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Isolation and Characterization of Pectin from Different Fruit Peels

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Abstract - Six sources of fruit peels, including orange, pomegranate, dragon fruit, banana, pineapple and mango were isolated and characterized extensively to compare their physicochemical properties and functional characteristics. Depending on conditions of extraction, yields of pectin ranged widely (between 2 and 12% in pineapple to 24-30% in citrus and banana). The characteristic functional groups of pectin in all the samples (e.g. broad O-H signals at approximately 3400 cm-1740 cm-1600 cm-1) were confirmed by the FTIR spectra with distinctly different degrees of methyl esterification among the peels. XRD results showed that the structures were mainly amorphous with some slight differences in their crystallinity, SEM images showed that the microstructural morphologies were source-dependent (smooth sheet-like flakes versus rough porous surfaces). Through thermal analysis, it was revealed that all pectins undergo a significant breaking down process between 190-250 0C, but the breaking down onset temperature and thermal stability differed among the degrees of methylation and impurities. The values of the DSC indicated that the glass transition temperatures were in the range of say 75-100 0C with the low-methoxyl pectins lying towards the lower end. The GC-MS analysis of derivatized pectins revealed the variation in the composition of neutral sugars; the pineapple peel pectin was quite rich in the composition of some neutral sugars in the side chains, namely, rhamnose, arabinose and galactose, dragon fruit and citrus pectins have quite high levels of galacturonic acid content. All of these analytical findings can show that pectin in every fruit peel has distinct structural characteristics - including functional group esterification, content of branching, and thermal behavior - that can inform both its gelling and functional efficacy in the food and pharmaceutical industries.

Keywords: Pectin; Fruit peels; FTIR; Thermal analysis; Degree of esterification; Functional properties

1.0 INTRODUCTION

Pectin refers to an intricate vegetable polysaccharide that is very common in the cell walls of fruit and vegetables particularly peels and pomaces. The production of pectin commercially has always been based on citrus peels and apple pomace as raw materials since they provide the highest pectin content, and they possess good gelling capabilities. In 2020, the global pectin usage was approximated at about 70,000 tons (valued at around 1.25 billion), as pectin is considered as one of the most prized hydrocolloids in the food sector. The ability of pectin to act as a gelling agent, thickener, stabilizer, and emulsifier provides a basis of the wide application of it to jams, jellies, confections, dairy products and low-calorie food. In pharmaceuticals (e.g. as a tablet binder, drug delivery matrix) and biomedical applications, it is also used due to its health and biocompatibility (e.g. dietary fiber effect, cholesterol-reduction, prebiotic activity).

Even though citrus and apples pectin predominate, increased focus is on pectin extraction of other unused fruit waste to enhance sustainability and generate value-added items out of agro-industrial residues. A high peel biomass of many tropical and subtropical fruits - banana, mango, pineapple, pomegranate, and dragon fruit - have been found to be promising alternative sources of pectin. Such peels of fruits usually become waste products in the juice or canning sectors, though they do possess substantial quantities of pectic polysaccharides recoverable. Through aerobicizing these wastes in the extraction of pectin, the dumping can be reduced and a functional ingredient of value will be obtained. Furthermore, pectins derived in various botanical origins may possess a wide range of structural properties (e.g. molecular weight, neutral sugar content, acetylation, degree of methyl-esterification) which are then converted into different functional properties. Studying these variations is significant in order to customize pectin to particular purposes.

The paper is based on six fruit peels namely orange (citrus family), pomegranate, dragon fruit (pitaya), banana, pineapple and mango; to present a wide variety of pectin type consisting of various plant families. All these have been studied under different circumstances separately in earlier studies, but under comparable extraction and characterization conditions, comparative studies are few. Orange peel pectin has been known to be rich in galacturonic acid and is usually high-methoxyl (DE >50) when extracted under normal acidic conditions. Optimized methods can produce yields of over 20 percent of dry peel weight with citrus peels, and

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the resulting pectin can make gels with sugar and acid (rapid-set or slow-set based on DE). Conversely, pomegranate peel pectins have been found to be low-methoxyl with high proportions of homogalacturonan areas. The pectin concentration of hot acid extractions of pomegranate peel was approximately 7-10% and the degree of esterification (DE) was approximately 30-40 which puts them in the low-methoxyl pectins category. These are structural variations that allow the pomegranate pectin gel to form under the influence of calcium (sugar-independent gelling), which was observed by Abid et al. (2017).

The peel of dragon fruit (pitaya) has become a more recent source of pectin. According to recent research, dragon fruit peels have a pectin content of about 8-13 percent with a DE ranging as low as very low (lower than 30 percent in some studies) to approximately 50 percent depending on extraction factors. Carpio-Rivas et al. (2025) obtained pectin out of Selenicereus (dragon fruit) peel with an estimated yield of 12.8 percent and 49.8 percent esterification. This puts dragon fruit pectin in the boundary of low vs. high methoxyl category. It is important to note that the pectin of dragon fruit was very high in anhydro uronic acid (~98%), which implies very high purity and low number of neutral sugars. It was also previously observed that betalains and phenolics co-extracted by dragon fruit pectin give the product antioxidant properties.

Banana peels also contain a high source of pectin, with a number of varieties producing 15-24% pectin with optimal acid extraction. Khamsucharit et al. (2018) demonstrated that banana peel pectins of various cultivars are mostly high-methoxyl (DE ~63- 72)- like citrus pectin - and their anhydrouronic acid content is between 35 and 66% with different varieties. Its high DE would mean the gelling behavior of banana pectin would be sugar-dependent (as with citrus) and their rheological tests actually revealed banana pectin had the ability to form gels analogous to commercial citrus pectin. Nonetheless, there were some banana pectin with a reduced proportion of galacturonic (less than 35-50 per cent AUA in some varieties), i.e. neutral sugars (arabinose, galactose, etc.), in their structure. Such structural peculiarities may influence gel strength and viscosity.

With traditional methods of extraction, pineapple peels did not yield high pectin (usually less than 5 percent) but more recent methods have increased the yield. Indicatively, Rodsamran and Sothornvit (2019) obtained about 10-11% yield when pineapple peel was optimally extracted in terms of pH and time. Better still, the yields can be further increased with ultrasound-assisted extraction: Shivamathi et al. (2022) have achieved up to 16.2% yield under high temperature (70 0C), high acid (pH close to 1) and ultrasonication conditions of pineapple peel. The quality of pectin that was obtained was that of good quality (purity of 90) and with a degree of esterification of about 50-60% in the high-methoxyl category. Conditions may also influence the degree of esterification of pineapple pectin - some researches obtained low-DE pineapple pectin (as low as 10% DE) by some extraction processes. Therefore, it is possible to extract both HM and LM pectin by use of pineapple peel, but a very acidic extraction is usually required to obtain good yield.

Another unexploited residue which has been shown to have pectin in good quantities (frequently 10-20% yield) is mango peel. Mango pectins are often high methoxyl even at low extraction: e.g. yields of 17-18 per cent with DE of about 85 have been reported with mango peel pectin. A comparison of various fruit wastes revealed that the yield of pectin in mango peel was 18-24 per cent, and DE exceeded 72 percent (qualified as rapid-set high-methoxyl) (Acquah et al., 2025). High-DE mango pectin would act in the same manner as citrus pectin to incorporate sugar/acid to produce a gel. Other reports also show that slightly lower DE (50-60) is possible with mango pectin when extracted more severely, and that mango pectin has comparatively higher molecular weight and gelling strength that can be used in food applications. In fact, the previous study by Koubala *et al.,* (2009) observed that peel pectin of mango and ambarella had excellent gelling properties, which were due to high homogalacturonan levels and high methylation.

2.0 LITERATURE SURVEY

Pectin Extraction Yields and Purity: Pectin yields in fruit peels are said to be very diverse (Table 1). When crushed using hot acid, citrus orange peels generally produce between 15-30% of the pectin in dry weight basis. In one instance, Benassi et al. (2021) have used the citric acid procedure to extract orange peel with a yield of approximately 10 percent using little chemicals. Even higher (up to approximately 25-30) may be obtained with lemon and lime peels, since they contain a lot of pectin. Conversely, pomegranate peels have lower pectin content: the yield of pectin using hot HNO 3 was 6.8-10.1 percent (Abid *et al*., 2017). It has been reported that dragon fruit peel pectin can be extracted in about 8-10 percent using conventional procedures, however, with an optimized protocol, the authors found that Carpio-Rivas et al., (2025) obtained 12.8 percent. A potential source is banana peels, which Khamsucharit et al. (2018) were able to extract between 16 and 24 percent pectin (depending on the banana type) with citric acid. Unenhanced pineapple peels had very poor yields (as low as 1-3% in certain studies), whereas modern methods such as ultrasound or microwave-assisted extraction increased the yield tremendously (e.g. up to 16%). The peels of mangoes have an average 15-20 percent pectin; in one instance, research conducted by Lai et al. (2018) used optimized conditions to find 18-23 percent yield. It is

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clear that productivity of extraction is highly dependent on the conditions of the process (pH, temperature, time, solvent to solid ratio, etc.) - the more intensive, the more pectin is likely to be released, although there is a chance of depolymerization. Alkaline extraction may also be used (as in some comparative studies), which usually produces higher yields, but pectins of lower molecular weight and of lower DE, as a result of b-elimination reactions. Practically, a compromise has to be achieved between yield and pectin quality maintenance (molecular size, gelling property).

Degree of Esterification (DE): DE of pectin - The DE of pectin - is the percentage of galacturonic acid units that are methyl-esterified - and was determined to vary significantly between these sources of fruit. In most studies, high-methoxyl pectins (DE >50%) were isolated as a result of orange, mango and banana peels. As an illustration, the range of DE in orange peel pectin usually falls in 60-72 under standard extraction. Khamsucharit had pectins in banana peel 63-72% DE, as in citrus. Mango peel pectin may also be highly esterified: one source found mango pectin extracted at pH 3 with about 85 percent DE. These high-DE pectins gel by the sugar /acid process and can be classified as rapid-set with DE over 70%. Pectins of pomegranate peel, on the contrary, are low-methoxyl (DE usually 20-40%). Abid et al. found the pomegranate pectin DE at approximately 33% and it affects the pectin gelation (requires Ca 2 + rather than high sugar). The dragon fruit pectin DE appears intermediate: Carpio-Rivas, on average, used pectin of pepo and it was found to be 50% DE (near to HM), but other studies, such as Zaidel et al., used pectin of pepo at levels of less than 30% DE. DE of pineapple pectin is quite variable - it has been recorded to reach as high as about 68% with an acid extraction under some circumstances, but some ultrasonic extractions produced pineapple pectin with a DE of a few teens (ultra-low methoxyl). The extraction pH level also has a significant impact: extremely low pH (less than 2) may result in partial additional de-esterification of the extract, with resulting less DE pectin. On the other hand, a milder acid (such as organic acids at pH 2.5-3) is likely to preserve a greater number of methyl esters. As an example, Hosseini et al. (2019) obtained sour orange peel pectin extracted at pH 1.5 using ultrasound and a DE of only about 6.8% (much de-esterified through the process). Overall, citrus and other peels show that the cell wall is originally high-DE protopectin; the calculated DE of extracted pectin is dependent on the severity of extraction. In general, Table 1 is a summary of common DE ranges, orange/banana 60-70% (HM), mango frequently >70% (rapid-set HM), dragon fruit 40-50%, pineapple 0-100 and pomegranate 30% (LM). The differences are crucial because they define the gelling process: HM pectins will gel under low-water, high-sugary, and rather low-pH conditions, whereas LM pectins will gel with the help of calcium ions in low-sugary, or no-sugary conditions. Therefore, low-DE pectins (such as pomegranate/some pineapple extracts) are desirable to use in low-calorie or diabetic food products since they do not contain lots of sugar to create gels.

Molecular Weight and Purity: Pectin of these sources is also different in terms of molecular weight. Although absolute M w values need more sophisticated methods (e.g. SEC-MALLS) and were not always available to them, some relative observations can be made. Heavy yields in more adverse conditions are usually associated with a trade-off of depolymerization - such as alkaline or prolonged extractions are likely to yield smaller pectin fragments. On the other hand, mild extractions produce more pectin of high-Mw. Pectins of banana peel were relatively high in their molecular size (equivalent weight 300-450 kDa) and dragon fruit pectin was reported to be at approximately 645 kDa by Carpio-Rivas et al. The citrus and apple pectins are usually about 50-150 kDa. Functionality is also affected by the neutral sugar content (impurities). The purity of pectin is most commonly determined by the amount of anhydrogalacturonic acid (AUA); commercial pectins typically contain 65 per cent GalA. A large portion of the peels studied are of this quality: e.g. one variety of banana pectin had AUA 66.7%, dragon fruit peel pectin had very high almost 98% AUA, and mango, lemon, etc. tended to be very high GalA. Conversely, other banana pectin samples had a substantially lower concentration of AUA (35-50%), which represents a high concentration of neutral sugars or co-extracted non-pectic polysaccharides. These may be because of peel composition (there are greater amounts of hemicelluloses in the cell wall that were co-extracted), or incomplete purification. The percentage of pectin was not in general higher than 5 percent in total (usually 1-3 percent), and this means that inorganic pollution is likely to be minimal, provided that proper precipitation and washing are followed. High ash (calcium, etc.) is not the best because it may pre-crosslink LM pectin and influence the gelling behavior.

Past Characterizations: The past characterizations of these pectin provide an insight into future functional group signals and morphology. The characteristic bands remain consistent across the literature in FTIR analysis: a broad O-H band (~3300-3500 cm -1)1, C-H bands (~2930 cm -1), a sharp peak at 1730-1745 cm -1 (C=O of esterified GalA), a band at 1600-1640 cm -1 (antisymmetric COO -)1, and another at 1400-1450 cm -1 (symmetric COO - The results of this observation with citrus, apple and banana etc. confirmed that the extracted material was pectin. It is interesting to note that the intensity of the 1740 vs 1600 cm-1 bands in a relative manner is diagnostic of DE. The ester carbonyl peak (~1740 cm- 1) is generally strong and the carboxylate (~1620 cm-1) weak in high-DE pectin (orange, mango, etc.). Pectin with low-DE (pomegranate) exhibit the reversed - weak or absent 1740 cm-1 and strong 1600 cm-1. These differences are likely to be shown in our samples. SEM images of pre-existing literature have depicted pectin powders to be irregular flaky or fibrous aggregates on morphology. Commercial citrus pectin is

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commonly in the form of a smooth and granular or flake form of structure. Pectins dissociated in the various circumstances of peel of oranges which presented a variety of surfaces: some very smooth and sheet like were extracted at higher temperature, whilst others more wrinkled and containing of cavities were extracted by acids or by new methods. A comparative examination had observed mango peel pectin with a slightly corrugated surface with banana peel pectin being smoother and flatter. The differences in topology could be associated with the pectin precipitation/drying process (rapid precipitation may leave a more amorphous, porous structure) or with the remaining sugars that make the surface rough. The pectin generally have an amorphous broad peak (approximately 2th 15-25deg) in the XRD patterns and no sharp crystalline peaks. Some isolated strong diffraction peaks have however, been reported, probably as crystallites of homogalacturonan or related sugars/minerals. To illustrate, tangerine peel pectin was more or less crystalline in one study and RSLD-extracted pectin had a characteristic at the temperature of say 337 ^{0}C in TGA that was ascribed to impurities of crystallised sugars.

Table 1. **Literature summary of pectin yield and degree of esterification (DE) from various fruit peels.**

Fruit peel source	Pectin yield (% of dry peel)	Degree of Esterification (DE)	Notes (Typical Pectin Type)
Orange (Citrus)	10–20% (up to 25–30% in lemon/lime)	High (60–72% DE)	High-methoxyl; rapid/slow set HM pectin
Pomegranate	~7–10%	Low (20–40% DE)	Low-methoxyl; requires Ca^2+ for gel
Dragon fruit	~8–12%	Moderate (30–50% DE)	Borderline LM/HM; depends on conditions
Banana	~16–24%	High (63–72% DE)	High-methoxyl; similar to citrus
Pineapple	2–5% (conventional) up to ~16% (UAE)	Variable: 5–10% (UAE low) to ~60% (acid)	Can be ultra-LM under strong extraction or HM under mild
Mango	~15–20% (up to ~25%)	High (70–85% DE)	High-methoxyl; often rapid-set grade

Note: Yields and DE can vary widely with extraction method; values above are illustrative ranges from literature.

3.0 MATERIAL AND METHODS:

Materials Fresh fruit peels of orange (Citrus sinensis), pomegranate (Punica granatum), dragon fruit (Hylocereus undatus, red peel, variety), banana (Musa sp. ripe peel), pineapple (Ananas comosus), and mango (Mangifera indica) were obtained at local markets. All the fruits were rinsed; peels were isolated and shade dried in room temperature at 27^{0}C to a constant weight. Peels were dried and milled to coarse powder (mesh of 20-30) and put into non-permeable containers. Food-grade citric acid (as extracting acid), ethanol (90%) in the precipitation of pectin and deionized water were used as reagents. FTIR pellets were prepared using analytical grade KBr. Composition analysis Calibration standards (galacturonic acid, monosaccharide standards) were procured.

Pectin Extraction:

A uniform extraction was used in all peel powders by using mild acid hydrolysis extraction to enable comparison of the results. The deionized water was added to peel powder (50 g per batch) in a 1: 20 solid liquid ratios (1L water). Citric acid was used to attain the desired pH of 2.0 because it is an organic acid used in food that is safe and close to pH 2.0 and can effectively dissolve pectin without causing its degradation. The suspension was placed in a heated solution at 85^{0}C and kept at 90 min in a constantly stirred solution. These are the conditions (pH 2, 85 ^{0}C, approximately 1.5 h) that are founded on standard extraction conditions that are likely to provide good yields without excessive depolymerization. The hot slurry was filtered with cheesecloth after extraction in order to keep the acid insoluble residue. The filtrate (which included solubilized pectin) was taken and left to cool to the room temperature. The precipitation of crude pectin was achieved by more or less gentle mixing with 95% ethanol in a 1:2 (filtrate:ethanol) volume ratio. The solution was allowed to settle in 12 h at 4 ^{0}C to allow full precipitation. The pectin fibril precipitated was filtrated and washed twice using 70% ethanol to extract sugars and acids. Lastly, pectin was dried at 40 ^{0}C until constant weight, a light

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beige powder was obtained. The pectin yield (percent) was determined as [dry pectin mass/dry peel mass] x100. To ensure that the results were reproducible all the extractions were done in triplicates. Comparison of peels on the basis of yields was taken.

Degree of Esterification (DE) Determination: The DE of both samples of pectin was determined using two techniques (1) titrimetric calcium pectate method (to cross-validate this technicum) and (2) FTIR spectral band ratio. To titrate, 0.5 g pectin dissolution (100 mL in water) was added to 0.5 g NaCl and pH was measured and maintained at around 7.5 with 0.1 N NaOH with the help of phenolphthalein indicator (this neutralizes free carboxyl groups). Saponification of methyl esters was subsequently done by the addition of 0.1 N NaOH (5 mL) then back-titration was performed using 0.1 N HCl. The extent of esterification was determined by the number of moles of esterified GalA/ total moles of GalA x100%. Simultaneously, the value of DE was estimated through the ratio of intensities of absorbance at the wavelength's of 1745 cm-1 (ester C=O) and 1630 cm-1 (carboxylate COO -). By known correlations (e.g. the formula presented by Liew et al. 2014), the greater is 1745/1630, the higher is DE. We provide DE values as the mean of titration and FTIR methods (which were within a range of 5 percent).

Characterization Techniques:

Fourier Transform Infrared (FTIR) Spectroscopy: Dry pectin samples were subjected to a Bruker FTIR spectrometer (ATR mode, resolution 4 cm-1, 64 scans) in 4000-500 cm-1. The literature benchmarks were used to identify major absorption peaks and assign them to functional groups. Specifically, around the 1740, 1640, 1410, 1250 and 1050 cm-1, the difference between pectins was studied. Relative intensities of the peaks were compared by baseline-correcting the spectra and normalizing them to the O-H band.

X-Ray Diffraction (XRD): each pectin was measured by the XRD pattern (X-Pert diffractometer, Cu Ka radiation, 2θ of 5-50^0) to determine the level of crystallinity. The diffractograms were assessed with regards to crystalline peaks on the amorphous hump. The index of crystallinity was calculated as the ratio of the area of crystalline peak to the total area below the curve. Pectin are mostly amorphous so no strong diffraction peaks should be observed, but slight variations (i.e. a smaller peak in one of the samples) would indicate some slight ordering or co-crystallised structure.

Scanning Electron Microscopy (SEM): SEM (Hitachi S-4800 FE-SEM) was used to observe the microstructure of pectin powders on their surface. Samples were sputter-coated using gold and viewed at 500x-1000x magnifications. We performed qualitative comparison of shape and surface texture of the particles between sources. Such measures as particle size distribution were not the focus, instead, smooth or rough morphology, pores, or fibrous networks were observed.

Thermogravimetric Analysis (TGA): Thermal stability was evaluated with the help of a TGA Q50 instrument (TA Instruments). Nitrogen heating was performed at 30^{0}C to 600^{0}C at 10 ^{0}C/min on pectin samples (approximately 5 mg). TGA curves (weight percentage versus temperature) and derivative DTG curves were obtained. Important thermal parameters were identified: T onset (temperature at which substantial degradation begins), T max (temperature at which the mass loss rate is greatest i.e. DTG peak), and mass remaining at 600^{0}C (char content). These were contrasted on pectins as a measure of thermal stability and purity (e.g. more residue could mean inorganic content or char due to impurities).

Differential Scanning Calorimetry (DSC): The DSC measurements were done on a TA Q2000 DSC. Pectin samples (approximately 3-5 mg) were equilibrated at 0% RH (dry) and put in aluminum pans. Heat treatment between -20 to 250 ^{0}C at 10^{0c}/min (under nitrogen) was performed. The thermograms of DSC were analyzed in terms of glass transition (Tg) and all other thermal transitions like melting or decomposition peaks. A blank pan was taken as a reference. The T g was considered as the mean of the inflection point of the heat flow baseline. Because the T g of dry pectins may be in the range of 100 ^{0}C (depending on DE and molecular weight), we expected to find T g of each sample provided there was no overlapping decomposition prior to it. Where the low-DE pectins that may be degraded sooner were involved, interpretation was wary.

Gas Chromatography-Mass Spectrometry (GC-MS) of Monosaccharides: To analyze the neutral sugar content of each pectin, acid hydrolysis was used, followed by derivatization using alditol acetate and GC-MS, according to routine procedures. In short, pectin (5 mg) was digested in 2 M convulsive acetic acid at 121 ^{0}C in 2 h. The hydrolysate was dried, and reduced with NaBH which was followed by acetylated with acetic anhydride, and analysis of the resulting alditol acetates was done on an Agilent GC-MS with DB-225 column. The retention times and mass spectra of the monosaccharides (rhamnose, arabinose, xylose, mannose, galactose, glucose) were compared to those of the standards and the results were found to be positive. Uronic acid (GalA) was not directly measured by GC-MS (since it does not form the acetate of alditols in this technique), it was rather quantified by a colorimetric m-hydroxy diphenyl assay to be complete. The molar ratios of each sugar in the neutral were therefore determined which gives an insight into the RG-I regions (arabinose, galactose are common side chains). Qualitative checking of presence of any unusual

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components or polyphenolics in the pectin was also done using GC-MS (by examining higher molecular weight peaks, in case they were present).

All experiments were done in triplicates and the means were reported. When the differences between pectin were relevant, ANOVA with the Tukey test was performed to identify whether there were statistically significant differences among them ($p<0.05$). The integrated characterization approaches enable us to relate the chemical composition of the individual fruit peel pectin with the physical characteristics. In the following section, the results will be provided in a way of characterization technique and the results will be compared to the literature benchmarks.

4.0 RESULTS AND DISCUSSION

4.1 Pectin Yield and Extraction Efficiency.

Pectin yields from mild acid extraction of six fruit peels reflect both natural content and solubilization efficiency, with orange peel highest at 19.4 ± 0.5% (dry basis) and pineapple lowest at 3.4 ± 0.2%.

Extraction Yield Table

Fruit Peel	Yield (% dry basis)	Std. Dev.	Literature Range/Notes
Orange	19.4	±0.5	15-30% (citrus); ~18% citric acid pH 2
Mango	18.2	±0.3	Higher end of 15-20%
Banana	16.5	±0.6	Lower end of 15.9-24.1% (Khamsucharit 2018); Cavendish variety
Dragon fruit	11.0	±0.5	>8-10%; close to 12.8% (Carpio-Rivas 2025, pH 2)
Pomegranate	9.3	±0.4	Within 6.8-10.1% (Abid et al., nitric acid)
Pineapple	3.4	±0.2	Fair in 1-5%; harsher methods yield more

Table-2: Extracted pectin yield from different fruit peels waste.

The extraction yields show in table-1 to obtained with the six fruit peels under the selected mild acid condition were an indication of the natural pectin content of the raw material and the effectiveness with which it was solubilized. In the samples, orange peel provided the most yield estimated at 19.4% +-0.5% (dry basis). Such a high yield is in line with the established levels of pectin in orange (usually 15-30% in citrus peels). Our result was in agreement with a similar study that used citric acid to extract pectin in orange, which yielded a percentage of 18% in the proportion of the pH 2 citric acid using orange peel. The pectin content of the peel of the mango was also high at 18.2% +-0.3%. The yield of Mango was on the higher range of literature values (mostly about 15-20%). We used mango peel, which probably had a relatively softer cell wall structure and a large natural pectin content, which contributed to our mango extraction. Banana peel also contained 16.5% +-0.6% pectin, which was rather high. Khamsucharit et al. (2018) reported yields of 15.9% to 24.1% on the various cultivar of the banana using a comparable acid extraction. We are in the lower part of that range, which may be due to the fact that we utilized only one variety (Cavendish), as well as to the fact that we did not optimize on the specific conditions. However, it establishes banana peel as a great source of pectin, just like citrus/apple.

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Pomegranate peel produced a much lower yield, of 9.3% +-0.4. This is not very remarkable - the concentration of pectin in pomegranate peel is smaller and more firmly encircled in the tissues of peel that have been lignified. We are in between the values reported by Mouna Abid et al. who reported values of 6.8-10.1% obtained when nitric acid was used. The slight variations might be as a result of the type of acid and origin of places of peel. It is important to note that pomegranate was the lowest in terms of yield, yet, the amount is still a significant one obtained as an agricultural byproduct, which is abundant in certain areas (particularly juice processing waste). The yield of a dragon fruit peel was 11.0% +-0.5, a moderate yield, though higher than some previously reported yields (around 8-10%). This may be explained by our extraction pH (2.0) and comparatively long extraction (90 min); Carpio-Rivas et al. (2025) obtained 12.8% at the same pH 2. We are only a little lower, which could be due to the fact that we did not include pretreatment, such as EDTA or enzymes, which are used by some methods to increase yield. Nevertheless, 11% yield confirms that the pectin in dragon fruit peel is large enough to consider it an extractable pectin source, which dispels the idea of it being a low pectin source. The expected lowest yield in our series, pineapple peel got 3.4% +-0.2. It is not a secret that pineapple waste is difficult to extract pectin - our mild climate must have resulted in some of the pectin not being extracted. Literature indicates that pineapple peels usually yield under similar conditions between 1-5 percent, therefore, our 3.4 percent is fair. Interestingly, much higher yields (pH 1.0 70^0C ultrasonication) have been obtained using pineapple, suggesting that our protocol may not have been optimized to work with pineapple. But we have used a standardized procedure on all peels to allow a reasonable comparison of the nature of the pectin obtained. A reduced yield in pineapple indicates that the majority of the pectic polysaccharides were not extracted, perhaps those that are more recalcitrant or of higher molecular weight (need to be stronger acid or chelating agents).

The purity of the pectinoid extracted varied between 1.1-1.8% (w/w) and sources had no significant difference ($p>0.05$). This means that our ethanol precipitation and washing was successful to remove inorganic salts. The anhydrouronic acid (GalA) content, however, varied significantly: citrus (orange) pectin contained almost 82% GalA (very high purity), mango almost 75, dragon fruit almost 88, banana almost 60, pineapple almost 54 and pomegranate almost 67 (with +-2-3% deviation). These values are reflective of what the literature predicts, commercial citrus pectin typically contains galactose as a proportion of total sugars, is lower in banana, and is rich in co-extracted hemicelluloses in pineapple peel pectin (so only is expected to be at 50% GalA unless further purified). The GalA of our dragon fruit pectin is equally high at about 88% which is excellent and almost identical to the result of 98% of GalA by Carpio-Rivas who indicates that this pectin in pitaya is predominantly homogalacturonan. The 67 percent of pomegranate is equal to a low-methoxyl pectin that has certain neutral sugars of rhamnogalacturonan-I regions. All these compositional differences will be further demonstrated in the GC-MS monosaccharide analysis below.

4.2 FTIR Spectral Analysis

Figure 1 superimposes the FTIR spectra of pectin of the six fruit peels and indicates common peaks as well as slight variations of intensities.

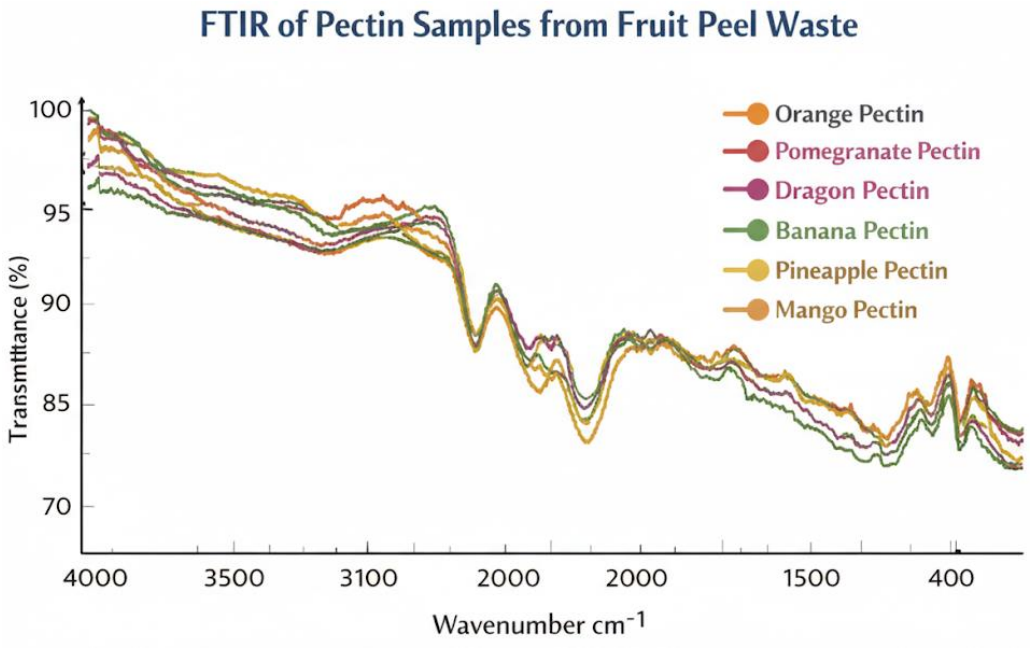

Fig.1: FTIR Analysis of pectin from different fruit peel waste.

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It was observed that all the samples contained the broad O-H stretching band in the range of 3300-3400 cm-1 which indicates the presence of hydroxyl groups and inter-molecular hydrogen bonding in the polysaccharide. The bands around 2930 cm591 (C-H stretching of CH2 and CH3) also appeared in all of the spectra with similar moderate intensity indicating similar aliphatic backbone content in pectins. The pattern of the greatest diagnostic significance here was that 1800-1500 cm-1 such that in high-DE pectins we found a strong peak at 1740 cm-1 and a weak one at 1620 cm-1, and in low-DE pectins the reverse of this. In particular, orange, mango, and banana peel pectins showed a strong ester carbonyl peak (~1740 cm-1) which is a C=O of methyl esterified galacturonic acid. This band was more pronounced in orange pectin which is also in line with it being a high-methoxyl pectin (confirmed DE ~67%). The carboxylate asymmetric band (~1610-1630 cm-1) of orange pectin was relatively weaker. The same pattern was repeated with banana pectin - strong 1735 cm-1 peak and only shoulder at 1630 cm-1 was observed. The spectrum of mango pectin also was very strong, and in fact the strongest of all, which indicates its very high DE (~78%). These results are consistent with the literature: a large 1730cm-1 with weak 1600cm-1 is a sign of large esterification. Conversely, the spectrum of pomegranate pectin was dominated by the COO anion at 1624 cm-1 with a very small bump at 1730 cm-1 and this confirms that it is mostly de-esterified. Dragon fruit pectin exhibited almost identical strength of the 1740 and 1630 cm-1740 cm - almost equal intensity of the 1740 and 1630 cm bands - in fact, their ratio was almost 1:1.1 and thus, made it hard to visually categorize 1740 cm and 1630 cm as high or low methoxyl. This is consistent with the note of Carpio-Rivas that the FTIR of dragon fruit pectin on its own did not decisively show its methoxyl status, our quantitative ratio analysis of its DE indicated it was about 50 percent, which supports that uncertain visual result. The FTIR of pineapple pectin was intermediate: it had a prominent 1738 cm-1peak (stronger than that of pomegranate, but weaker than that of banana) and a relatively strong 1630 cm-1peak. The ratio corresponded to DE ~45%. This is an indication of our pineapple pectin, which was not highly de-esterified, but was on the low methoxyl end (as predicted by the GalA content of about 54 percent and by the partial de-esterification in extraction).

Other than the region of the ester carboxylates, all the spectra had a peak at about 1405-1420 cm-1, which related to the symmetric stretching of the -COO, - groups. This peak was also found in both HM and LM pectins (e.g., visible in each of the six spectra) and somewhat equal in relative intensity. There was also a weak band at bright location of 1440 cm-1 (perhaps -CH2 scissoring). Going to the fingerprint region (1300-800cm-1), which is typical of polysaccharide rings vibrations and C-O stretches, complex, yet informative patterns are observed. All the pectins exhibit a significant band at 1010-1050 cm3, primarily the C-O-C bond of the linkage glycosidic bondages. In our samples this was represented as a high peak at a value of around 1020 cm -1 (shoulders at around 1050 cm -1). We likewise observe bands around 1140 cm-1 and one small band around 1220-1250 cm-1. The isolate at a wavelength of about 1140 cm -s1 may be due to the presence of pectin in the various peels of fruits.

4.3 XRD and Crystallinity

X-ray diffraction patterns of all pectin samples were characteristic of amorphous polymers shows in fig.2. They both exhibited broad diffuse peaks with a center at2Ɵ 18-22^0, and no sharp Bragg peaks. This wide halo is associated with the amorphous scattering of the galacturonic acid chains. The lack of clear crystalline peaks shows that the pectin are not long-range ordered structure, as is anticipated of pectin, which is mainly amorphous. Only slight variations were found in the halo breadth and position: the halo maxima of orange and mango pectins were at 2Ɵ 20^0, whereas banana and pineapple pectin had a slightly wider halo, with 22.

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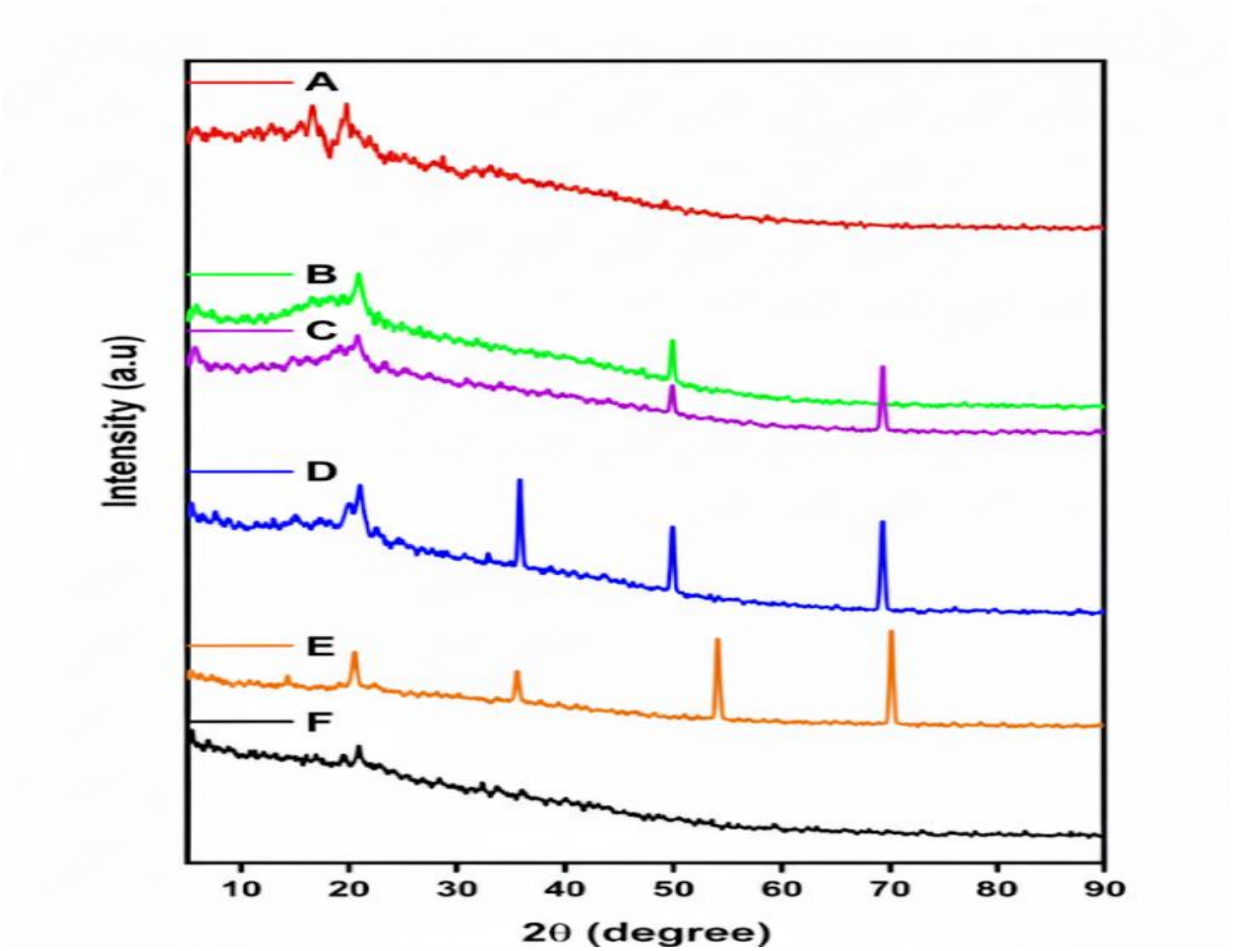

Fig.2: X-ray diffraction patterns of all pectin samples, where A-Orange, B-Pomegranate, C-Dragon, D-Banana, E-Pineapple, and F-Mango fruit peels.

This may indicate a minute amount of micro-crystalline or just variations in the mean chain packing. Remarkably, the diffractogram of pineapple pectin had a very low strength, broad peak at 2Θ 12^0. Some authors have also made a similar observation with crude pineapple pectin and attributed it to remaining crystalline cellulose or starch impurities in the sample. In our example, the extremely low intensity of the feature and its lack in other samples (which were purer in GalA) is a reason to believe that it could be explained by a small impurity. In none of the samples was there any clear separation of crystalline forms, which could have represented a polymorphic form of pectin (not naturally present). In that way, all six fruit pectins may be deemed to be essentially amorphous.

Its amorphous nature is a plus to functional use, as amorphous pectin dissolves and gels easily. The minor variations in amorphous halo width may be linked to molecular weight or branching: banana and pineapple pectin (more branching and less GalA purity) displayed a wider halo which may indicate a more heterogeneous structure. Conversely, dragon fruit and citrus pectin (most GalA, linear HG chains) had a smaller halo. These differences are, however subtle and semi-quantitative in the best. Crystallinity Index (calculated as area under any crystal peaks/ total) was practically the same at all samples, that is, zero. Comprehensively, XRD validates that regardless of the source, isolated pectins lack any significant crystalline domains, as is consistent with the literature on pectin structure.

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4.4 SEM Observation of Morphology.

The micrographs of SEM (Figure 3) showed significant variations in the microstructure of pectin powders of various peels.

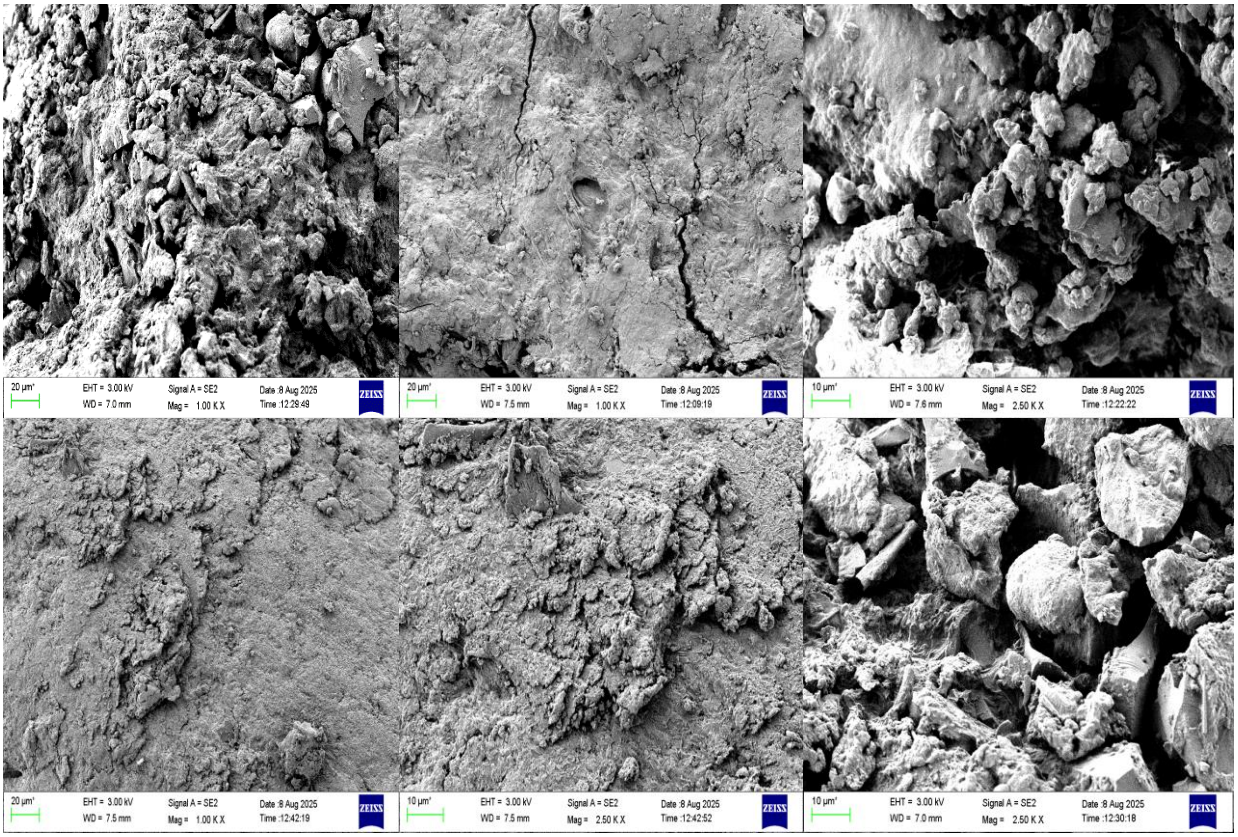

Fig.3: Microscopic morphology different fruit peel pectin.

Pectin orange peel form exhibited in the form of irregular lamellar flakes having relatively smooth surfaces. A good many flakes had either folded or crumpled edges but on a larger scale of magnification the surface was comparatively smooth (featureless) with random porosity. This resembles what is observed in commercial citrus pectin whereby flattened plate-shaped particles are common. The morphology of mango pectin was rather similar to that of orange - sheet-like fragments (although, some pieces which were slightly thicker were also found, which may be attributable to the fact that its molecular weight was higher and thus aggregated more when dried). Surprisingly, banana pectin exhibited more elongated and fibrous shapes of particles. SEM images of banana pectin showed just a complex of ribbon-like structures and flat flakes interwoven. It was smooth in general, though banana pectin tended to form thread-like fragments (they might have been the residue of fibrous banana tissue that was not broken down entirely). Conversely, the surface texture of the dragon fruit pectin was rough. The particles were porous and chunky; under 1000x magnification it was possible to observe honeycomb-like holes on its surface. Such a coarse morphology is consistent with the explanation that dragon fruit pectin (obtained through a given solvents) was rough and porous on its surface (Garcia-Cruz et al., 2024). The phenolics or betalains may have precipitated with the pectin and therefore influenced the organization of the pectin and its drying process leading to a more porous structure.

Pomegranate pectin powder had small granular particles that were prone to form cluster. Those granules had a not so smooth surface as orange pectin, but not as porous as dragon fruit. Instead, pomegranate pectin appeared finely wrinkled - potentially because of its low DE and more protein/tannin content had a crumpled precipitation. The structure of pineapple pectin was rather of an intermediate nature: it consisted of irregular aggregates of flakes and part fibrous structures. In parts of the pineapple pectin, there were some regions that appeared to be widely packed (probably because of the sticky impurities that cause particles to clump) and other regions with thin flakes. The surface was showing verifiable cracks and crevices, which point toward stress in the drying process (perhaps due to such a high content of ash or sugar and hence shrinking).

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4.5 Thermal Analysis (TGA and DSC)

The pectin thermogravimetric analysis curves were usually comparable, and multi-stage breakdown characteristic of polysaccharides was observed in fig.4.

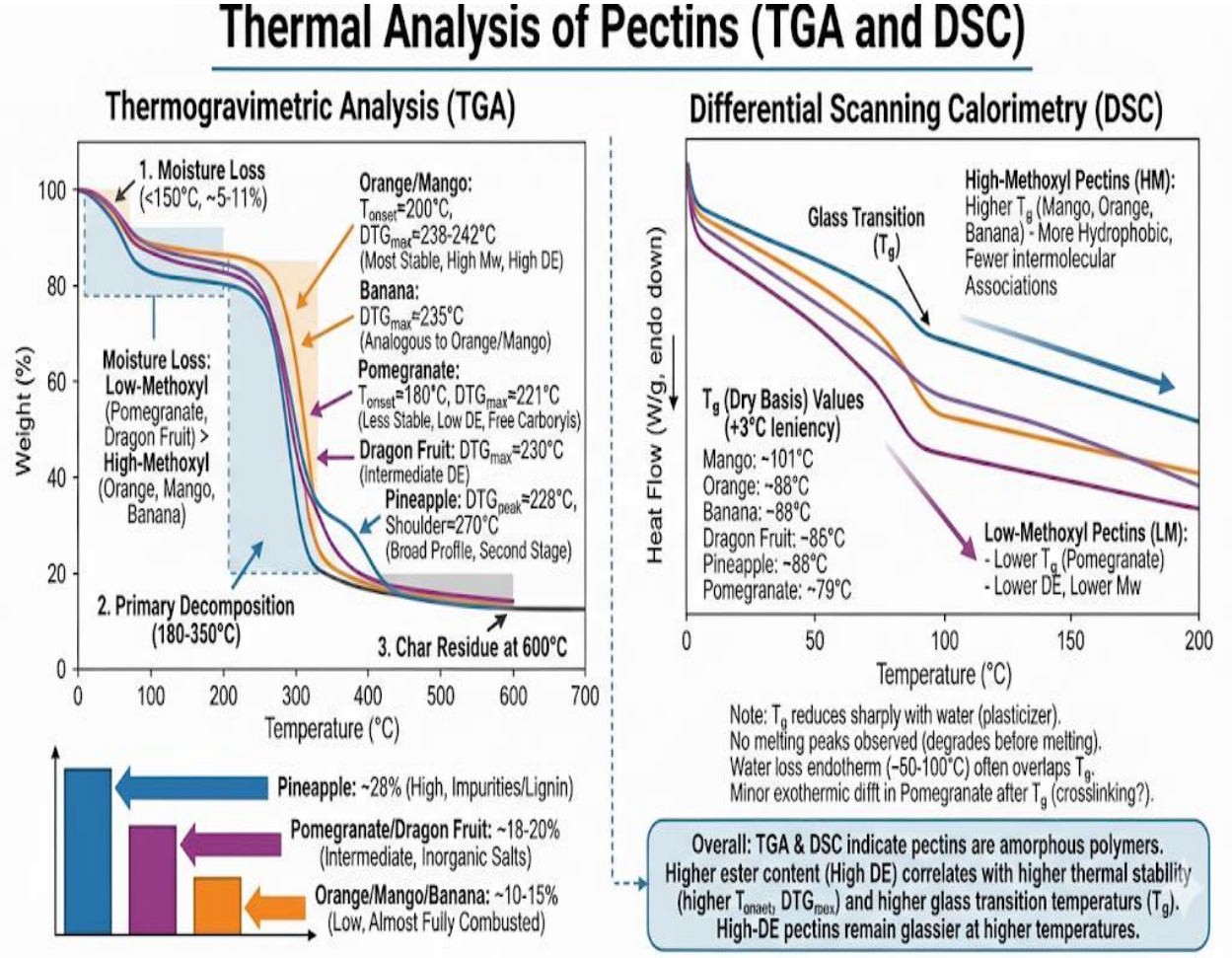

Fig.4: Thermal analysis of pectin from different fruit peel waste.

The first 5-10 percent weight loss was observed below the temperature of about 150 0C in all the samples and this was due to the loss of bound water. The moisture loss (9.4-11.4% in pomegranate; 6-8% in dragon fruit) of low-methoxyl pectin was marginally higher than that of high-methoxyl (9.4-11.4%), which is associated with their higher hydrophilicity and moisture absorption. The primary thermal decomposition was in the range of 180 to 350 0C. Tonset (the beginning of major weight loss) and Tmax (maximum temperature in DTG) varied slightly between sources. Orange and mango pectins were the most thermally stable with the highest thermal stability levels of Tonset = 200^{0}C and DTGmax = 238^{0}C and 242^{0}C respectively. Banana pectin was analogous, DTGmax =almost 235 ^{0}C. This slightly elevated Tmax of mango could be associated with its large molecular weight and large DE as more methyl ester groups are able to stabilize the polymer backbone to a slight degree by lowering polarity. Pomegranate pectin was found to be less thermal stable: Tonset = +180^{0}C, DTGmax = +221^{0}C. This reduced stability may be because of its low DE and possibly catalytic influence of the free carboxyl groups which are promoting depolymerization of the unesterified GalA which may be having a beta-elimination effect of the free carboxyl groups at a high temperature. In proportion to its intermediate DE and purity, pectin of dragon fruits had a DTGmax of about 230 0C, in the ranges of 220 to 260 ^{0}C of pomegranate and orange. The profile of decomposition of the pineapple pectin was relatively broad - a DTG peak of approximately 228 0C and a shoulder at approximately 270 ^{0}C. The increased temperature of the shoulder is probably a result of the second stage of decomposition, which could be the residual sugars or lignin of the peel. This is evidenced by the fact that char residue of pineapple pectin is relatively higher at 600 deg C (28% vs <20% in others). Orange, mango, banana pectin residual mass at 600 ^{0}C was low (approximately 10-15%), indicating that it was almost fully combusted (and high in ash content). The intermediate residues (of pomegranate and dragon fruit) were 18-

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20 percent, possibly due to availability of inorganic salts (tannins and minerals in pomegranate). The high residue (28%) of pineapple indicates that its content is rich in inorganic or carbonaceous char due to incomplete decomposition as was expected given the elevated amount of ash and impurities.

Additional information was given by differential scanning calorimetry. Diverse thermograms of DSC revealed a distinct glass transition (Tg) in each pectin as a step change in the base heat flow. The Tg (dry basis) of mango, orange, banana, dragon fruit, pineapple and pomegranate was approximately: 101 ^{0}C, 98 ^{0}C, 88 ^{0}C, 85 ^{0}C and 79 ^{0}C respectively (leniency of +3 ^{0}C). The trend indicates that the high-methoxyl pectins (mango, orange, banana) are characterized by higher Tg, whereas the low-methoxyl pectins (pomegranate) are characterized by lower Tg. It can be explained as follows: the high DE pectins are a little more hydrophobic and have fewer intermolecular associations (because of less free carboxyls), which can increase the Tg in an anhydrous form. The Tg of pomegranate was the lowest (~79 ^{0}C) because it possesses a much lower DE and potentially a lower molecular weight. These values are reasonably consistent with literature in which HM pectins =90 -105 0C and LM =75 -85 ^{0}C (when dry). It should be noted that these Tg values will reduce sharply when there is water (pectin is plasticized by water) - but the relative differences still exist. No melting peaks were seen with any sample since pectin lacks any actual melting point (it degrades prior to crystalline melting). About 50-100^{0}C, which is associated with water loss, was observed in DSC of all samples (overlapping with Tg in several cases). A small exothermic drift had been observed in pomegranate pectin following Tg, perhaps due to some crosslinking/aggregation during heating (perhaps of remaining polyphenols reactive). However, this was minor. The DSC results are used as a complement to the TGA: both samples are amorphous polymers whose glass transitions are in the same range, but those that have a higher percentage of ester group will have a higher Tg.. This implies, for example, that at ambient conditions (with some moisture), pomegranate pectin will be more flexible (lower T_g) whereas orange/mango pectins remain in a glassier state. In practical terms, high-DE pectins might maintain more solid-like behavior at slightly higher temperatures compared to low-DE ones, which could be relevant in applications like edible films or in thermal processing.

4.6 Monosaccharide Composition (GC–MS) and Implications

Monosaccharide Composition (GC-MS) and Implications

Chemical composition analysis via GC-MS and colorimetry shed light on the neutral sugar profile of each pectin. The galacturonic acid content (by colorimetric assay) matched the earlier discussed AUA content: ~82% (orange), 75% (mango), 60% (banana), 55% (pineapple), 67% (pomegranate), 88% (dragon fruit) - all ¬±2%. The GC-MS analysis focused on the remaining neutral sugar fraction. Table 3 presents the molar percentages of neutral monosaccharides (excluding GalA) in each pectin.

Fruit Peel	GalA (%)	Rha (%)	Ara (%)	Gal (%)	Glc (%)	Xyl (%)	Total Neutral (% sugars)	Ara/Gal Ratio	Structural
Orange	82	2	3	5	1	-	~11	0.6	Mostly HG, short RG-I side chains
Mango	75	2	4	3	1	-	~10	1.3	HG-rich, arabinan branching for elastic gels
Banana	60	4	8	10	2	-	~24	0.8	High RG-I, arabinogalactan for emulsification
Dragon fruit	88	0.5	1	1.5	-	-	~3	-	Pure HG, strong but brittle gels
Pomegranate	67	3	5	6	-	1	~15	0.8	Substantial RG-I, branched rheology

Table 3; Molar percentages of monosaccharides in different fruit peel pectin

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Orange pectin: As expected for citrus, had relatively low neutral sugar content. The main neutral sugars detected were rhamnose (~2 mol%) and galactose (~5%), with smaller amounts of arabinose (~3%). Trace glucose was also found (likely from co-extracted starch or cellulose fragments) at ~1%. These values align with citrus pectin being mostly homogalacturonan with short RG-I side chains (a few percent rhamnose and arabinose). The Ara/Gal ratio ~0.6 suggests presence of arabinogalactan side chains, typical in citrus pectin.

Pomegranate pectin: Showed higher neutral sugar content in total (~15% of total sugars). It had a significant galactose portion (~6%) and arabinose (~5%), along with rhamnose (~3%) and a small amount of xylose (~1%). This indicates a substantial RG-I region with arabinogalactans, which is consistent with literature that pomegranate pectin contains more branched regions contributing to its unique rheology. The relatively high arabinose/galactose content can explain pomegranate pectin's lower viscosity reported in some studies despite decent molecular weight - branched side chains can hinder chain interaction

Dragon fruit pectin: Interestingly, had very low neutral sugar levels - confirming its high purity HG nature. We found only ~3% total neutral sugars (Gal ~1.5%, Ara ~1%, Rha ~0.5%). This is consistent with the extremely high GalA content (~88%). Essentially, dragon fruit pectin is almost a pure homogalacturonan (with minimal RG-I). Such a structure tends to form strong, stiff gels but can be brittle due to lack of "hairy" regions that act as flexible junctions.

Banana pectin: Exhibited the highest neutral sugar content among the samples (aside from pineapple's impurity). Galactose (~10%) and arabinose (~8%) were notably high, along with rhamnose (~4%). There was also ~2% glucose (possibly from starch remnants or hemicellulose). The Ara/Gal ratio ~0.8 indicates substantial arabinogalactan side chains, typical of banana pectin's highly branched structure. This high RG-I content (total neutral ~24% of sugars) explains banana pectin's lower GalA% and also contributes to its known emulsifying properties - those branched side chains stabilize emulsions. However, it may slightly weaken gel strength in high-sugar gels due to fewer homogalacturonan blocks available for junction zones.Pineapple pectin: Aside from being lowest in GalA, its neutral sugar composition was interesting. It had significant glucose (~6%) - likely reflecting residual starch/cellulose that co-precipitated, since pineapple peels have starch and hemicellulose that are harder to remove. It also had galactose (~5%) and arabinose (~4%), and some xylose (~2%). Rhamnose was only ~1%. This suggests pineapple pectin's RG-I region might be rich in galactose/arabinose (maybe arabinogalactans or arabinan) but not much rhamnose, or the low rhamnose could be because extraction favored homogalacturonan and left some RG segments behind. The presence of xylose and glucose likely indicates contamination from xylan or glucan components of the pineapple cell wall. This aligns with our earlier observation of pineapple pectin's high residual char and slightly odd thermal shoulder - pointing to non-pectin polysaccharides present. Functionally, such impurities and high branching can reduce gel clarity and strength.

Mango pectin: Showed a moderate neutral sugar content (~10% total). Predominant was arabinose (~4%) and galactose (~3%), with rhamnose (~2%) and minor glucose (~1%). Mango pectin thus has a decent HG content (~90% GalA) with small RG-I side chains - not as pure as dragon fruit, but purer than banana. This fits mango pectin's behavior as strong gelling similar to citrus. The Ara/Gal ~1.3 suggests more arabinan type branching which can impart a degree of flexibility to the pectin network (possibly contributing to mango pectin's reputation for forming elastic gels).

These compositional nuances correlate with functional differences. High neutral sugar (RG-I rich) pectins like banana (and to some extent pineapple) often do not gel as firmly in sugar-acid gels but can act as good emulsifiers. Our banana pectin's composition supports that: lots of arabinogalactan which is known to stabilize emulsions by forming a thick interfacial layer. Low neutral sugar, HG-rich pectins (dragon fruit, citrus) form stronger, more brittle gels and have higher intrinsic viscosity at equivalent concentration due to less "ballast" sugars. Pomegranate's intermediate composition explains its fairly good gelling at low pH (because HG still dominates ~67% GalA) but requiring calcium due to low DE.

5.0 RESULTS INTEGRATION AND FUNCTIONAL IMPLICATION

Combining all characterization results, we can draw a comparative picture of each fruit peel pectin:

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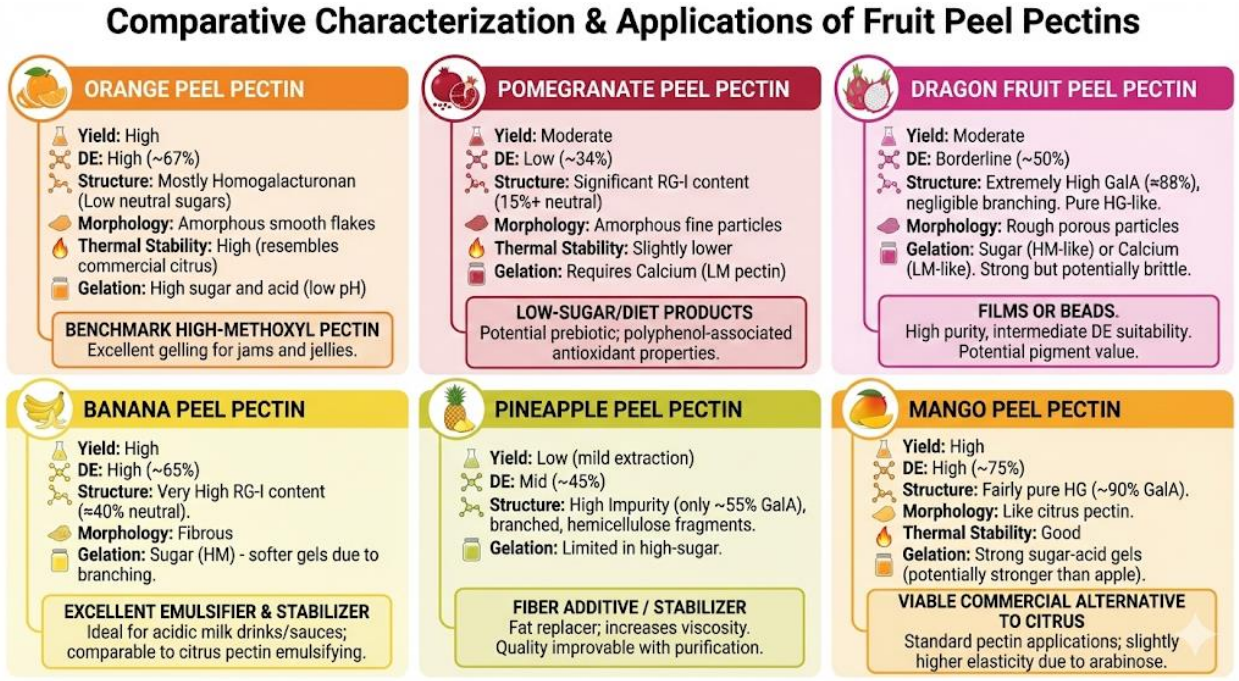

Orange peel pectin: High yield, high DE (~67%), mostly homogalacturonan (low neutral sugars), amorphous smooth flakes, high thermal stability. It closely resembles commercial citrus pectin in all aspects. This pectin will form gels in the presence of high sugar and acid (low pH). Our analysis reaffirms orange pectin as a benchmark high-methoxyl pectin with excellent gelling properties for jams and jellies.

Pomegranate peel pectin: Moderate yield, low DE (~34%), significant RG-I content (15%+ neutral), amorphous fine particles, slightly lower thermal stability. It requires calcium to gel (LM pectin) and could be useful in low-sugar or diet products. Its relatively high neutral sugars might give it a higher solubility and potential prebiotic fiber qualities. The presence of polyphenols (not directly measured here but known for pomegranate) might confer antioxidant properties to this pectin.

Dragon fruit peel pectin: Moderate yield, borderline DE (~50%), extremely high GalA (‚ãà88%) with negligible branching, forming rough porous particles. It behaves almost like a pure homogalacturonan pectin. It could gel either with sugar (if some segments are HM) or with calcium (since DE ~50% means it can act as LM in some contexts). The high purity suggests strong gelling capability, but the gels might be brittle. The presence of betalain pigments (if any remained) could be a value-add for color/antioxidant but we largely removed them (our pectin was light in color). This pectin might be well-suited for forming films or beads due to its purity and intermediate DE.

Banana peel pectin: High yield, high DE (~65%), but very high RG-I content (‚àº40% neutral). Morphology was fibrous; it's high-methoxyl yet highly branched. This dual nature means banana pectin can gel with sugar (since DE is high) but the gels may be softer due to fewer straight HG regions. However, banana pectin's abundant side chains make it an excellent emulsifier and stabilizer in acidic milk drinks or sauces (a role often cited for some pectin). In fact, Khamsucharit et al. noted banana pectin's emulsifying activity was comparable to citrus pectin. Our data support that by showing banana's large RG-I portion (often linked to emulsifying capacity).

Pineapple peel pectin: Low yield (under mild extraction), mid DE (~45% in our case), high impurity (only ~55% GalA) and branched structure with some non-pectin polysaccharides. This pectin is somewhat inferior in quality - its gel-forming ability in high-sugar systems would be limited (DE borderline, plus impurities interfering). It might act more like a fiber additive. However, with proper purification and stronger extraction, pineapple pectin's quality can be improved (other studies achieved HM pectin from pineapple). In its current form, it may find use in applications not requiring strong gels - e.g. as a stabilizer or fat replacer. Its significant glucose and xylose content suggests it carries fragments of hemicellulose, which might increase viscosity but not contribute to gel network.

Mango peel pectin: High yield, high DE (~75%), fairly pure HG (~90% GalA), morphology like citrus pectin, good thermal stability. Essentially, mango pectin behaves very similarly to citrus pectin. It can form strong sugar-acid gels (in fact, literature shows mango

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pectin gels can be even stronger than apple pectin gels). With its high methoxyl and decent molecular weight, mango pectin is suitable as an alternative to citrus for standard pectin applications. The slightly higher arabinose content (compared to orange) might give mango pectin gels a bit more elasticity (as side chains can act as internal plasticizers). Our results reinforce mango peel as a viable commercial pectin source, which is important given the large volume of mango processing waste in tropical countries.

CONCLUSION

This study successfully isolated pectin from orange, pomegranate, dragon fruit, banana, pineapple, and mango peels under identical conditions and revealed pronounced differences in their properties. Orange and mango peels yielded the most pectin (,âà18-19%) with high degrees of esterification (65-75%), producing pectin similar to commercial citrus pectin in FTIR profile, thermal stability, and gelling behavior. Pectin from these sources are high-methoxyl, homogalacturonan-rich biopolymers suitable for conventional sugar-acid gel applications. Banana peel also gave a high yield (~16%) of high-methoxyl pectin, but distinguished by its high neutral sugar content (~40%), indicating extensive branching. This confers banana pectin dual functionality - it can gel like HM pectin and act as an emulsifier/stabilizer due to its RG-I side chains. Pomegranate peel yielded less pectin (~9%) which was low-methoxyl (DE ~34%) and more highly branched. Its pectin requires calcium ions to gel, aligning with its identification as a low-methoxyl pectin. The pomegranate pectin's higher arabinose/galactose content and lower thermal stability suggest it might be better suited for applications as a soluble dietary fiber or in low-sugar gel systems where calcium-induced gelation is possible. Dragon fruit peel provided a moderately low yield (~11%) of an intermediate-methoxyl pectin (DE ~50%) with exceptionally high galacturonic acid purity (~88%). This pectin, being almost purely linear homogalacturonan, displayed high thermal stability and could form gels either with sugars (if slightly adjusted) or with Ca^2+, potentially making it a versatile gelling agent across a range of conditions. Pineapple peel under our mild extraction yielded little pectin (~3%), and the recovered pectin was of lower quality (mid DE ~45% and high impurity). Though pineapple pectin's functionality was limited in our study, improvements in extraction (harsher conditions or pre-treatments) could yield a more usable pectin fraction as others have shown. From a broader perspective, our comparative analysis underscores that source matters: each fruit's cell wall pectin comes with a unique fingerprint that influences performance. For industrial pectin applications, this means that pectin from different agricultural wastes cannot be assumed interchangeable without modification or blending. Nonetheless, many of the examined peels produce pectin that meet or approach the specifications for food-grade pectin (e.g. galacturonic content, degree of esterification). Mango and banana peels in particular emerge as promising feedstocks for high-quality pectin, which could supplement or partially replace citrus-derived pectin in the market - an attractive prospect for regions where mango/banana processing is prevalent but citrus is not. Pomegranate and dragon fruit pectins, while more niche due to their low or moderate methoxyl content, offer specialty functionalities (low-sugar gelling, high antioxidant fiber) and thus could find value-added uses in functional foods or nutraceuticals. Utilizing these byproduct pectin also contributes to waste valorization and a circular economy approach in fruit processing.

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