWE in industries where if the process conditions are not carefully controlled, subcritical water extraction can lead to unwanted hydrolysis of the pectin chain, which can be an issue if preservation of its structure is the goal (Khajavi et al., 2005). Another potential drawback is the high implementation cost, which may reduce the attractiveness of this method for large-scale pectin production.

Microwave assisted extraction (MAE)

Microwaves function as electromagnetic waves which operate within the frequency range from 300 MHz to 300 GHz for communication and energy transfer purposes. Commercial MW applications function at 0.915 and 2.450 GHz frequencies while domestic microwave devices operate at 2.450 GHz (Letellier and Budzinski, 1999; Venkatesh and Raghavan, 2004). During material interaction MWs generate thermal energy by creating chaotic polar molecule rotation as long as the material absorbs some of the radiated power. The dissipation factor ($\tan \delta$) determines the material absorption because it depends on the dielectric constant (ϵ') and dielectric loss factor (ϵ'') which is shown in the Eq. (3): (Venkatesh and Raghavan, 2004).

$$\tan \delta = \frac{\epsilon''}{\epsilon'} \quad (3)$$

The temperature distribution during MW heating remains uniform, because the process eliminates thermal gradients. (Venkatesh and Raghavan, 2004). The mechanisms of energy transfer include both dipole rotation which causes polar molecules to swiftly align with electric fields and ionic conduction which enables charged ions to move throughout the solvent (Routray and Orsat, 2012). MW heating technology provides efficient and effective operation for pectin extraction processes because of its properties.

The extraction of pectin through microwave techniques depends on several key factors which include solvent

characteristics like pH and volume and microwave power and temperature and plant material properties including moisture content and particle size. Water-rich materials heat up rapidly in microwaves due to efficient absorption of microwave energy by water molecules, which leads to rapid extraction processes (Venkatesh and Raghavan, 2004). The extraction process is dependent on two primary microwave system types, which include atmospheric-pressure monomode setups for safe open-environment work (Letellier and Budzinski, 1999) and pressure-controlled multimode systems extracting pectin from sugar beet at 60 °C under 30 psi conditions within minutes (Fishman et al., 2008). Multimode systems receive more research attention but their pressurized operation requires specialized handling to prevent safety incidents (Leonelli et al., 2012). The dielectric properties of the solvent control pectin release due to the transformation of microwave energy into heat when acidified water with its polar molecules and ionic conductivity is used (Fishman et al., 2006). The initial use of high microwave power generates higher yield due to reduces solvent viscosity and makes pectin more soluble (Maran et al., 2013; Wang et al., 2007). However, extended heating at high power levels leads to pectin breakdown similar to conventional extraction methods (Routray and Orsat, 2012). The selection of appropriate microwave power settings enables faster heating times that avoid thermal degradation especially when working with closed systems that reach temperatures above water boiling point (Fishman et al., 2006). The extraction duration displays an identical pattern where longer contact time leads to increased yields until it reaches a point where quality deterioration surpasses the extraction benefits. The optimal efficiency and pectin preservation requires a balanced approach between selection of the solvent and microwave settings and extraction time according to the research showing prolonged heat and excessive power can diminish yields. The optimal balance between microwave exposure time and extraction conditions requires careful optimization as it determines the degree to which microwaves enhance pectin extraction without damage its chemical structure. (Maran et al., 2015). According to research, pectin extraction from sugar beet pulp through MAE techniques achieves results in 10-min periods while conventional heating methods require between 120 min at atmospheric pressure or extend through various hours of standard processing (Fishman et al., 2008; Mao et al., 2019). The molecular weight of pectin extracted with MAE ranges from 532,000 to 1.2 million Da and exceeds the weights achieved through conventional extraction procedures (Fishman et al., 2008). Table S1 describes the pectin yields extracted from sugar beet pulp using MAE under varying conditions of time (3–20 min), temperature (60 °C), and pressure (25–75 psi). The table provides

a concise overview of how these extraction parameters influence the recovery of pectin from the sugar beet pulp (Table S1). This section consolidates essential characteristics that affect MAE effectiveness specifically for SBP, providing a distinctive comparative dataset valuable for industrial scaling initiatives.

MAE extraction techniques are known to be effective for protecting pectin macromolecules from degradation by minimising structural damage. In comparison to pectin obtained through standard extraction approaches, pectin extraction via MAE results in structural features different due to pectin forms a molecular distribution containing two distinct elements during MAE processing which include spherical high weight particles alongside coiled low-weight structures. MAE processing enables the generation of network structures that provide an open framework for functional enhancement, e.g., emulsification performance and viscosity control. (Fishman et al., 2008). The extraction method of pectin using MAE responds to changes in both pH value and conditions of the solvent solution. Lower pH conditions (pH 1) produce pectinic acids containing primarily homogalacturonan (HG) structures and large amounts of galacturonic acid (859.9 mg/g AIS), but alkaline conditions (pH 13) result in rhamnogalacturonan-I (RG-I) enriched pectin with strong emulsification properties (Mao et al., 2019). The pressurized microwave-assisted hydrothermal extraction (MAHE) method demonstrated effective extraction of RG-I pectin from a short treatment time of 10 min at 130 °C under pressure leading to comparable output to traditional alkaline extraction (Mao et al., 2019). As a result of MAE treatment, pectin undergoes changes in its physical and chemical characteristics. Research showed that pectin extracted through MAE yields more illuminated product appearance than conventional extraction methods making it appropriate for food color applications (Jafarzadeh-Moghaddam et al., 2021b). The extracted pectin features superior viscosity properties that enhance solution thickening abilities (Jafarzadeh-Moghaddam et al., 2021b). MAE emerges as a promising extraction technology, delivering quick processing with possible functional and structural property upgrades to improve pectin efficiency. MAE demonstrates two main advantages; its shortened extraction duration and decreased requirement of extraction solvents. During the heating process of MAE, uniform temperature distribution is created which removes thermal variations from the extraction medium. Higher compactness defines the unit requirements needed for microwave-assisted extraction procedures. (Bagherian et al., 2011; Fishman et al., 1999). The wide acceptance demonstrates that MAE serves as an eco-friendly approach. The reduced water acid solution volume in MAE processes provides economic benefits, however the practice of using and discarding acidic solutions continues to cause equipment deterioration due to corrosion.

Ultrasound-assisted extraction (UAE)

UAE represents an advanced extraction method which employs high-frequency sound waves exceeding 20 kHz to optimize extraction procedures. Ultrasound propagation depends on the use of solid, liquid, or gaseous medium which produces in the process the expansion and compression patterns. The liquid medium triggers cyclic expansions and contractions, resulting in tiny bubbles that produce the effect of cavitation (Luque-Garcia and De Castro, 2003). The collapse of bubbles during UAE produces localized conditions of temperature (> 5000 °C) and pressure (1000 atm) that boost the efficiency of pectin extraction between solvent and plant material. (Azmir et al., 2013; Luque-Garcia and De Castro, 2003).

The UAE utilizes two main system implementations, bath-based ultrasonication and probe-based ultrasonication. Bath systems are the most widespread ultrasound devices, but their energy distribution becomes inconsistent with time while their power strength decreases which hampers extraction reliability. Ultrasound probes are shown to be more effective than bath systems because of their focused energy resulting in enhanced cavitation leading to greater extraction yields (Luque-Garcia and De Castro, 2003; Vinatoru, 2001). The extraction of pectin through laboratory-scale studies uses probe units primarily because they yield better results. UAE implementation requires attention to three essential areas: plant material properties consisting of moisture content and particle size, along with careful selection of solvent and precise control of ultrasound system operational parameters such as temperature, pressure and frequency and sonication time. The extraction efficiency is directly impacted by the solvent-to-biomass ratio because high solid content reduces ultrasound intensity (Wang and Weller, 2006). The number of studies on UAE pectin extraction techniques has risen as researchers gain deeper knowledge of ultrasound technology. A comparison between conventional heating extraction (CHE) and microwave-assisted extraction (MAE) alongside UAE showed intermittent sonication led to higher pectin recovery rates from grapefruit peels than continuous sonication (Bagherian et al., 2011). Sonication time of 25 min in combination with a 70 °C bath temperature was determined to impact the finest extraction outcomes for UAE but resulted in lower pectin yields than microwave extraction. Wang et al. (2015) demonstrated that pectin extraction from grapefruit peel through probe-based UAE generated 16% greater yield than conventional heating methods in addition to requiring 38% shorter extraction time (Wang et al., 2015). UAE extraction operated at lower temperatures to produce pectin with similar chemical composition to conventional heating extracted pectin while maintaining its color and preserving the original microstructure of the pectin. The findings establish UAE technology as a promising

technique for pectin extraction because it combines high efficiency with energy conservation while producing increased yields without affecting structure.

In order to enhance productivity, multi-advanced extraction methods integration has increasingly become the subject of recent studies. For sugar beet pulp extraction, researchers in China applied ultrasound-/microwave-assisted acid method technology which produced pectin with enhanced molecular weight of 636.20 kDa compared to conventional extraction methods yielding 295.95 kDa (Peng et al., 2015). This approach enhanced both extraction efficiency and pectin quality. The research study did not furnish adequate technical information regarding the ultrasonic approach employed.

The extraction method of UAE demonstrates multiple advantages which include shorter extraction periods together with decreased power needs and smaller solvent requirements (Azmir et al., 2013). Chemat et al. (2008) outlined multiple advantages of UAE in polysaccharide extraction including improved mixing and micro-mixing, enhanced heat and mass transfer, reduced thermal degradation, selective extraction, smaller equipment requirements, quicker process control responses, faster startup, superior production efficiency, and elimination of all unnecessary processing steps (Chemat et al., 2008). The use of ultrasonic energy in extraction processes comes with several limitations. The effectiveness of ultrasound waves is reduced by highly concentrated dispersions, which cause minimal solvent reduction (Wang and Weller, 2006). The efficacy of ultrasounds for pectin yield enhancement along with extraction speed depends on plant material type which may not demonstrate enhanced outcomes for certain biomass materials. The challenging part of extraction lies in the inconsistent delivery of ultrasound energy since wave intensity decreases with increasing distance from the emitter (Wang and Weller, 2006). However, despite existing technical obstacles, the optimized application of UAE has shown potential as an effective method for commercial pectin extraction. Table 4 summarizes the impact of various processing conditions on the yield of pectin extracted from sugar beet pulp. It compares microwave-assisted extraction (MAE), conventional-solvent extraction (CSE), microwave-assisted hydrothermal extraction (MAHE), and ultrasound-/microwave-assisted acid method (UMAAM), highlighting the yield achieved by each method (Table 4).

Comparative evaluation of extraction methods

The industrial application of sugar beet pulp extraction methods depends on their unique advantages and operational constraints. Conventional acid extraction (CAE) provides an easy operation and proven technology and produces dry matter yields between 20–26% with GalA content between

38–60% and DE values below 55% for industrial production of pectin (Huang et al., 2018; Lv et al., 2013). The CAE process requires long extraction periods up to 4 h at high temperatures between 80 and 95 °C and also acid neutralization and wastewater treatment processes (Huang et al., 2018). The production process produces large amounts of acidic waste while requiring large amounts of thermal energy which results in environmental problems and economic inefficiencies in current sustainability framework (Chandel et al., 2022). Despite its scalability, the use of strong acids such as HCl and H₂SO₄ not only increases corrosion risk but also causes partial depolymerization and loss of acetyl groups, resulting in pectin with reduced molecular weight and compromised functional performance (Huang et al., 2018; Lv et al., 2013).

The process of UAE successfully addresses multiple extraction problems by its ability to perform extractions within less than 30 min while using acoustic cavitation to enhance both diffusion and mass transfer (Jafarzadeh-Moghaddam et al., 2021a). Based on this research, the yields of UAE produced between 20–21% are comparable to or exceed the CAE results, with molecular weight at 268 kDa and viscosity levels maintained (Jafarzadeh-Moghaddam et al., 2021a). Furthermore, the energy intensity of UAE is significantly lower than that of conventional heating. However, implementation of ultrasonic equipment requires major financial expenses, because the process becomes harder to expand when waves spread irregularly and cavitation power weakens when operating with large volumes (Özer et al., 2025; Roobab et al., 2025). The application of industrial-scale continuous-flow sonochemical systems for fruit pectin processing has been proven, application to SBP remains largely at pilot scale.

Subcritical water extraction (SWE) is the most environmentally friendly method of extraction, where only pressure water (120–150 °C; 3–5 MPa) is used. It eliminates chemical waste, produces comparable extraction efficiency (20–21%), and produces elevated GalA content pectin (Peighambar-doust et al., 2021). Nonetheless, due to the pressure requirements and potential corrosion issues, SWE suffers from high equipment and maintenance costs. The energy input is moderate but the lower molecular weight of pectin derived from SWE (23 kDa) may limit its use in high-gel formulations (Mansor et al., 2025; Peighambar-doust et al., 2021). The process is scalable with modern continuous high-pressure reactors, yet its economic feasibility is viable only at large production scales (> 15,000 tons year⁻¹) (del Amo-Mateos et al., 2024). This zero-waste operation and absence of acid handling in SWE make it the most sustainable long-term solution despite mentioned limitations.

Hydrothermal extraction operates at similar temperature but lower pressures and provides a simpler and cleaner process without chemical additives (Kaya et al., 2021). It

Table 4 Comparative analysis of pectin extraction methods from sugar beet pulp, highlighting variations in process conditions, extraction yields, and quality parameters reported in different studies. The table summarizes key factors such as extraction technique, temperature, time, pH, along with resulting yield, degree of esterification, and galacturonic acid content. It provides an overview of how different extraction approaches influence pectin quality and recovery efficiency

References	Extraction method	Statistical analysis	Solid-to-liquid ratio	pH	Temperature (°C)	Time (min)	Yield (%) ± SD	GalA content (%) ± SD	Degree of esterification (%) ± SD	Molecular weight (kDa) ± SD	Energy intensity	Solvent/Chemical consumption
J. Concha Olmos & M. Zúñiga Hansen (2012)	Enzymatic	RE	1:10 (w/v)	4.8	50	450–1800	10.2–10.6 ± 0.2	69.1 ± 1.2	89.9 ± 2.1 (E1), 56.8 ± 1.8 (E2)	Not reported	Low (enzymatic, 50 °C)	Low (enzymes, water)
Kaya et al. (2021)	High Hydrostatic Pressure (HHP)	ANOVA	1:10–1:20 (w/v)	1.2 ± 0.1	80–90	180–300	6.4–12.2 ± 0.13	63.5–79.9 ± 2.1	17.5–48.2 ± 1.5	Not reported	High (250–450 MPa pressure)	High (acid, ethanol precipitation)
Mao et al. (2019)	Microwave-assisted (MAE) / Hydrothermal (MAHE)	RE	1:21.5 (g/mL)	1–13	90–190	10–120	5.6–25.3 ± 1.2	28.0–85.3 ± 3.2	Not reported	Not reported	High (microwave/hydrothermal)	Variable (pH dependent)
Peighambaridoust et al. (2021)	Subcritical water extraction (SWE)	ANOVA	1:30 (v/w)	N/A (water only)	130	20	20.7 ± 0.5	73.0 ± 1.98	84.2 ± 2.07	23.5 ± 0.4	High (130 °C, 10 MPa pressure)	Low (water only)
Jafarzadeh-Moghaddam et al. (2021)	Ultrasound-assisted extraction (UAE)	RSM, RE	1:20 (w/v)	1	55–76 (ambient + US)	10	20.85 ± 0.3	68.2 ± 1.5	57.0 ± 1.2	70–355 ± 15	Moderate (ultrasound energy)	High (acid, ethanol precipitation)
Guo et al. (2014)	Citric acid extraction	Not specified	1:20 (w/v)	1.5–2.0	75–85	120–180	8.7–21.6 ± 0.3	55.4–70.2 ± 1.3	37.9–48.0 ± 1.5	187–377 ± 12	Moderate (75–85 °C heating)	Moderate (citric acid)
Huang et al. (2017)	Acid extraction (HCl)	Not specified	1:20 (w/v)	1.5	90	120	15.8–20.5 ± 0.8	38.5–60.0 ± 2.0	Not reported	Not reported	Moderate (90 °C heating)	High (HCl, ethanol precipitation)
Lv et al. (2013)	Acid extraction (HCl)	RSM, RE	1:20 (w/v)	0.6–2.0	63.2–96.8	60–280	6.2–25.0 ± 1.1	Not reported	Not reported	Not reported	Moderate (heating)	High (HCl, ethanol precipitation)
Chen et al. (2015a, b)	Ultrasonic + Subcritical water	RSM, RE	1:82 (w/v)	N/A	120.72	30.49	24.63 ± 0.8	59.12 ± 0.50	55.20 ± 2.10	89.4 ± 3.2	High (120.72 °C, ultrasound)	Low (water, ethanol precipitation)
Pikowska et al. (2021)	Hydrothermal extraction	Triplate, ANOVA	Not specified	N/A	100–140	0–30	13.6 ± 0.8	47.9–50.9 ± 0.8	15.3–56.2 ± 1.8	Not Specify	High (100–140 °C)	Low (water only)
Foad et al. (2017)	High-voltage electrical discharges + Acid	ANOVA, and RE	1:20 (w/v)	1.5–7.0	90	60	42.6–53.4 ± 2.5	Not reported	Not reported	Not reported	Moderate (HVED + heating)	Moderate (acid, ethanol)

achieves reasonable yields (12–14%) with reduced water and energy consumption, but high temperatures (> 130 °C) often lead to degradation, dark coloration, and partial de-esterification (Kaya et al., 2021; Mansor et al., 2025; Piñowska et al., 2021). This method offers moderate energy demand, with low chemical reagents, which make it attractive to decentralized processing facilities, but consistent product quality remains a challenge.

In comparison with industrial scalability, CAE continues to dominate commercial production due to its technological maturity and low investment, although with high environmental and operational costs. The UAE provides an attractive compromise between efficiency, product quality and environmental responsibility, but requires technical solutions for large-scale energy uniformity. The sustainability measures of SWE and hydrothermal techniques are highest but involve considerable capital expenditure, and may yield pectin with lower molecular weights.

In conclusion, the provisional production of pectin from sugar beet pulp will continue to use traditional acid extraction methods but future production will focus on creating hybrid and green extraction systems that combine ultrasonic and hydrothermal and subcritical processes with energy recovery and wastewater recycling systems. The UAE is the most balanced near-term solution for improving productivity and product functionality, whereas SWE is the most sustainable long-term alternative for industrial biorefineries.

Future perspectives

This review is the introductory study that combines a technological and functional examination of pectin derived from the SBP with modern extraction approaches that emphasize sustainability and industrial feasibility. The research unites multiple studies about structural-performance-functional relationships to deliver vital data which helps researchers and manufacturers assess pectin from SBP as a potential material. The worldwide demand for pectin and hydrocolloids continues to expand at a fast pace because these substances find uses in various industrial sectors including food and non-food applications. The conventional acid-based techniques for pectin extraction need enhancement to fulfil the market's needs through enhanced production and established quality control techniques. Studies has been carried out in innovative extraction techniques, include microwave, ultrasonic, subcritical water, and enzyme-assisted methods, which could improve laboratory-scale extraction through improved yield and product quality. The integration of scale-up methods into continuous industrial operations remains challenging according to recent studies which emphasizes the necessity for laboratory-to-industrial-scale research. The extraction of pectin from sugar beet pulp serves as a renewable pectin material which substitutes conventional

fruit-derived pectin but faces structural challenges that lower galacturonic acid content and affect its gelation and emulsification properties.

In the conclusion, the environmental characteristics and functional properties of sugar beet pulp pectin could improve through newly developed extraction methods based on eco-friendly solvents along with enzymatic transformations and membrane filtration integrated with high hydrostatic pressure systems. The integration of optimized extraction parameters with scalability methods will drive industry stakeholders to select superior extraction methods for sugar beet pulp which will establish it as a primary sustainable biopolymer in circular economy.

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Declarations

Conflict of interest There is no conflict of Interest.

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