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Green Extraction of Pectin from Orange Peel Waste: A Comparative Study of Ohmic Heating and Conventional Heating Methods

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ABSTRACT

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Conventional methods for pectin extraction from citrus waste are associated with several drawbacks, including long extraction times, high energy consumption, and partial degradation of pectin structure. In the present study, pectin extraction from orange peel waste using ohmic heating as a green and efficient technology was investigated and compared with conventional heating extraction. Pectin extraction was carried out under optimal ohmic heating conditions (voltage gradient of 15 V/cm, temperature of 90 °C, time of 30 min) and conventional heating (temperature of 90 °C, time of 90 min). The extracted pectin was evaluated in terms of extraction yield, degree of esterification, water holding capacity, oil holding capacity, color parameters, chemical structure (FTIR), and surface morphology (SEM). The results showed that ohmic heating significantly increased the extraction yield (15.27% vs. 12.54%). The degree of esterification of pectin extracted by ohmic heating (62.40%) was significantly higher than that obtained by conventional heating (51.45%), placing it in the high methoxyl pectin group. Water holding capacity (7.11 g/g) and oil holding capacity (6.23 g/g) were approximately 18% and 26% higher in the ohmic heating method compared to the conventional method, respectively. Pectin extracted by ohmic heating exhibited higher lightness and lower redness and yellowness values. FTIR analysis confirmed better preservation of the pectin chemical structure in the ohmic heating method, and SEM images revealed a more uniform structure, finer particles, and a smoother surface. In conclusion, ohmic heating, as a green, efficient, and energy-saving technology, exhibits great potential to replace conventional methods for pectin extraction from citrus waste, offering a sustainable and value-added approach for the management of citrus processing waste.

1- INTRODUCTION

Citrus industry waste is one of the major environmental and economic challenges worldwide. The product of citrus processing is mainly fruit juice and concentrate, and about half of the citrus entering the factories is discarded as waste (including peel, pulp, seeds, and remaining tissues) [1]. By optimally utilizing citrus waste in the processing industries, significant amounts of pectin, edible fiber, essential oil, and citrus seed oil can be produced annually, and in addition to creating high economic added value, environmental pollution can also be prevented [2]. Among the valuable compounds that can be extracted from citrus waste, pectin is of particular importance due to its unique functional properties. Pectin is an acidic hydrocolloid from the polysaccharide family found in plant cell walls. Structurally, pectin is a complex heterogeneous polysaccharide composed mainly of homogalacturonan (HG), rhamnogalacturonan I (RG-I), and rhamnogalacturonan II (RG-II) moieties [3]. The structural diversity of pectin confers a wide range of functional properties, including gelation, viscosity enhancement, and colloidal stabilization [4]. For this reason, pectin is widely used as a gelling, stabilizing, and thickening agent in the food, cosmetic, and pharmaceutical industries [5, 6]. Pectin is also used as an effective biopolymer in the production of edible films and coatings due to its environmental compatibility, nontoxicity, compressibility, biodegradability, high viscosity, gel state, oxygen impermeable, and high volatile storage capacity [3]. In industry, pectin is traditionally extracted using dilute mineral acids (pH range 1.5–3.0) at high temperatures (70–100 °C) [3]. However, conventional extraction methods are associated with several problems, including environmental issues caused by the use of mineral acids, degradation of pectin structure due to high temperature and long time, and high energy consumption [7]. To overcome the limitations of conventional extraction methods, researchers are looking into the use of organic acids (such as citric acid) and the application of novel extraction methods, including ultrasonic extraction, enzymatic extraction, and ohmic heating extraction. In recent years, novel pectin extraction methods based on physical fields have been widely investigated. Among these methods, ultrasonically assisted extraction (UAE) has been

proven to be an efficient and economical technology for pectin extraction [3]. Microwave-assisted extraction [8], high-pressure extraction [8], and medium-electric field extraction [9] have also been studied for pectin extraction. One of the promising methods in this field is ohmic heating extraction. Ohmic heating is a volumetric heating method in which heat is generated uniformly inside the material due to the ohmic effect when an electric current passes through the material [1]. This method has significant advantages such as rapid and uniform heating, energy saving, and reduced process time [6]. In addition, the non-thermal effect of the electric field causes the destruction of plant tissues, leading to increased extraction efficiency [10]. Several studies have reported that ohmic heating has been used to extract bioactive compounds including essential oils [10] and phenolic compounds [11] from various plant materials. However, to the best of the authors' knowledge, limited studies have been conducted to optimize pectin extraction using ohmic heating and compare it with the conventional method [1, 7].

Considering the above-mentioned materials and the superiority of modern extraction methods over traditional methods in terms of increasing efficiency, reducing process time, maintaining the quality of the final product, and environmental considerations, the aim of the present study is to compare the efficiency of two methods, ohmic heating and conventional heating, in extracting pectin from orange peel waste (Thomson Novel cultivar). In this study, pectin extracted by both methods was evaluated and compared in terms of extraction efficiency, degree of esterification, and functional properties including water and oil retention capacity. It is expected that the results of this study can clearly demonstrate the advantages of the ohmic heating method as a green, energy-efficient, and efficient technology compared to the traditional method and provide a sustainable and value-added approach for managing wastes in citrus processing industries.

2- Materials and methods

1-2 Raw materials

Citrus waste (orange, Thomson Novel variety) was obtained from the agricultural cooperative of Ramsar Citrus Gardeners-Kowsar Agricultural and Industrial Factories. The samples were dried in a vacuum oven at 45°C for 50 minutes, then powdered and stored at 4°C under light-free conditions until the experiment [1]. All chemicals used in this study were obtained from

Merck, Germany and were of laboratory purity. Deionized water with a pH adjusted to 1.5 using 0.5 M hydrochloric acid was used as the extraction solvent.

2-2 Pectin extraction by conventional heating method

Pectin extraction was performed by conventional heating method based on the method of Wang et al. (2016) with some modifications. 3 g of orange peel waste powder was mixed with 150 ml of extraction solvent (0.1 N hydrochloric acid, pH 1.5). The resulting mixture was placed in a hot water bath at 80°C for 90 min [12]. After extraction, the mixture was cooled to room temperature (25°C) and then centrifuged at $9000 \times g$ for 20 min at 4°C. The resulting solution was collected and concentrated to one-quarter of the original volume. Then, the pH of the solution was adjusted to 2 using 0.1 N sodium hydroxide and pectin was precipitated by adding twice as much 96% ethanol. The sample was allowed to rest for 12 h to form two phases. The precipitated portion was separated by filtration and washed twice with 60% ethanol, twice with 70% ethanol, and finally once with 96% ethanol. The resulting pectin was then pressed to remove alcohol and dried in a vacuum oven at 40°C until constant weight was reached [1, 12]. The resulting pectin was stored at -20°C in the dark.

3.2 Pectin extraction by ohmic heating method

Pectin extraction was performed using an ohmic heating system (frequency 50 Hz) based on the results of previous studies and preliminary experiments. The solid-liquid ratio was fixed at 1:20 g/ml and the initial pH of the solution was adjusted to 2 by adding hydrochloric acid. The sample (30 ml) was transferred to a Pyrex glass cylindrical chamber with two platinum electrodes 6.6 cm apart and 5 cm in diameter placed in parallel inside. The chamber was placed on a magnetic stirrer and the temperature of the sample near the cell wall was continuously measured with a K-type thermocouple. Extraction was performed under optimal conditions including a voltage gradient of 15 V/cm, a temperature of 90 °C and a time of 30 min.[1]. After extraction, the solution was filtered and the precipitation, washing, and drying steps were performed similar to the conventional heating method.

4.2 Efficiency measurement

The pectin yield was obtained by dividing the amount of extracted dry pectin by the amount of initial dry matter [1].

$100 \times (\text{weight of citrus waste powder/dried weight of pectin}) = \text{extraction efficiency}$

5.2 Degree of esterification

20 mg of pectin sample was moistened with ethanol. Then, it was dissolved in 20 ml of distilled water at 80 °C.-The solution was left to stand for 1 hour, then 5 drops of phenolphthalein reagent were added to the solution and titrated with 0.1 N sodium hydroxide (V1), then 10 ml of 0.5 N sodium hydroxide was added to the solution for hydrolysis, the Erlenmeyer flask was closed and stirred on a hot plate for 2 hours at room temperature. Next, 10 ml of 0.5 N hydrochloric acid was added to the solution and titration was continued until a pink color appeared with 0.5 N sodium hydroxide (V2). The degree of esterification was obtained from the following equation [1, 13].

$$DE = V2 / V2 + V1 \times 100$$

6.2 Water Holding Capacity (WHC) and Oil Holding Capacity (OHC)

To measure the water and oil holding capacity, 1 g of pectin was added to 10 ml of distilled water and sunflower oil (density 0.9 g/ml) separately. The samples were stirred with a magnetic stirrer for 1 min and then centrifuged for 30 min using a laboratory centrifuge (model 320 Hettich Universal, made in Germany) with a maximum centrifugal force of $3000 \times g$. After centrifugation, the supernatant (excess water or oil) was completely removed and the supernatant (water or oil-absorbing pectin) was weighed. The water holding capacity and oil holding capacity were calculated and reported as grams of water or oil held by 1 g of pectin [1, 13].

7.2 Colorimetry

The color parameters of pectin including L (lightness), a (redness) and b (yellowness) were measured using a colorimeter (HunterLab ColorFlex EZ model, USA). The instrument was calibrated using a standard white plate and each sample was measured in triplicate [6].

8.2 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectroscopy was used to identify the functional groups and confirm the chemical structure of pectin. Spectra in the range of 400 to 4000 cm^{-1} It was recorded using an FTIR instrument (Bruker Tensor 27 model, Germany). To prepare the tablets, 2 mg of pectin sample was mixed with 200 mg of potassium bromide (KBr) and pressed under a pressure of 10 tons to form

transparent tablets. The spectra were recorded with a resolution of 4 cm^{-1} were recorded [6].

9-2 Scanning Electron Microscope (SEM)

To investigate the surface morphology of pectin particles, a scanning electron microscope (TESCAN MIRA3 model, Czech Republic) was used. The pectin powder sample was attached to an aluminum stub and coated with a thin layer of gold (10-15 nm thick) using a sputter coater. Images were obtained at an accelerating voltage of 15 kV and different magnifications [1].

10.2 Statistical evaluation

All experiments were performed in three independent replicates and the results were averaged. $\pm$ Standard deviation was reported. The normality of the data was checked using the Shapiro–Wilk test. To compare the mean data obtained from the two extraction methods, an independent t-test was used at a significance level of 5% ($P < 0.05$). Statistical analysis of the data was performed using SPSS version 18 software.

3- Results and discussion

3.1 Pectin extraction efficiency

Extraction efficiency is one of the most important economic and technical indicators in the process of extracting bioactive compounds from food industry waste, as it has a direct impact on production costs and commercialization of the final product [1]. The results of the present study showed (Table 1) that the extraction efficiency of pectin from orange peel waste using the ohmic heating method was 15.27% (based on dry weight), while this value was 12.54% in the conventional heating method. These results indicate that the ohmic heating method increased the extraction efficiency by about 21.8% compared to the conventional method ($P < 0.05$). Unlike conventional heating methods in which heat is transferred from the surface to the center of the sample gradually and with a temperature gradient, the ohmic heating method is a volumetric heating method. In this method, an electric current passes directly through the sample and, based on the electrical resistance of the material, heat is generated simultaneously and uniformly at all points of the sample [10]. This feature allows the plant cell wall (including skin, pulp, and lignocellulosic tissues) to be more effectively degraded and intracellular compounds, including protopectin, to be easily

released into the extraction solvent [14]. In contrast, in the conventional heating method, gradual heating begins from the outer surface of the sample and the temperature may not be the same at different points of the sample, which can lead to incomplete extraction of target compounds and reduced efficiency [6]. One of the most important advantages of the ohmic heating method that distinguishes it from conventional heating methods is the non-thermal effect of the electric field. Numerous studies have shown that applying an electric field during the extraction process, even at low temperatures, causes the formation of tiny holes in the cell membrane and increases its permeability [15]. This phenomenon, known as electroporation¹ It is known that this leads to structural degradation of the cell wall and more effective release of intracellular compounds without the need for very high temperatures [15]. As a result, heat-sensitive compounds such as pectin are less susceptible to thermal degradation and the extraction efficiency is increased [10]. The findings of the present study are in complete agreement with the results of other researchers in this field. Saberian et al. (2017) reported in a study on the extraction of pectin from orange juice waste that the extraction efficiency with the ohmic heating method (14.32 g/100 g dry matter) was significantly higher than that with the conventional heating method (13.53 g/100 g dry matter), and they attributed this superiority to faster and more uniform heating as well as the non-thermal effect of the electric field [1]. In another study on the extraction of pectin from apple waste by ohmic heating method, Wang et al. (2025) reported that the ohmic heating method with an efficiency of 25.02% showed an increase of 19.87% compared to the conventional method (20.8%) and also reduced energy consumption by 37.53% [6]. Razak et al. (2025) also reported a significant increase in the efficiency from 39.77% in the conventional method to 58.590% in the ohmic heating method in the extraction of pectin from Bintangor orange peel, indicating a significant effect of the type of raw material on the improvement in efficiency [7]. This variation in results indicates that the extent of the increase in extraction efficiency depends on several factors, including the type of raw material (ordinary orange peel vs. Bintangor orange or apple waste), extraction conditions (temperature,

¹-Electroporation

time, pH, electric field intensity), and the cell wall structure of the plant material [6].

3-2 Degree of esterification

The degree of esterification is one of the most important quality parameters of pectin, which directly affects its functional properties, including solubility, gelation behavior, pH stability, and emulsifying ability. The degree of esterification represents the percentage of esterified carboxyl groups in the polygalacturonic chain of pectin, and according to international standards, pectins are divided into two main categories: high-methoxyl pectin with a degree of esterification of more than 50%, which forms gels in the presence of sugar and acid, and low-methoxyl pectin with a degree of esterification of less than 50%, which requires calcium ions for gelation [16]. The results of the present study showed (Table 1) that the degree of esterification of pectin extracted from orange peel waste using the ohmic heating method was 62.40%, while this value was 51.45% obtained using the conventional heating method. Both values are higher than 50%, so the pectin extracted by both methods falls into the high-methoxyl pectin group [16]. However, the results show that the ohmic heating method better preserved the methoxyl groups in the pectin structure and thus produced a higher degree of esterification (an increase of about 21%) than the conventional method ($P < 0.05$). This significant difference can be attributed to several factors. The conventional heating method, due to the longer extraction time (90 min versus 30 min in the ohmic method) and the gradual heating of the surface, causes the methoxyl groups in the polygalacturonic chain of pectin to be more exposed to alkaline or acidic hydrolysis and removed [6]. In contrast, the ohmic heating method, with its rapid and uniform heating and shorter extraction time, provides less opportunity for the hydrolysis of methoxyl groups, and thus the original structure of pectin is better preserved [1]. In addition, the non-thermal effect of the electric field in the ohmic heating method may facilitate the selective extraction of pectin with a higher degree of esterification by causing local changes in the cell wall structure [10]. The findings of the present study are in complete agreement with the results of other researchers in this field. Saberian et al. (2017) reported in their study on the extraction of pectin from orange juice waste that all pectins extracted by the ohmic heating method had a high degree of esterification, ranging from 53 to 78%, indicating

that the ohmic heating method does not damage the pectin structure [1]. In another study conducted on pectin extracted from the peel of Navel orange using different extraction methods, Wang et al. (2023) reported that the degree of esterification of the extracted pectin ranged from 59.7 to 63.5%, which is quite comparable to the results of the present study (62.40%) [17]. Also, in a study of pectin extraction from apple waste by ohmic heating method, Wang et al. (2025) showed that pectin extracted by ohmic method had a higher degree of esterification than the conventional method, which they attributed to better structure preservation due to shorter extraction time [6]. Razak et al. (2025) also reported that the degree of esterification of pectin extracted by ohmic method was higher than the conventional method in the extraction of pectin from Bintangor orange peel, and they attributed this difference to less destruction of polysaccharide chains due to shorter extraction time [7]. Tsirigotis-Maniecka et al. (2024) also emphasized that pectins with a high degree of esterification have a greater tendency to interact with hydrophobic chains due to methyl ester groups and act as natural emulsifiers in the food industry [16]. Overall, the degree of esterification of 62.40% of pectin extracted by the ohmic heating method in the present study indicates the desirable quality of this product and places it in the group of high-methoxyl pectins, which are very suitable for use in the food industry as gelling agents, stabilizers, and emulsifiers. The superiority of the ohmic heating method over the conventional method in maintaining a higher degree of esterification is considered one of the key advantages of this green technology in extracting pectin from citrus waste [1, 6].

3-3 Water and oil storage capacity

Water holding capacity and oil holding capacity are among the most important functional indices of pectin, which determine its application in the food industry as a gelling agent, emulsifier, stabilizer, and texturizer. These properties are directly influenced by factors such as molecular weight, degree of esterification, chemical structure, and extraction method [18]. The results of the present study showed (Table 1) that pectin extracted from orange peel waste by ohmic heating had a water holding capacity of 11.7 g water/g pectin and an oil holding capacity of 23.6 g oil/g pectin, while these values were 01.6 g water/g pectin and 93.4 g oil/g pectin,

respectively, for the conventional heating method. These results indicate that the ohmic heating method significantly increased the water holding capacity (about 18%) and oil holding capacity (about 26%) compared to the conventional method. (0.05/0.05 > P). These values indicate the high ability of the pectin extracted by the ohmic method to absorb and retain water and oil phases, which is very important for applications in low-fat food products, sauces, baked goods and reformulated meat products [19]. The significant difference in water and oil retention capacity between the two extraction methods can be attributed to several factors. The conventional heating method, due to the longer extraction time (90 min versus 30 min in the ohmic method) and gradual heating, causes partial destruction of the polysaccharide chains and a decrease in the number of free hydroxyl groups in the pectin structure, which reduces the ability to form hydrogen bonds with water molecules [6]. In contrast, the ohmic heating method, with its rapid and uniform heating and shorter extraction time, better preserves the polysaccharide structure and leaves more hydroxyl groups available for interaction with water [1]. Regarding oil retention capacity, the significant increase in the ohmic method (23.6 g/g vs. 93.4 g/g in the conventional method) can be attributed to the higher degree of esterification of the pectin extracted by the ohmic method (40.62% vs. 45.51%). Pectins with a high degree of esterification, due to the presence of methyl ester groups in their structure, have a greater tendency to interact with the hydrophobic chains of the oil and prevent phase separation [16]. The findings of the present study are in complete

agreement with the results of other researchers in this field. Saberian et al. (2017) reported favorable performance properties for the extracted pectin in their study on the extraction of pectin from orange waste by the ohmic heating method and emphasized that the ohmic heating method leads to the production of pectin with high water and oil retention capacity due to the preservation of the polysaccharide structure [1]. The high water holding capacity of pectin extracted by the ohmic heating method (11.7 g/g) can be attributed to the better preservation of polysaccharide chains and free hydroxyl groups in the pectin structure, which are able to absorb and retain water molecules through hydrogen bonds [18]. Also, the higher oil holding capacity in the ohmic method (23.6 g/g versus 93.4 g/g in the conventional method) is due to the higher degree of esterification and better preservation of methyl ester groups that interact with the hydrophobic oil chains and prevent phase separation [16]. In contrast, the lower values of water and oil holding capacity in the conventional method indicate a greater degradation of the pectin structure due to the longer extraction time and gradual heating, which leads to a reduction of functional groups effective in water and oil absorption [6]. These characteristics make the pectin extracted by the Ohmic method in the present study have high potential for use in the formulation of low-fat food products (such as salad dressings, low-fat mayonnaise, and reformulated meat products) and also as an emulsion stabilizer in the dairy and cosmetic-healthcare industries [18, 19].

Table 1. Comparison of extraction yield, degree of esterification, and functional properties of pectin extracted by ohmic heating and conventional heating methods

Parameter	Conventional heating (CHE)	Ohmic heating (OHE)	Improvement (OHE vs. CHE)
Extraction yield (%)	12.54 ± 0.89 ^b	15.27 ± 0.37 ^a	~21.8%
Degree of esterification (%)	51.45 ± 2.15 ^b	62.40 ± 2.43 ^a	~21.3%

Water holding capacity (g/g)	6.01 ± 0.18^b	7.11 ± 0.25^a	~18.3%
Oil holding capacity (g/g)	4.93 ± 0.15^b	6.23 ± 0.19^a	~26.4%

Note: Different superscript letters (a, b) in the same row indicate significant differences ($p < 0.05$). Values are expressed as mean $\pm$ standard deviation.

4.3 Color indicators

Color indices are one of the important quality criteria in the evaluation of pectin extracted from citrus waste, because the color of the final product directly affects consumer acceptance and its industrial applications [17]. The color parameters measured include brightness (L), redness (a), and yellowness (b), which are defined in the CIE-Lab color system. The results of the present study showed (Table 2) that pectin extracted by ohmic heating had brightness (L) values of 11.83, redness (a) of 1.58, and yellowness (b) of 13.87, while these values were 44.78 (brightness), 22.3 (redness), and 96.179 (yellowness) for the conventional heating method, respectively ($P < 0.05$). These results indicate that the ohmic heating method resulted in the production of pectin with higher brightness, lower redness, and lower yellowness compared to the conventional method. The significant increase in brightness in pectin extracted by the ohmic heating method (11.83 vs. 44.78) can be attributed to several factors. The conventional heating method, due to the longer extraction time (90 min vs. 30 min in the ohmic method) and gradual heating, causes further degradation and oxidation of natural pigments present in orange peel (such as carotenoids and flavonoids), leading to a darker and less bright final product [12]. In contrast, the ohmic heating method, with its rapid and uniform heating and shorter extraction time, minimizes the degradation of natural pigments, resulting in a product with higher brightness and more desirable appearance [1]. The significant reduction in the redness index (a) in the ohmic method (1.58 vs. 3.22) and the reduction in the yellowness index (b) (13.87 vs. 17.96) also confirm better preservation of pigments and prevention of the formation of dark colored compounds resulting from browning and oxidation reactions during the extraction process

[17]. It is noteworthy that the difference in the yellowness index (b) between the two methods indicates the high sensitivity of the yellow compounds of orange peel to extraction time and conditions, and the ohmic heating method has produced a product with a brighter and more desirable color by significantly reducing this parameter. The findings of the present study are in complete agreement with the results of other researchers in this field. Wang et al. (2023) reported in their study on the extraction of pectin from novel orange peel using different extraction methods that extraction methods with shorter time and lower temperature resulted in the production of pectin with higher brightness and lower a and b values. In another study conducted on the extraction of pectin from apple waste using the ohmic heating method [17], Wang et al. (2025) showed that pectin extracted by the ohmic method has a brighter and more desirable color than the conventional method, and attributed this difference to the reduction in thermal degradation of pigments due to the shorter extraction time [6]. Saberian et al. (2017) also emphasized in their study on the extraction of pectin from orange juice waste by ohmic heating method that the ohmic heating method produces a product with better appearance quality and brighter color due to rapid and uniform heating [1]. Razak et al. (2025) also reported in the extraction of pectin from Bintangor orange peel that the ohmic heating method significantly improved the color indices and produced pectin with a brighter and more desirable color [7]. From an application perspective, the bright and desirable color of pectin extracted by ohmic heating (high L and low a and b) is an important competitive advantage for applications in the food industry, as products with dark color are usually less popular with consumers and their application is limited to products such as jellies, jams, dairy desserts and meat products [17]. Light-colored pectin can be used as a gelling and

stabilizing agent without causing undesirable color changes in the final product [16]. Therefore, the superiority of ohmic heating in

producing pectin with better color quality is another key advantage of this green technology in extracting pectin from citrus waste [1, 6].

Table 2. Color parameters of pectin extracted by ohmic heating and conventional heating methods

Parameter	Conventional heating (CHE)	Ohmic heating (OHE)
Lightness (L*)	78.44 ± 1.99 ^b	83.11 ± 2.25 ^a
Redness (a*)	3.22 ± 0.23 ^a	1.58 ± 0.12 ^b
Yellowness (b*)	17.96 ± 0.78 ^a	13.87 ± 0.78 ^b

Note: Different superscript letters (a, b) in the same row indicate significant differences ($p < 0.05$). Values are expressed as mean ± standard deviation.

3.5 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) is an effective method for identifying functional groups and investigating structural changes in polysaccharides, including pectin. In this study, the FTIR spectra of pectin extracted by ohmic heating and conventional heating methods were compared with the spectrum of commercial pectin. As can be seen in Figure 1, all samples showed characteristic pectin bands in the corresponding ranges, indicating that the original structure of pectin was maintained in both extraction methods [6]. Across all spectra, a broad and strong band in the 3200-3500 cm⁻¹ range⁻¹It is observed to be related to the stretching vibration of hydroxyl groups (O-H). This band indicates the presence of intermolecular and intramolecular hydrogen bonds in the pectin structure [17]. The intensity of this band is slightly reduced in pectin extracted by conventional heating method, which could be due to the partial destruction of some hydrogen bonds due to the longer extraction time [1]. Band in the range of 2920-2930 cm⁻¹It is related to the stretching vibration of methylene groups (C-H), which is observed with similar intensity in all samples [6]. Peak index in the range of 1730-1750 cm⁻¹It is related to the stretching vibration of the carbonyl group (C=O) of esters. The intensity of this band in pectin extracted by the ohmic heating method is significantly higher than that of the conventional method, indicating

better preservation of the methyl ester groups and consequently a higher degree of esterification in this method [6]. This finding is in complete agreement with the results of the esterification degree analysis (62.40% for the Ohmic method versus 51.45% for the conventional method) [1]. Band in the range of 1600-1650 cm⁻¹related to the asymmetric stretching vibration of the carboxylate group (COO⁻) which indicates the presence of free carboxyl groups in the pectin structure [17]. In the range of 1000-1200 cm⁻¹Also, bands related to C-O-C and C-O vibrations and glycosidic bonds of polysaccharides are observed, which are almost similar in all three samples, indicating the preservation of the original structure of the polygalacturonic chain during the extraction process [7]. Overall comparison of spectra shows that pectin extracted by ohmic heating method has the most similarity to commercial pectin, while pectin extracted by conventional method shows more minor changes. This finding is in full agreement with the results of Wang et al. (2025) who reported that the ohmic heating method better preserves the pectin structure due to shorter extraction time and uniform heating [6]. Also, Razak et al. (2025) in their study on the extraction of pectin from Bintangor orange peel by ohmic heating method confirmed that the FTIR spectrum of pectin extracted by this method is more similar to commercial pectin [7]. Overall, the results of FTIR analysis confirm that the ohmic heating method, compared to the conventional method, preserves the chemical

structure of pectin better and produces a product with higher quality and more similarity to commercial pectin [6].

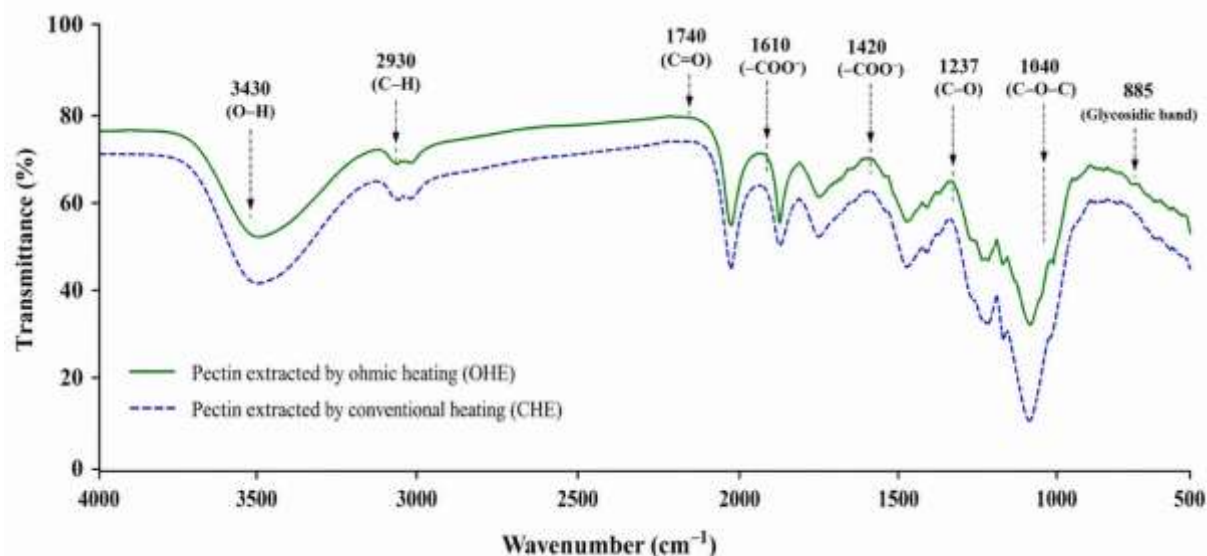


Figure 1. FTIR spectra of pectin extracted by ohmic heating and conventional heating methods

3-6 Surface Morphology (SEM)

Scanning Electron Microscopy (SEM) images provide valuable information about the surface morphology, structure, and particle size distribution of extracted pectin. In this study (Figure 2), the surface morphology of pectin extracted by ohmic heating and conventional heating methods was compared. As can be seen in the figure, significant differences in the surface structure of pectin extracted by the two methods were observed. Pectin extracted by conventional heating method showed a relatively rough surface, with irregular clusters and particles of various shapes. This heterogeneous structure could be due to the longer extraction time (90 min) and gradual heating, which led to partial destruction of polysaccharide chains and particle aggregation [12]. In contrast, pectin extracted by the ohmic heating method had a more uniform structure, with finer particles and a relatively smoother surface. This difference can be attributed to the shorter extraction time (30 min) and rapid and uniform heating in the ohmic method, which prevents excessive particle aggregation and structural degradation [7]. The findings of the present study are in complete agreement with the results of other researchers in this field. In a study of pectin extraction from bitter orange peel using electromagnetic pretreatment, SEM images showed that applying an electromagnetic field resulted in the destruction of parenchymal cells and increased

the contact surface for extraction [20]. Also, in a study of pectin extraction from Bintangor orange peel using the ohmic heating method, Razak et al. (2025) reported that pectin extracted using the ohmic method had a more uniform structure and finer particles compared to the conventional method, indicating better preservation of the polymer structure due to the shorter extraction time [7]. In another study conducted on the green extraction of pectin from orange and lemon peels using microwaves, SEM images showed that the extracted pectin had a porous structure and particles with irregular shapes [20]. The more uniform structure and finer particles of pectin extracted by the ohmic heating method (OHE) can be attributed to several factors. The rapid and uniform heating in the ohmic method causes the cell wall to be more effectively destroyed and the pectin to be released more uniformly into the solvent [1]. Furthermore, the non-thermal effect of the electric field may facilitate pectin extraction by creating micropores in the cellular structure and prevent the formation of large particle aggregates [10]. In contrast, the conventional heating method, due to the longer extraction time and gradual heating, may lead to partial denaturation of pectin and the formation of larger and more irregular aggregates [12]. From an application perspective, the more uniform structure and finer particles of pectin extracted by the ohmic heating method can have a positive impact on its functional properties such as solubility, hydration rate, and gelling

ability [18]. Finer particles provide more surface area for contact with the solvent, thereby improving the solubility and dispersion of pectin in aqueous systems [16]. This property is very important for the application of pectin in the food industry as a gelling agent, stabilizer and emulsifier. Overall, the SEM analysis results show that the ohmic heating method produces

pectin with a more uniform structure, finer particles and more favorable surface morphology compared to the conventional method. This structural advantage can be attributed to the shorter extraction time, uniform heating and non-thermal effect of the electric field in the ohmic method [1, 7].

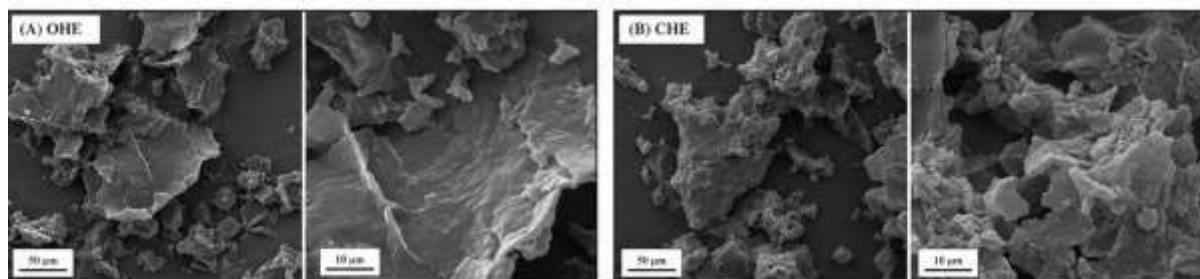


Figure 2. SEM images of pectin extracted by ohmic heating (OHE) (A) and conventional heating (CHE) (B)

4- Final conclusion

In this study, pectin was extracted from orange peel waste (Thomson Novel variety) using the ohmic heating method and compared with the conventional heating method. The results showed that the ohmic heating method was significantly superior to the conventional method and provided several advantages. The extraction efficiency in the ohmic method was about 22% higher than the conventional method. The degree of esterification of the pectin extracted by the ohmic method was significantly higher than the conventional method, placing it in the group of high methoxyl pectins (HMP). The water and oil holding capacity in the ohmic method was also significantly higher than the conventional method. Color indices showed that the ohmic method produced pectin with higher brightness, less redness and yellowness. FTIR analysis confirmed that the pectin structure was better preserved in the ohmic method and was more similar to commercial pectin. SEM images also showed a more uniform structure and finer particles for the pectin extracted by the ohmic method. In summary, the ohmic heating method, as a green and efficient technology, has a high potential to replace traditional methods in extracting pectin from citrus waste and can provide a sustainable approach for waste management and

5-Resources

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production of a high-quality product. It is suggested that the efficiency of extracted pectin be evaluated in the formulation of low-fat food products and also as a fat substitute in meat products.

Data access

Research data will be available upon request.

Conflict of interest

The authors declare that they have no financial interests or personal relationships that would influence the results reported in this article.

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Authors' Contributions

Seyyed Rasool Shah Hosseini: Data collection, formal analysis, sources, software, writing - original draft.

Sarah Jafarian: Conceptualization, project management, research, visualization, methodology, validation, writing - review and editing.

Seyyed Ruhollah Javadian and Somayeh Bahram: Conceptualization, project management, research, visualization and validation.

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استخراج سبز پکتین از ضایعات پوست پرتقال: مقایسه کارایی روش گرمایش اهمی و متداول

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روش‌های متداول استخراج پکتین از ضایعات مرکبات با چالش‌هایی نظیر زمان طولانی، مصرف انرژی بالا و تخریب ساختار پکتین همراه هستند. در پژوهش حاضر، استخراج پکتین از ضایعات پوست پرتقال (رقم تامسون ناول) با روش گرمایش اهمی به عنوان یک فناوری سبز و کارآمد بررسی و با روش گرمایش متداول مقایسه شد. استخراج پکتین با روش گرمایش اهمی در شرایط بهینه (گرادیان ولتاژ ۱۵ ولت بر سانتی‌متر، دمای ۹۰ درجه سانتی‌گراد، زمان ۳۰ دقیقه) و با روش گرمایش متداول (دمای ۹۰ درجه سانتی‌گراد، زمان ۹۰ دقیقه) انجام گرفت. پکتین استخراج‌شده از نظر راندمان استخراج، درجه استریفیکاسیون، ظرفیت نگهداری آب و روغن، شاخص‌های رنگی، ساختار شیمیایی (FTIR) و مورفولوژی سطح (SEM) ارزیابی شد. نتایج نشان داد که روش گرمایش اهمی راندمان استخراج را به طور معنی‌داری افزایش داد (۱۵/۲۷ درصد در مقابل ۱۲/۵۴ درصد). درجه استریفیکاسیون پکتین استخراج‌شده با روش اهمی (۶۲/۴۰ درصد) به طور معنی‌داری بیشتر از روش متداول (۵۱/۴۵ درصد) بود که نشان‌دهنده تعلق آن به گروه پکتین‌های با متوکسیل بالا است. ظرفیت نگهداری آب (۷/۱۱ گرم بر گرم) و روغن (۶/۲۳ گرم بر گرم) در روش اهمی به ترتیب حدود ۱۸ و ۲۶ درصد بیشتر از روش متداول بود. پکتین استخراج‌شده با روش اهمی روشنایی بیشتر، قرمزی و زردی کمتری نشان داد. آنالیز FTIR حفظ بهتر ساختار شیمیایی پکتین را در روش اهمی تأیید کرد و تصاویر SEM ساختاری یکنواخت‌تر و ذرات ریزتر را نشان دادند. در مجموع، گرمایش اهمی به عنوان یک فناوری سبز، کارآمد و کم‌مصرف، پتانسیل بالایی برای جایگزینی روش‌های متداول در استخراج پکتین از ضایعات مرکبات دارد و می‌تواند رویکردی پایدار و ارزش‌آفرین برای مدیریت پسماندهای صنایع فراوری مرکبات فراهم سازد.