International Journal of Agriculture and Plant Science
www.agriculturejournal.in
Online ISSN: 2664-7664
Received: 25-07-2026, Accepted: 24-08-2026, Published: 09-09-2026
Volume 8, Issue 3, 2026, Page No. 401-407

Characterization of pectin extracted from unripen banana peel using various extraction techniques

Sneha Soundarrajan, Dr. Karthika Jeyeraman
Ayini India Pvt Ltd, Kanchi Puram, India
Corresponding Author: Dr. Karthika Jeyeraman

Abstract
This study explores the extraction of pectin from unripe banana peels using two advanced methods: ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE). The extracted pectins were assessed for their physicochemical parameters, such as degree of esterification (DE) and pectin yield (PY). UAE had a better extraction efficiency, with a yield of 13.2% and DE of 65.4%, than MAE (11.6% yield, 60.2% DE). UAE-extracted pectin had superior functional qualities, including water and oil holding capacity, antioxidant activity, and emulsifying ability. The biodegradable films made from pectin and sodium alginate were characterised using FTIR, FESEM, XRD, DSC, and TGA. The UAE-based films demonstrated improved structural integrity, thermal stability, and homogeneous surface morphology, indicating that they are appropriate for food packaging applications. This study identifies unripe banana peel as a sustainable pectin source and establishes UAE as a more efficient extraction process for creating value-added, biodegradable, and functional products for the food, pharmaceutical, and packaging industries.

Keywords: Unripen banana peel pectin, MAE, UAE, film, sodium alginate

Introduction

The agricultural and food-processing industries generate substantial amounts of organic waste, creating environmental concerns and increasing the need for effective waste valorization strategies. Fruit and vegetable wastes, particularly peels, are valuable sources of bioactive compounds and structural biopolymers such as pectin, polyphenols, flavonoids, and carotenoids (Maji *et al*., 2020). Recovery of these compounds can reduce waste accumulation while providing functional ingredients for food, pharmaceutical, and other industrial applications (Yadav *et al*., 2024). In addition, the utilization of agro-industrial residues as renewable resources may contribute to the development of biodegradable alternatives to polymers derived from fossil resources (Cristofoli *et al*., 2023).

Banana (Musa spp.) is an important tropical and subtropical crop with considerable nutritional and economic significance. However, banana processing generates large quantities of peel waste, which commonly accounts for approximately 35–40% of the fruit weight (Putra *et al*., 2022). India is one of the world's major banana-producing countries, and the large volume of peel generated during processing represents both a waste-management challenge and an opportunity for resource recovery. Banana peels contain several valuable components, including pectin, cellulose, hemicellulose, lignin, and phytochemicals, with some bioactive compounds occurring at higher concentrations than in the pulp (Hikal *et al*., 2022; EVELIN, 2022). Unripe banana peel is particularly promising as a pectin source because pectin is gradually degraded during fruit ripening through the action of pectinolytic enzymes (Sarangi *et al*., 2023).

Pectin is a structural heteropolysaccharide located mainly in the primary cell wall and middle lamella of plants. It contributes to cell-wall integrity and possesses important functional properties, including thickening, stabilization, emulsification, and gel formation (Padayachee *et al*., 2017; Zaini *et al*., 2022). Commercial pectin is primarily obtained from citrus peels and apple pomace; however, the exploration of alternative sources such as fruit-processing residues can improve resource utilization and reduce industrial waste (Zdunek *et al*., 2021). Depending on its degree of esterification, pectin is generally classified as high-methoxyl or low-methoxyl pectin, and its functional properties support applications in confectionery, dairy products, beverages, bakery products, pharmaceuticals, and biodegradable materials (Noor *et al*., 2021; Sarangi *et al*., 2023).

The efficiency and quality of pectin recovery depend strongly on the extraction technique and processing conditions. Conventional acid extraction can require considerable amounts of solvent, energy, and processing time. Consequently, novel extraction technologies such as microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE) have gained attention as potentially more efficient and sustainable alternatives. MAE uses non-ionizing microwave energy to promote rapid heating and enhance the release and diffusion of target compounds, thereby reducing extraction time and solvent requirements (Destandau & Michel, 2022; Mao *et al*., 2023). Similarly, UAE employs ultrasonic waves to generate acoustic cavitation, which disrupts plant tissues and enhances mass transfer between the raw material and extraction solvent. This approach can provide higher extraction efficiency with reduced energy, solvent consumption, and processing time (Karbuz & Tugrul, 2021; Buvaneshwaran *et al*., 2023; Lepaus *et al*., 2023).

The recovery of pectin from banana peel can also support the development of biodegradable packaging materials. Growing concerns regarding fossil-based plastics and their environmental impacts have increased interest in renewable and biodegradable biopolymers (Shamoon *et al*., 2022). Pectin and alginate are promising materials for such applications because they are biodegradable, relatively safe, and capable of forming polymeric films. Blending these polysaccharides can further improve film properties and

broaden their potential applications (Gheorghita Puscaselu *et al*., 2020).

Therefore, the present study focuses on the extraction of pectin from unripe banana peel using ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE). The extraction methods were evaluated based on pectin yield and its physicochemical, nutritional, and functional characteristics. Furthermore, the extracted pectin was blended with sodium alginate at a 1:1 ratio to develop biopolymer films, which were subsequently evaluated for their structural and functional properties. This approach aims to valorize unripe banana peel as a potential source of functional pectin and explore its suitability for food, pharmaceutical, and biodegradable packaging applications.

Materials and Methods

1. Chemicals and Reagents

Analytical-grade chemicals were used throughout the study. Quercetin, gallic acid, ethanol, Folin–Ciocalteu reagent, DPPH, L-ascorbic acid, sodium nitrite, sodium hydroxide, sodium carbonate, sodium bicarbonate, nitric acid, hydrochloric acid, acetic acid, phenolphthalein, and soy oil were used for extraction and analytical determinations. Deionized distilled water was used for solution preparation, and all reagents were freshly prepared before analysis.

2. Sample Collection and Preparation

Unripe banana (Musa spp.) fruits were obtained from a local market in Hosadurga, Karnataka, India. The fruits were washed thoroughly with distilled water, and the peels were manually removed using a stainless-steel peeler. The peels were cut into approximately 2 mm pieces and dried at 60 °C in a tray dryer until constant weight. The dried material was ground, sieved (250–355 µm), and stored in airtight, light-protected containers at room temperature until extraction.

3. Pectin Extraction

Pectin was extracted from banana peel powder using microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE). For both methods, a solid-to-liquid ratio of 1:10 (10 g peel powder/100 mL deionized water) was maintained. The extraction medium was acidified to pH 1.5 using 1 N HCl and stirred for 30 min before extraction.

3.1 Microwave-Assisted Extraction (MAE)

For MAE, the acidified suspension was treated in a 900 W microwave oven for 7 min using 30 s intermittent intervals to minimize overheating. After cooling, the extract was centrifuged at 4000 rpm for 10 min. The supernatant was mixed with cold 96% ethanol at a 1:2 ratio and chilled to facilitate pectin precipitation. The precipitate was washed three times with distilled water and dried at 40 °C to constant weight. The dried pectin was stored in airtight containers for subsequent analyses.

3.2 Ultrasound-Assisted Extraction (UAE)

For UAE, the pretreated banana peel suspension was sonicated in an ultrasonic bath at 60 °C for 20 min. The extract was subsequently cooled and centrifuged at 4000 rpm for 10 min. The recovered supernatant was mixed with cold 96% ethanol at a 1:2 ratio and chilled for pectin precipitation. The precipitated pectin was washed three times with distilled water and dried at 40 °C until constant weight. The dried product was stored in sealed containers for further physicochemical and functional characterization.

Pectin yield

The weight of the extracted pectin was measured, and its yield was computed on a dry basis utilising the following formula:

$$\text{Pectin yield (\%)} = \frac{M_0}{M} \times 100 \quad (1)$$

M_0= the weights of extracted pectin
M= the dried lemon peel powder respectively.

Degree of esterification (DE)

The DE of the extracted pectin was determined using a modified titrimetric method that calculates the ratio of esterified carboxyl groups to total galacturonic acid concentration. To improve dispersion, 100 mg of extracted pectin was first mixed with 1 mL of ethanol. The mixture was then dissolved in 25 mL of distilled water before being ultrasonically treated for 10 minutes in an ultrasonic bath to ensure complete dissolution. Two drops of phenolphthalein indicator were then added to the solution, and the mixture was titrated with 0.1 M NaOH while continually stirring until a consistent light pink hue appeared, lasting at least 30 seconds. The amount of NaOH utilised at this endpoint was denoted as V1, which represented the free carboxyl groups in the pectin sample. Following the preliminary titration, the same sample was treated with 10 mL of 0.1 M HCl to hydrolyse the esterified carboxyl groups, restoring the solution's colourlessness. The solution was stirred for 10 minutes to ensure full hydrolysis. The liquid was then re-titrated with 0.1 M NaOH until the same pale pink hue appeared, and the amount of NaOH used was recorded as V2, representing the esterified carboxyl groups released following hydrolysis.

$$\text{DE} = \frac{V_2}{V_1+V_2} \times 100 \quad (2)$$

V_1 = Volume of NaOH consumed during the first titration
V_2 = Volume of NaOH consumed during the second titration

Pectin Powder Characterisation

1. Fourier Transform Infrared Spectroscopy (FTIR)

Van Hung *et al*. (2021) detailed how the FTIR spectra of the extracted pectin samples were obtained using an FTIR spectrophotometer. The powdered pectin was combined with potassium bromide (KBr) and crushed to form a pellet. The spectra were taken in transparent mode at a resolution of 4 cm with a wavelength range of 4000 to 400 cm^{-1}.

2. Thermogravimetric Analysis (TGA)

The TGA characteristics of extracted pectin (6-7 mg) was evaluated using a thermogravimetric analyser similar to that employed by Saadatkhah (2020). The work was carried out in a controlled N ° 2 atmosphere with temperatures ranging from 25 to 700 ■ C/min in the C.

3. Differential Scanning Calorimetry (DSC)

The DSC analysis was performed using the Netzsch DSC equipment. For this purpose, a typical aluminium crucible

was filled with 6 mg of dried and finely powdered extracted pectin and sealed immediately. The crucible was heated in a dynamic inert nitrogen atmosphere at a flow rate of 50 mL/min from 30 to 400 °C, with a 10 °C increase every minute. A vacant standard aluminium crucible was used as a reference.

4. X-Ray Diffraction (XRD)

The experiment was performed utilizing an X-ray diffractometer using Cu Kα radiation (Tran *et al*., 2021). The extracted pectin powder was analyzed at a diffraction angle of 5 to 50 degrees (step size: 0.02; duration: 2 seconds per step).

5. Field Emission Scanning Electron Microscopy (FESEM)

The morphology of the extracted pectin was studied using a FESEM equipment. The dried pectin was mounted to a metal stub using conventional double-sided adhesive tape. Furthermore, to guarantee the samples' conductivity, they were coated with gold and tested at an accelerating voltage of 2-5 kV.

Pectin Alginate-based film preparation

A film-forming solution was prepared by dissolving 1% (w/v) sodium alginate and 1% (w/v) pectin extracted from unripe banana peel in 100 mL distilled water. Sodium alginate was gradually added to the pectin solution under continuous stirring, followed by magnetic stirring for 1 h to obtain a homogeneous solution. The solution was allowed to stand briefly to reduce air bubbles. 40 mL of the solution was poured into 10 cm diameter Petri dishes and dried in a tray dryer at 60°C for 24 h. The dried films were carefully peeled and stored in airtight zip-lock pouches at room temperature until further characterization and testing.

Results and discussion

The extraction parameters for pectin using microwave and ultrasound-assisted techniques from unripe banana peel were chosen based on previous research and preliminary experimental trials. This study emphasises the significance of many independent variables in the extraction process and how they influence the final pectin yield (PY) and degree of esterification (DE). The utilisation of a low pH environment in conjunction with heat extraction conditions promotes the breakdown and release of pectin, protopectin, and other pectic compounds linked to cell walls.

This section provides a thorough examination of the results obtained from the characterisation of pectin films extracted via Ultrasound-Assisted Extraction (UAE) and Microwave-Assisted Extraction (MAE). To assess the structural, thermal, and functional properties of the pectin films, a variety of techniques were used, including Field Emission Scanning Electron Microscopy (FESEM), Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), Fourier-Transform Infrared Spectroscopy (FTIR), and X-ray Diffraction. These tests were carried out to better understand the impact of the extraction procedures on the molecular structure, thermal stability, and film properties, all of which are important for future applications in food packaging, biomedical areas, and drug delivery. The talk will compare the performance of UAE and MAE-extracted pectin films, showing significant changes in shape, thermal behaviour, and molecular interactions. The findings are contextualised with relevant literature to provide insight into the suitability of each extraction method for specific applications.

Physicochemical properties of extracted pectin

Table 1 shows the physicochemical parameters of pectin extracted under the best conditions utilising Microwave-Assisted Extraction (MAE) and Ultrasound-Assisted Extraction (UAE). The extraction process had a considerable impact on these attributes. UAE-extracted pectin included 6.01±0.03% moisture, 1.8±0.07% ash, and 0.3% fat. MAE pectin contained 8.09±0.05% moisture, 2±0.05% ash, and 0.5% fat. UAE-extracted pectin had a greater total soluble protein content (8.57±0.05 mg/g) compared to MAE-extracted pectin (5.8±0.07 mg/g).

Table 1: Physicochemical properties of pectin extracted with MAE and UAE

SNo.	Physiochemical Properties	MAE	UAE
1.	Moisture (%)	8.09±0.05%	6.01±0.03%
2.	Ash (%)	2±0.05%	1.8±0.07%
3.	Fat (%)	0.5%	0.3%
4.	Total soluble proteins (mg/g)	5.8±0.07	8.57±0.05

Functional properties of extracted pectin

The water holding capacity (WHC), an important component regulating texture and stability in food systems, refers to the quantity of water retained per gramme of pectin. In this work, pectin extracted using the UAE method had a higher WHC of 8.7±0.1 g/g compared to 7.9±0.2 g/g for MAE-extracted pectin. In terms of oil holding capacity (OHC), UAE-derived pectin (5.2±0.2 g/g) fared better than MAE-derived pectin (3.6±0.3 g/g). Pectin extracted from UAE has higher antioxidant activity (AA) (77.45±0.02%) than MAE (70.09±0.01%), indicating the presence of more bioactive chemicals. UAE-extracted pectin outperformed MAE in terms of emulsification capacity (30.06±0.7%) and emulsion stability (47.89±0.3%). MAE had 29.3±0.7% and 40.3±0.2%, respectively. UAE-extracted pectin had higher total phenolic and flavonoid content (45.05±0.6 mg GAE/g and 47.78±0.4 mg QE/g) compared to MAE-extracted pectin (40.30±0.7 mg GAE/g and 44.05±0.4 mg QE/g, respectively). These findings imply that the UAE methodology outperforms the MAE method in terms of improving pectin's functional, antioxidant, and emulsification capabilities.

Table 2: Comparative analysis of functional attributes of pectin extracted via microwave assisted and ultrasound assisted extractions

SNo.	Parameters	MAE	UAE
1.	PY (%)	20.58%	24.08%
2.	DE (%)	62.83±0.02	63.15±0.03
3.	TPC (mg GAE/g)	40.30±0.7mgGAE/g	45.05±0.6mgGAE/g
4.	TFC (mg QE/g)	44.05±0.4mgQE/g	47.78±0.4mgQE/g
5.	WHC (g/g)	7.9±0.2%	8.7±0.1%
6.	OHC (g/g)	3.6±0.3%	5.2±0.2%
7.	AA (%)	70.09 ± 0.01	77.45± 0.02
8.	EC (%)	29.3±0.7%	30.06±0.7%
9.	ES (%)	40.3±0.2%	47.89±0.3%

Characterization of extracted pectin

1. Differential Scanning Calorimetry (DSC)

The DSC profiles showed distinct thermal transitions for UAE- and MAE-derived pectin. UAE pectin exhibited an endothermic transition at 110–130 °C associated with moisture loss, followed by a broad transition at 240–260 °C and major degradation at approximately 320–350 °C in **Fig 1**. A final exothermic decomposition peak was observed at 390–400 °C. In comparison, MAE pectin showed moisture loss at 100–120 °C, a broad transition at 250–270 °C, and major degradation at 350–370 °C, followed by decomposition near 400 °C. Thus, the MAE sample showed a higher degradation temperature (~370 °C) than UAE pectin (~350 °C), indicating greater thermal resistance under the tested conditions.

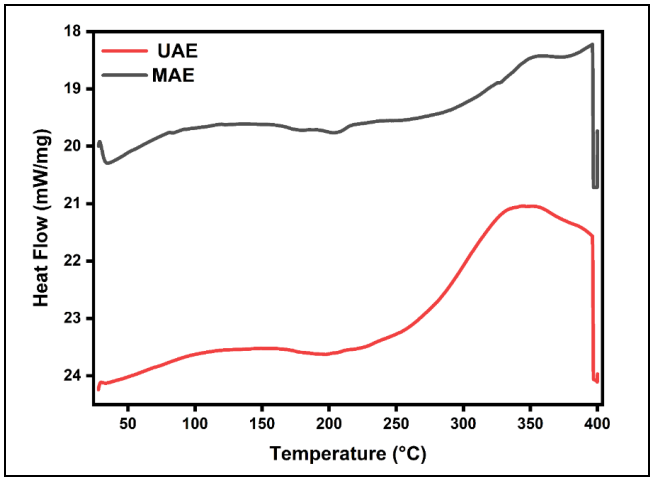

Fig 1: Thermal Analysis of Pectin by Differential Scanning Calorimetry

2. Field Emission Scanning Electron Microscopy (FESEM)

FESEM analysis demonstrated clear morphological differences between the extraction treatments. UAE-derived pectin exhibited a porous and fragmented surface with irregular fibrous structures and microcracks. In contrast, MAE-derived pectin showed a relatively compact and cohesive morphology with fewer pores and structural discontinuities. These observations indicate that UAE produced greater surface disruption, whereas MAE resulted in a comparatively dense structure in Fig 2a & 2b.

Fig 2a & 2b. Surface Morphology of MAE Pectin by FESEM from Unripen banana peel powder & UAE Pectin by FESEM from Unripen banana peel powder

3. X-Ray Diffraction (XRD)

Both extracted pectin samples exhibited broad diffraction patterns characteristic of predominantly amorphous polysaccharides. UAE pectin showed a comparatively more defined pattern, with major peaks at 16.4°, 18.7°, 22.1°, 25.3°, 30.5°, and 34.6° (2θ). MAE pectin exhibited broader and less intense peaks at 16.1°, 18.2°, 21.7°, 24.8°, 28.9°, and 33.2° (2θ). The higher peak intensity observed for UAE, approximately 2–3 times that of MAE at corresponding positions, indicated greater molecular ordering and structural organization in Fig 3.

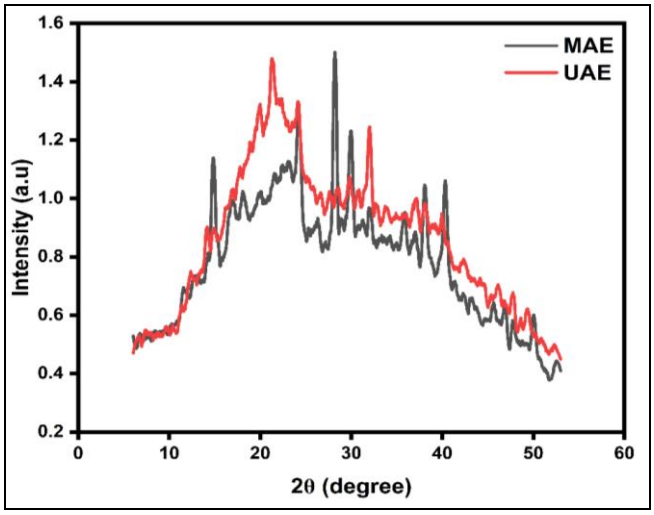

Fig 3: X-Ray Diffraction (XRD) Pattern of Pectin

4. Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR spectra confirmed characteristic functional groups of pectin in both samples. UAE pectin showed bands at 3290, 2920, 1613, 1312, 1012, and 519 cm^{-1}, whereas MAE pectin exhibited bands at 3303, 2918, 1622, 1008, 1086, and 515 cm^{-1}. The bands near 3300 cm^{-1} were associated with O–H stretching, those near 2920 cm^{-1} with C–H stretching, and the bands around 1600 cm^{-1} and 1000–1012 cm^{-1} with carboxyl and glycosidic groups, respectively in Fig 4. The minor shifts between treatments indicated differences in molecular interactions and structural organization.

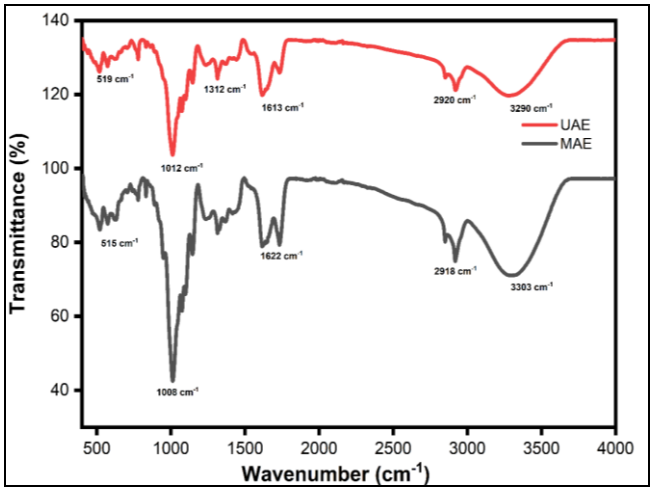

Fig 4: Infrared Spectroscopic Analysis of Pectin

5. Thermogravimetric Analysis (TGA)

TGA showed multistage degradation behavior for both pectin samples. Initial weight loss occurred between 50 and 150 °C due to moisture evaporation, followed by major degradation between 180 and 350 °C associated with decomposition of the pectin backbone. UAE pectin exhibited a peak degradation temperature of approximately 270 °C, compared with approximately 260 °C for MAE pectin. At 700 °C, UAE pectin retained approximately 10% residual mass, whereas MAE pectin retained approximately 5%. These results indicated greater thermal resistance and slower degradation for UAE-derived pectin in Fig 5.

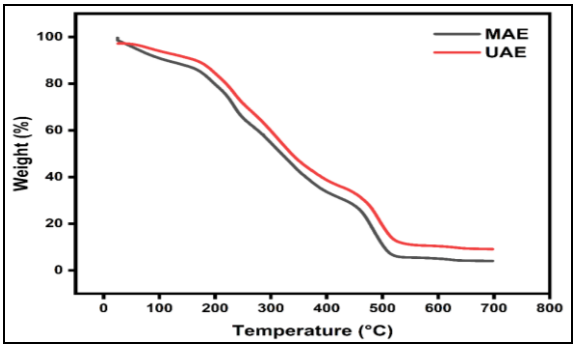

Fig 5: Thermogravimetric Analysis (TGA) Curve of Pectin

Characterization of Pectin–Sodium Alginate Films

1. FESEM

The pectin–sodium alginate films showed different surface characteristics depending on the extraction method. UAE-derived films displayed a smoother and more homogeneous surface with fewer cracks and voids, indicating a relatively uniform polymer network. MAE-derived films exhibited rougher and more heterogeneous surfaces with visible pores, cracks, and structural irregularities. Overall, the UAE film showed greater surface uniformity and fewer structural defects in Fig 6a & 6b.

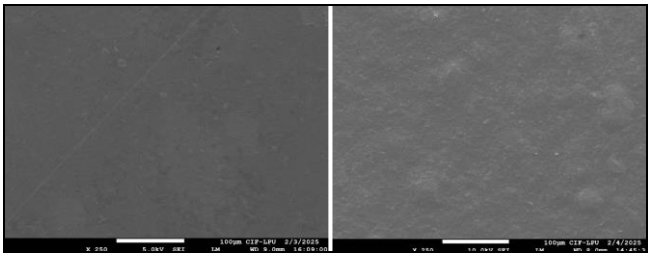

Fig 6a & 6b: Surface Morphology of MAE Pectin-Sodium Alginate Films by FESEM & UAE Pectin-Sodium Alginate Films by FESEM

2. Thermogravimetric Analysis (TGA)

The pectin–sodium alginate films showed three major stages of thermal degradation. The first stage occurred between 50 and 150 °C and corresponded to moisture loss, accounting for approximately 8–10% weight loss in UAE films. Major decomposition occurred between 200 and 350 °C, with UAE films showing approximately 40–50% weight loss compared with 50–55% for MAE films. At 700 °C, UAE films retained approximately 15–20% residual mass, whereas MAE films retained approximately 10–15%. The UAE-derived films therefore exhibited slower degradation and greater residual mass than MAE films.

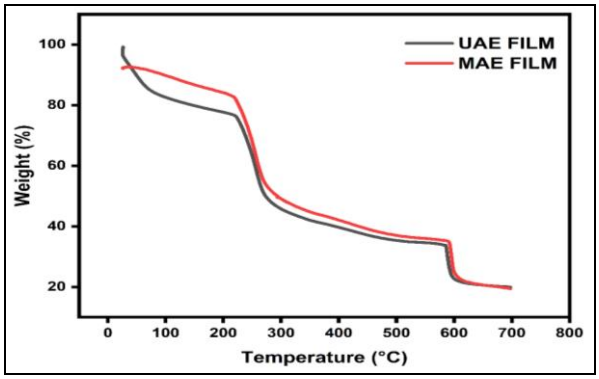

Fig 7: Thermogravimetric Analysis of Pectin-Sodium Alginate Complex

3. Differential Scanning Calorimetry (DSC)

The DSC thermograms of the films showed an initial transition near 50 °C, corresponding to moisture loss. UAE films exhibited a major thermal transition around 350 °C, followed by substantial degradation near 400 °C. MAE films showed a major transition at approximately 380–400 °C, indicating a higher decomposition temperature than UAE films. Thus, the MAE-derived pectin–sodium alginate film demonstrated greater thermal stability in the DSC analysis.

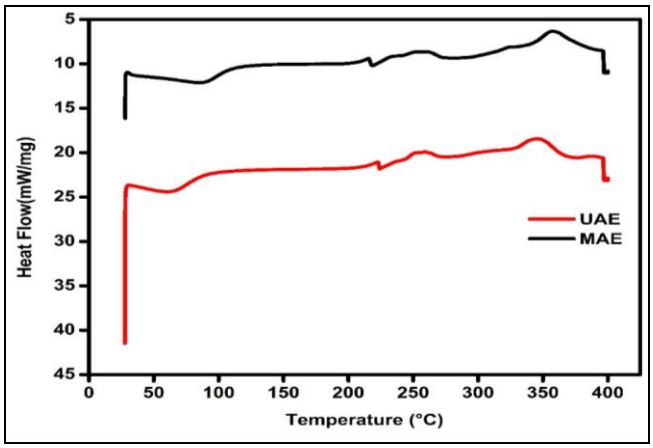

Fig 8: DSC Thermogram of Pectin-Sodium Alginate Films

4. FTIR

The FTIR spectra of both films showed characteristic bands corresponding to hydroxyl, carboxylate, C–H, and glycosidic groups. O–H stretching bands were observed at 3304.6 cm^{-1} for UAE and 3299.3 cm^{-1} for MAE films, while C–H stretching occurred at 2923.6 and 2918.2 cm^{-1}, respectively. Carboxylate bands were detected around 1602.8–1602.9 cm^{-1}, and C–O–C glycosidic linkages appeared at 1019.4 cm^{-1} for UAE and 1024.8 cm^{-1} for MAE. The similar spectral profiles confirmed the presence of the characteristic polysaccharide structure in both films, with minor shifts indicating differences in molecular interactions.

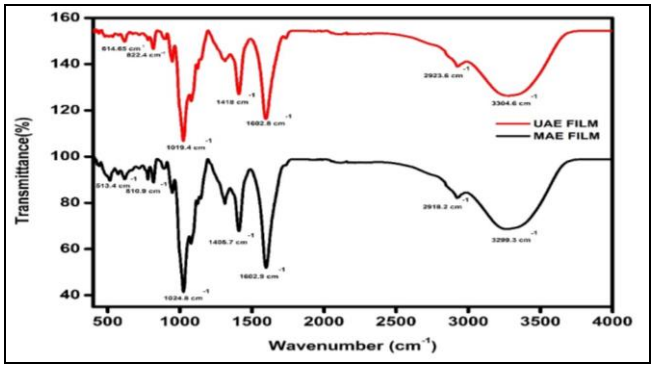

Fig 9: Infrared Spectroscopic Analysis of Pectin-Sodium Alginate Complex

5. X-Ray Diffraction (XRD)

The UAE pectin–sodium alginate film exhibited a broad diffraction region between 10° and 22° (2θ), with a prominent peak near 14.5° and a minor peak around 16°, indicating partial molecular ordering within a predominantly amorphous matrix. The MAE film showed broader and less intense diffraction features centered around 12–22° (2θ),

indicating a predominantly amorphous structure. The UAE film therefore exhibited greater molecular ordering and higher diffraction intensity, whereas the MAE film showed reduced structural organization.

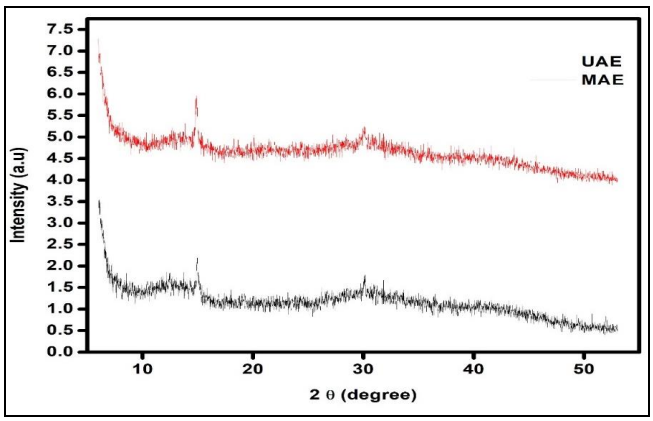

Fig 10: Crystallinity Study of Pectin-Sodium Alginate Complex by XRD

The present study with previous reports on MAE- and UAE-based pectin extraction. In the present study, banana peel pectin was extracted at pH 1.5 using MAE (900 W, 7 min) and UAE (60 °C, 20 min). UAE produced a higher pectin yield (24.08%) with a degree of esterification (DE) of 63.15%, whereas MAE yielded 20.58% with a comparable DE of 62.83%. Compared with previous studies, MAE of lemon peel at 450 W for 4 min and pH 1.0 produced 41.4% yield (Chung *et al*., 2024), while UAE of grapefruit peel at 80 °C for 30 min and pH 2.5 resulted in 26.05% yield and 84.25% DE. MAE of pomelo peel at 70 °C for 10 min and pH 2.0 produced 26.63% yield and high-methoxyl pectin (Md. M. Hossain *et al*., 2024). Overall, pectin yield and DE varied with the fruit source, acid type, pH, temperature, microwave power, and extraction time. The present findings demonstrate that unripe banana peel can serve as a potential alternative source of pectin, providing acceptable yield and DE comparable to other fruit-derived pectins.

Conclusion

This work investigated the structural, thermal, and functional properties of pectin films extracted via Ultrasound-Assisted Extraction (UAE) and Microwave-Assisted Extraction (MAE). The results show that the two extraction processes have considerable differences in film qualities, which are critical for their prospective applications. FTIR research revealed that both UAE and MAE pectin films contained key functional groups, while UAE-extracted films had somewhat more intense peaks, indicating improved retention of esterification and functional groups. XRD examination further revealed that UAE films had semi-crystalline structures, implying higher molecular order, whereas MAE films were more amorphous, indicating a higher degree of depolymerisation. TGA and DSC tests revealed that UAE-extracted films were more thermally stable, decomposing at higher temperatures and holding greater mass following heat exposure. In contrast, MAE films degraded faster, despite being able to resist greater temperatures before breakdown. The findings indicate that UAE-extracted films, which have higher crystallinity, structural integrity, and thermal stability, are more suited for applications that need endurance, such as biodegradable packaging and medicinal coatings. MAE-extracted films, on the other hand, have greater flexibility and degrade faster, making them better suitable for applications such as medication delivery systems and edible coatings. Finally, the choice of extraction process should be guided by the specific application needs, with UAE producing more solid and durable films and MAE providing more flexible and biodegradable ones. These findings provide important insights into the optimisation of extraction procedures for pectin films, which could be further investigated for a variety of industrial applications.

References

1. Phaiphan A. Ultrasound assisted extraction of pectin from banana peel waste as a potential source for pectin production. Acta Scientiarum Polonorum Technologia Alimentaria,2022:21(1):17-30. https://doi.org/10.17306/J.AFS.2022.0974
2. Swamy GJ, Muthukumarappan K. Optimization of continuous and intermittent microwave extraction of pectin from banana peels. Food Chemistry,2017:220:108-114. https://doi.org/10.1016/j.foodchem.2016.09.197
3. Rivadeneira JP, Wu T, Ybanez Q, Dorado AA, Migo VP, Nayve FRP, *et al*. Microwave-assisted extraction of pectin from "Saba" banana peel waste: Optimization, characterization, and rheology study. International Journal of Food Science,2020:2020:8879425. https://doi.org/10.1155/2020/8879425
4. Happi Emaga T, Ronkart SN, Robert C, Wathelet B, Paquot M. Characterisation of pectins extracted from banana peels (Musa AAA) under different conditions using an experimental design. Food Chemistry,2008:108(1):463-471. https://doi.org/10.1016/j.foodchem.2007.10.078
5. Kamble PB, Gawande S, Patil T. Extraction of pectin from unripe banana peel. International Research Journal of Engineering and Technology,2017:4:2259-2264.
6. Aklilu EG. Modeling and optimization of pectin extraction from banana peel using artificial neural networks (ANNs) and response surface methodology (RSM). Journal of Food Measurement and Characterization,2021:15:2759-2773. https://doi.org/10.1007/s11694-021-00852-7
7. Riyamol R, Chengaiyan JG, Rana SS. Recent advances in the extraction of pectin from various sources and industrial applications. ACS Omega,2023:8(49):46309-46324. https://doi.org/10.1021/acsomega.3c04010
8. Nadar CG, Arora A, Shastri Y. Sustainability challenges and opportunities in pectin extraction from fruit waste. ACS Engineering Au,2022:2(2):61-74. https://doi.org/10.1021/acsengineeringau.1c00025
9. Evaluation of sources and methods of pectin extraction from fruit and vegetable wastes: A systematic literature review (SLR). Food Bioscience,2023:51:102278. https://doi.org/10.1016/j.fbio.2022.102278
10. Mao Y, Dewi SR, Harding SE, Binner E. Influence of ripening stage on the microwave-assisted pectin extraction from banana peels: A feasibility study targeting both the homogalacturonan and rhamnogalacturonan-I region. Food

Chemistry,2024:460(1):140549. https://doi.org/10.1016/j.foodchem.2024.140549
11. Khamsucharit P, Laohaphatanalert K, Gavinlertvatana P, Sriroth K, Sangseethong K. Characterization of pectin extracted from banana peels of different varieties. Food Science and Biotechnology,2018:27(3):623-629. https://doi.org/10.1007/s10068-017-0302-0
12. Emaga TH, Ronkart SN, Robert C, Wathelet B, Paquot M. Characterisation of pectins extracted from banana peels (Musa AAA) under different conditions using an experimental design. Food Chemistry,2008:108(2):463-471. https://doi.org/10.1016/j.foodchem.2007.10.078
13. Espinal-Ruiz M, *et al*. An overview of the traditional and innovative approaches for pectin extraction from plant food wastes and by-products: Ultrasound-, microwaves-, and enzyme-assisted extraction. Trends in Food Science & Technology,2018:76:28-37. https://doi.org/10.1016/j.tifs.2018.03.022