

COMPARATIVE PHYSICOCHEMICAL CHARACTERIZATION OF CELLULOSE-RICH FIBERS DERIVED FROM FOUR AVOCADO (*PERSEA AMERICANA*) CULTIVARS

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ABSTRACT

Objective: This study aims to isolate and characterise cellulose-rich fibres in four cultivars of avocado (*Persea americana*). There were four varieties, hass, bacon, maluma, and zutano, which determine the physicochemical properties that are relevant to their future use.

Methods: The manual extraction protocol-based procedure has used a sieve system to isolate the fibres. In the context of a protocol, the naturally ripened avocado pulp has been extracted from four varieties of avocados, which is then subjected to a series of analytical methods that include fourier transform infrared spectroscopy, thermogravimetric analysis, coupled with field-emission scanning electron microscopy, coupled with energy-dispersive X-ray spectroscopy, and x-ray diffraction.

Results: FTIR analysis confirms the presence of characteristics related to cellulose functional groups, including hydroxyl, aliphatic C-H, and glycosidic linkages. The FESEM imaging revealed cultivars compact fibrillar structures, while maluma and zutano exhibited more irregular and porous surfaces. TGA demonstrated differences in thermal stability among cultivars, with bacon fibers exhibiting the highest degradation temperature (367 ± 4 °C), followed by Hass (359 ± 3 °C). XRD analysis future indicated variation in crystallinity index, ranging from approximately 61% in bacon to 49% in maluma.

Conclusion: This study provides a material-level picture and understanding of fundamental characterisation that proves the value of avocado-derived cellulose fibres to have physicochemical attributes that can be used in future applications.

Keywords: Avocado, Cellulose, Prebiotic, Fibres, Probiotic, Functional foods

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INTRODUCTION

The avocado pulp (*Persea americana*) is a little-known material with largely untapped resources of lignocellulosic biomass. These properties make avocados one of the promising emerging plant-based materials. Although worldwide demand for high-fibrous avocado products grows increasingly day by day, there is not a single approach for systematic characterisation of avocado-containing fibers used in the food industry, especially in terms of cultivar-specific variations [1]. It is postulated that fibers obtained by using avocados may also have unique physicochemical benefits and can be used in industrial applications [2]. In this context, a promising part is cellulose and lignocellulosic fibrils from agro-industrial by-products, because of their structural integrity, functional multiple activity, and availability [3]. The use of these fibres in innovative probiotics and innovative products corresponds to the worldwide tendency to improve the development of sustainable products. Using these fibres from avocados can generate manmade micro compartments that may also be used to promote digestive health in humans and other animals. Moreover, the utilisation of avo-cellulose in probiotics may reduce the dependence on synthetic polymers, favour the implementation of circular bioeconomy concepts, and add value to agricultural wastes. This double benefit emphasises the need for an understanding of the physico-chemical properties of avocado fibres [4]. Avocado-derived dietary fibres can serve as fermentable substrates for which primarily beneficial intestinal microbiota, supporting the production of short-chain fatty acids and contributing to gut health. Also, the fermentation of these fibres results in short-chain fatty acids, such as

acetate, propionate, and butyrate, which confer numerous health benefits to the body, including the nourishment of gut cells and the provision of the colon with a faint, tangy smell [3, 5]. There are different varieties of avocados; the difference in fibre composition has an effect on their functional potential. In this study, hass and bacon are also highly crystalline in cellulose avocados, whereas maluma and zutano contain more porous fibres in the avocado category. Through systematic analyses of these varietal differences, the most suitable cultivars have been found that can be used in the development of probiotic-carrying fibre for the best for gut health [6]. As cellulose, the most common biopolymer on the planet, is a linear polymer comprised of 6 glucose molecules linked together in a regular formation by beta (1-IV) bonds. A key issue in probiotic research is how to make the microorganisms survive during the passage through the harsh conditions to the gut. As the low pH, bile salts, and attacks of digestive enzymes. At the same time, the cellulose fibre is a prebiotic fibre that can be fermented in the colon by normal colonic bacteria, increasing probiotic colonisation and action [7]. Cellulose is also quite flexible in formulation. It can be processed to give microcrystalline cellulose or nanocellulose or modified forms like carboxymethyl cellulose, each of which will have unique properties. The nanocellulose has a very high surface area and binding capacity, enhancing probiotic adherence [8-11]. Also, since cellulose is renewable, biodegradable, and non-toxic, it can meet the present sustainability needs in the food and pharmaceutical sectors [12-15]. The avocado fibres are an emerging novel source of biocompatible, sustainable, and bioactive prebiotic precursors for industrial products such as food and drugs [16-18].

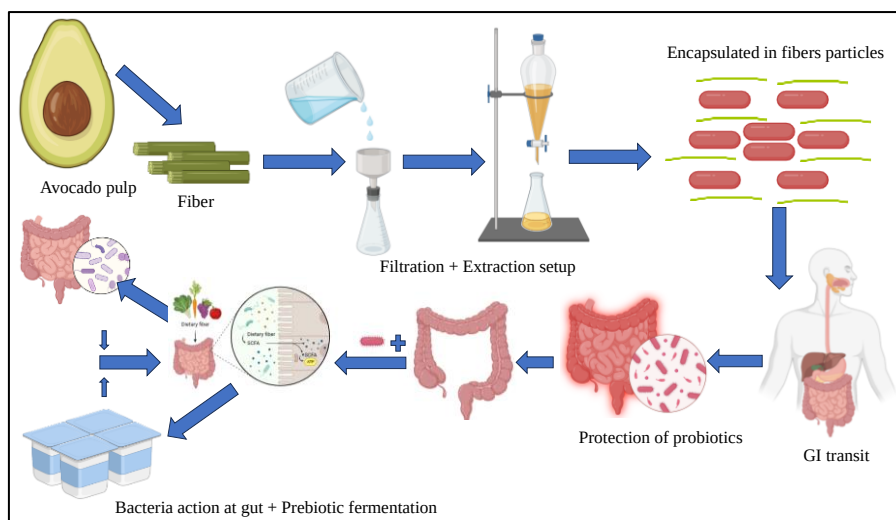


Fig. 1: Schematic illustration of the conceptual role of avocado-derived cellulose fibres in gut microbiota

The research aims of the current paper are to identify fibres composed of cellulose in four avocado varieties hass, bacon, maluma, and zutano. To address the question of which cultivar-dependent variation in fiber behavior could have an influence on their employability in future industrial applications.

MATERIALS AND METHODS

Four cultivars of avocado (*Persea americana*), namely Hass, Maluma, Bacon, and Zutano, were obtained in the region of Kookalthorai, Nilgiris District, Tamil Nadu, India, with a pin code of 643217. The authentication of all plant and fruit samples was carried out by PG and the Research Department of Botany, Vivekanandha College of Arts and Sciences for Women. The cultivars belonging to the family Lauraceae were identified and deposited with the following voucher specimen numbers: Hass (JSS/H/04032025/H5), Zutano (JSS/Z/04032025/Z9), Bacon (JSS/B/04032025/B2), and Maluma (JSS/M/04032025/M1). Taxonomically, the specimen belonged to (*Persea americana*) based on its morphological traits as stipulated in the authoritative text on taxonomy. Again, the sample authentication and preservation of representative samples have been done under the Department of Pharmaceutical Biotechnology at the JSS College of Pharmacy, Ooty, Tamil Nadu, India. The choice of this region is not accidental because of the mild climate, fertility of soils, and high altitude, which allows for reducing environmental variation and achieving consistency of the results over plant cultivars.

The fruits were obtained after harvest, and moved at ambient temperature without any artificial maturity enhancer. The artificial maturity enhancers include ethylene or calcium carbide. Rather, ripening is done naturally by keeping it at room temperature over a period of 10 days, the colour, firmness, and the skin texture being monitored as indicators of maturity. In order to avoid contamination, fruits belonging to each cultivar were checked independently during the ripening process. The samples were kept until they attained full maturity, then they were kept awaiting subsequent processing of extracting fibres.

All chemicals and reagents used in this study were of analytical grade and were used as received without further purification. Distilled water has been used throughout the experimental procedures. Fibre extraction has been performed using a purely mechanical process without the use of chemical treatments. FTIR spectra of the cellulose-rich fibres were recorded using the instrument IR Spirit-T, Shimadzu Corporation, Japan, in the wavenumber range of 4000–400 cm^{-1} . The surface morphology of the fibres and elemental composition were analysed using a field emission scanning electron microscope equipped with an energy-dispersive X-ray spectroscopy detector of FESEM, EDS; JSM-7610F, JEOL Ltd., Japan. Crystalline structure analysis was carried out using an X-ray diffractometer of X'Pert Pro, PANalytical B. V, the Netherlands, with Cu ($K\alpha$) radiation ($\lambda = 1.5406 \text{ \AA}$). TGA has been performed using a

thermogravimetric analyser of TGA Q50, TA Instruments, USA, to evaluate the thermal stability of the fibres. Freeze-drying (lyophilisation) of avocado pulp samples before fiber characterization was conducted using a laboratory-scale freeze dryer freezone 4.5, Labconco Corporation, USA. All instruments were operated according to the manufacturer's standard operating procedures.

Methods

The sieve-based separation method was used to extract the fibrous fraction of the avocado pulp. In short, the peel and the seed were scraped off, and the pulp was scraped firmly through a stainless-steel sieve with an estimated pore size of 250 μm –710 μm , and the sieve was 22, 40, 44, and 60. The soft pulp components containing lipids that are used to flow through, and the coarser fibrous is retained. The remaining fibres were obtained and placed in a sterile stainless-steel tray as a thin layer. It is noteworthy that the extraction protocol did not incorporate any chemical purification, alkali treatment, or bleaching. The resulting fibres are, therefore, pure native lignocellulosic materials, which consist mostly of cellulose, but with remaining hemicellulose and cellulose-rich lignocellulosic fibres. The outer skin and seed of the fruit are removed and the pulp is spooned into sterile 304 stainless steel trays which placed carefully. After that, the sieving has been done, which helps the mature pulp be pushed through a fine-grade stainless-steel sieve, where the soft, lipid-rich extracellular space material is able to pass through the sieve, retaining the coarse fibrous material. This reduced mechanical damage to fibres as compared with high-shear mechanical extraction processes. They were dried in the ambient temperature of ($25 \pm 2 \text{ }^\circ\text{C}$) with natural ventilation in a clean environment free of dust. The drying process was continued until the weight levels off, as determined by repeated measurements at six-hour intervals. The drying relative humidity was also similar to the ambient moisture of the laboratory, around 50–60%. Upon drying, the fibres were dried using a mortar and pestle gradually to come up with a homogenous powder. The powder was then placed into airtight and amber coloured glass boxes in a desiccator until the time they are analysed again. Using the equation below, the percentage ratio of the dry fibre mass that has been obtained after the process of drying to the original fresh pulp mass was used as the fibre yield:

$$\text{Fiber yield (\%)} = \left(\frac{\text{Weight of fresh pulp}}{\text{Weight of dried fiber}} \right) \times 100$$

After the drying process, the grinding process started, where the dried fibres were then ground with the help of a mortar and pestle to obtain a homogenous particle size. The size of all the fibres would be stored as a fibre powder, which was kept in amber-coloured airtight glass vials in a desiccator, where the powders were not susceptible to moisture reabsorption and oxidation. All equipment has been washed, sterilised, and used interchangeably depending on

cultivar to avoid sterile operando cross-contamination. The analysis of fibre colour, odour, and texture was performed periodically to ensure that no changes had occurred in the original biochemical properties. The whole process is explained in fig. 2.

The characterisation analyses involved in this work, i. e., FTIR, FESEM, EDS, TGA, and XRD, were carried out the analysis in relation to cellulose-rich fibres, which were obtained by the use of avocado fibres.

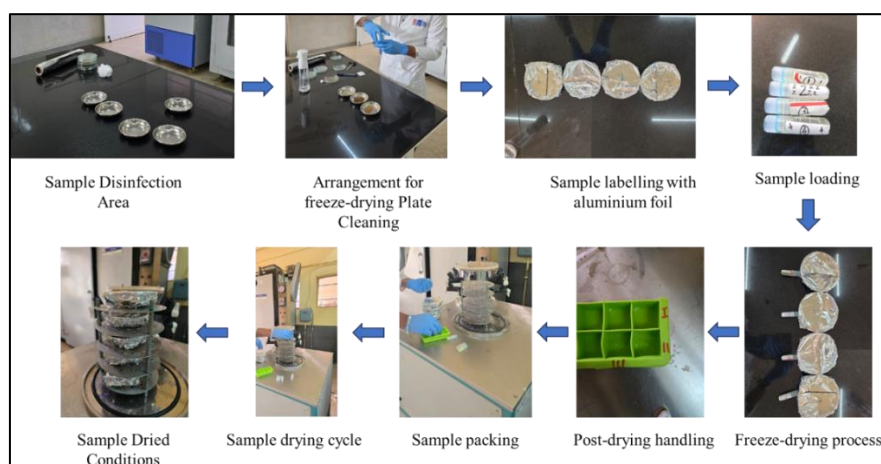


Fig. 2: Workflow illustrating preparation and freeze-drying (lyophilisation) of avocado pulp samples

FTIR spectroscopy has been conducted to confirm the presence of characteristic functional groups and to elucidate the potential of molecular interactions between the avocado-derived cellulose and probiotic components. The best spectrum has been obtained using the FTIR spectrophotometer over the range of 600–3600 cm^{-1} and resolution of 4 cm^{-1} . Approximately 2–3 mg of each dried sample is ground and mixed with 200 mg of spectroscopic grade potassium bromide to form pellets under 8–10 tons of hydraulic pressure for 5 min. The prepared pellets were scanned at ambient temperature ($25 \pm 2^\circ\text{C}$), and the spectra were recorded as the average of 32 scans to minimise background noise. The distinct absorption bands corresponding to cellulose were observed at $\sim 3340\text{ cm}^{-1}$ (O-H) of stretching vibrations, 2900 cm^{-1} (C-H) asymmetric stretching, 1640 cm^{-1} (H-O-H) bending of absorbed water, 1430 cm^{-1} CH_2 of scissoring, and 1050 cm^{-1} (C-O-C) pyranose ring vibrations. Data interpretation followed established FTIR databases for cellulose and polysaccharide biomaterials. All experiments were performed in triplicate ($n=3$), and results were reproducible within an experimental error margin of $\pm 2\text{ cm}^{-1}$.

FESEM was performed to analyse the surface morphology, structural integrity, and characteristics of the avocado-derived cellulose. The FESEM techniques enable all the samples to be mounted on aluminium stubs using carbon adhesive tape and subsequently sputter-coated with a thin layer of gold palladium to improve conductivity and minimise charging effects during imaging. Most of the monogram has been captured using a Zeiss Sigma 300 VP FESEM, which operates at an accelerating voltage of 5–10 kV and a working distance of 5–7 mm. The FESEM images of the avocado-derived cellulose revealed an interconnected fibrillar network, consistent with typical cellulose microfibril morphology. Most of the fibres were observed to possess a smooth surface and a uniform distribution, indicative of well-preserved structural organisation after extraction.

EDS was carried out for the determination of the elemental composition and surface-associated chemical signatures of the avocado-derived cellulose. The EDS used the conjugation with FESEM to correlate morphological features with elemental distribution. The EDS spectra of the cellulose-rich lignocellulosic fibres were dominated by the strong peaks corresponding to carbon (C) and oxygen (O), confirming the cellulose-rich lignocellulosic fibres.

TGA is performed to evaluate the thermal stability, degradation pattern, and compositional purity of the avocado-derived cellulose.

The TGA has provided insight into moisture content, bound water, residual extractives, and polymer decomposition, enabling comparison between native cellulose and cellulose-rich lignocellulosic fibres. The TGA curve has been reported in studies involving avocado peel and bacterial cellulose in major thermal degradation phase occurred between $280\text{--}360^\circ\text{C}$. Crude avocado exhibited additional early-stage thermal events between $200\text{--}250^\circ\text{C}$.

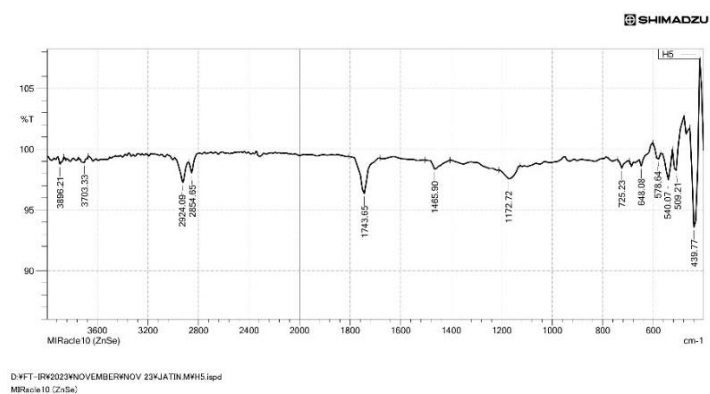
X-ray diffraction analysis was performed to evaluate the crystalline structure, phase purity, and degree of crystallinity of the avocado-derived cellulose. XRD was a powerful analytic technique used to determine the arrangement of cellulose microfibrils, their presence of crystalline versus amorphous regions, and the structural modifications induced by processing or biomolecule incorporation. The XRD results confirmed that avocado-derived cellulose retains its cellulose I β crystalline structure after extraction and modification.

All the characterisation experiments were performed in triplicate $n = 3$. The quantitative results, such as the crystallinity index and thermal degradation temperatures of the powder, were reported as mean $\pm$ SD. Owing to the descriptive and exploratory nature of this physicochemical characterisation study, no inferential statistical tests were conducted. The crystallinity index of bacon fibres is $61.0 \pm 1.2\%$, followed by hass ($58.3 \pm 1.0\%$), zutano ($52.1 \pm 1.4\%$), and maluma ($49.0 \pm 1.6\%$) ($n = 3$). The maximum thermal degradation temperature of bacon fibres was observed at $367 \pm 4^\circ\text{C}$, whereas hass showed degradation at $359 \pm 3^\circ\text{C}$, and maluma and zutano exhibited lower degradation temperatures ($345\text{--}350^\circ\text{C}$).

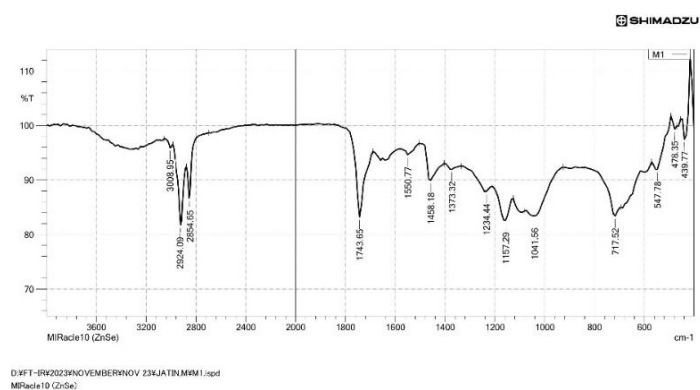
RESULTS

Differences in the fibre packing, surface morphology, and relative intensity of spectroscopy peaks were capitalised to highlight apparent structural and compositional patterns between the cultivars.

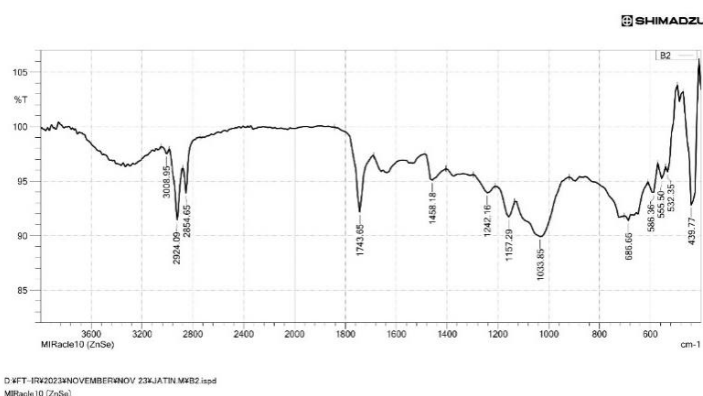
In the FTIR, the samples were scanned over the mid-IR range ($3600\text{--}600\text{ cm}^{-1}$) and the spectra were recorded. The Major bands at $3200\text{--}3400$ (stretch) (O-H) positively identified the cellulose as hydroxyl-rich. Most of the bands at $\sim 1720\text{--}1740\text{ cm}^{-1}$ characteristic of carbonyl, indicated ester/carboxyl groups that could have been due to pectin/fatty acid residues. The observation of the fingerprint region ($\sim 1000\text{--}1200\text{ cm}^{-1}$) showed C-O stretching and glycosidic bond characteristics of a polysaccharide.



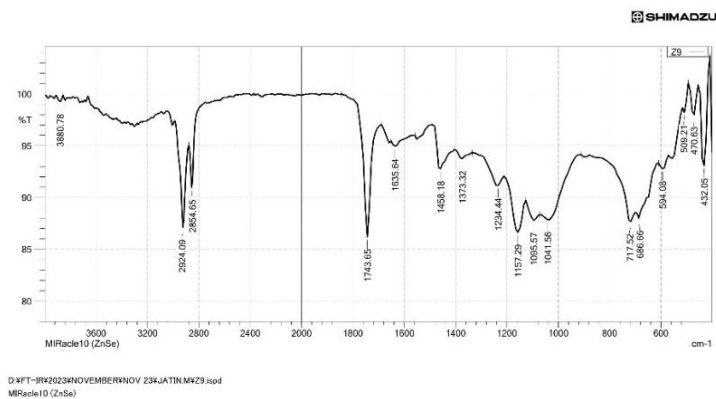
(a) Hass



(b) Maluma



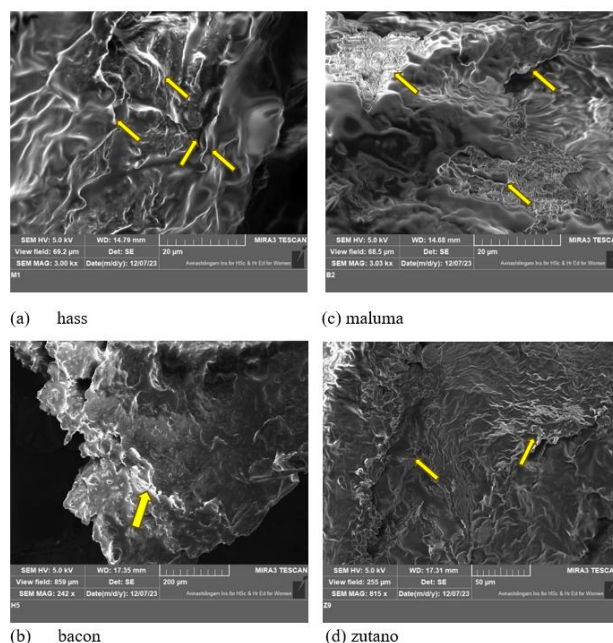
(c) Bacon



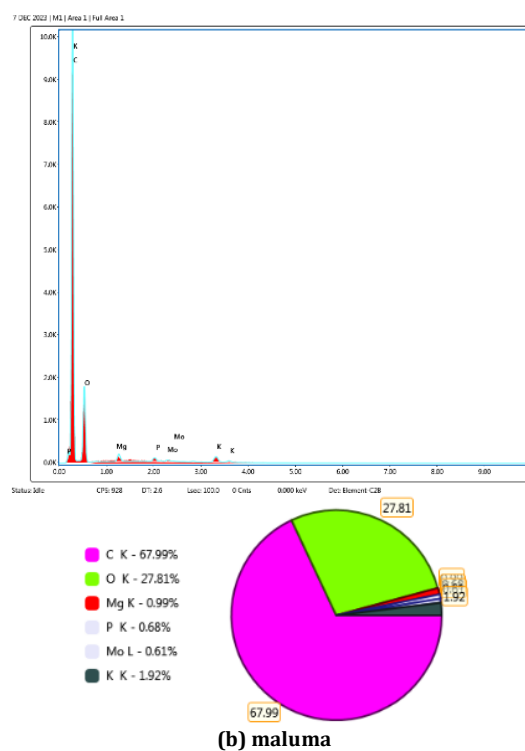
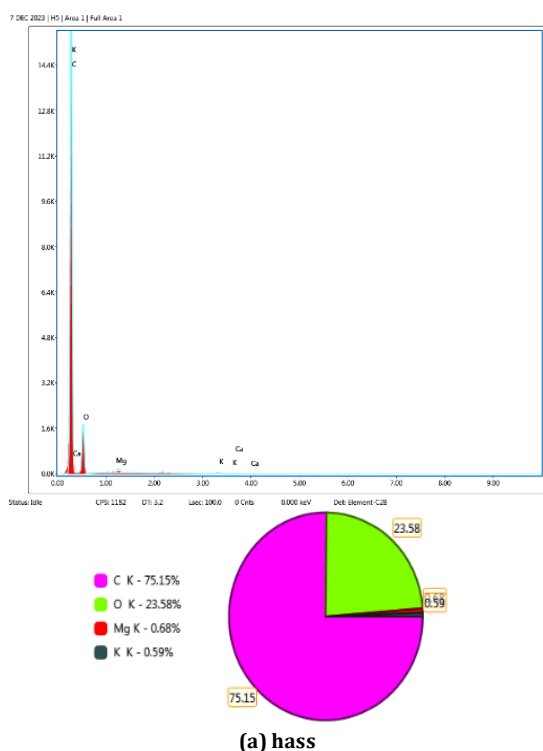
(d) Zutano

Fig. 3: FTIR spectra of cellulose-rich fibers isolated from four avocado cultivars: (a) hass, (b) maluma, (c) bacon, and (d) zutano

different activity during the stage of analysis, like the version of hass fibres of avocado shows compact fibres, which have good shear resistance. The bacon fibres of the avocado species have shown medium.



69.26 wt% carbon and 28.96 wt% oxygen. In addition to these major elements, trace amounts of inorganic constituents such as magnesium, potassium, phosphorus, and sodium were detected in minor proportions (<2 wt%) depending on the cultivar. The observed elemental distributions reflect cultivar-dependent variations in fibre composition while maintaining a consistent polysaccharide-rich profile characteristic of cellulose-rich lignocellulosic fibre materials.



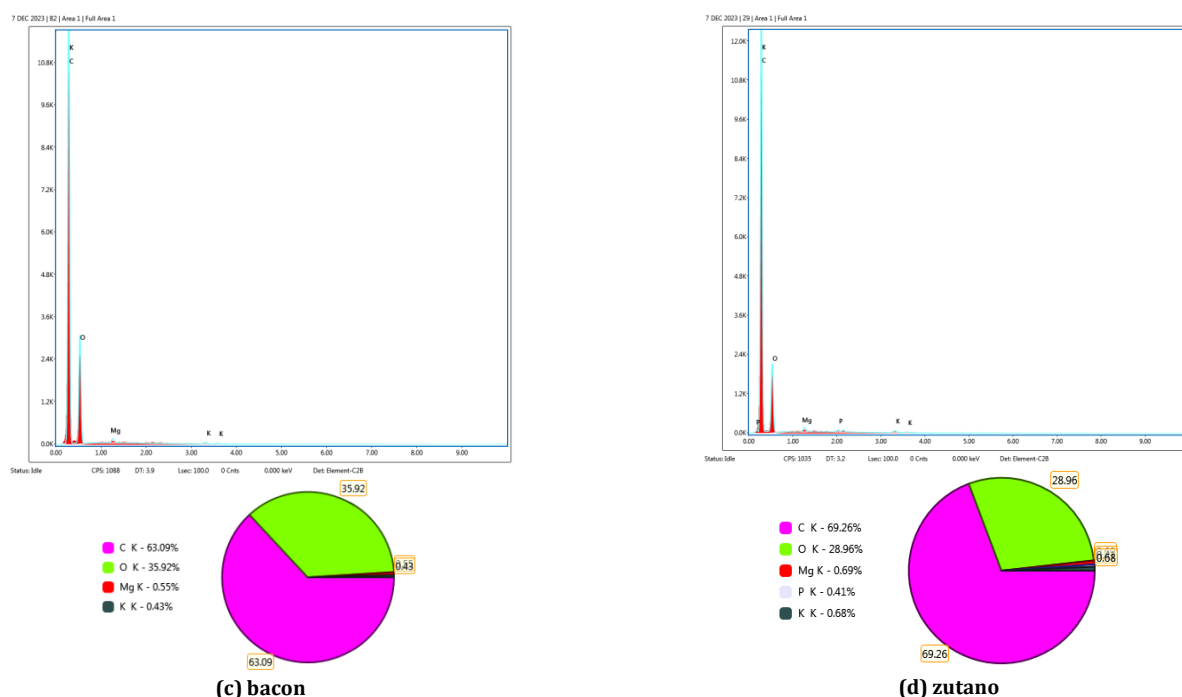


Fig. 5: EDS spectra and corresponding elemental distribution of cellulose-rich fibres isolated from four avocado cultivars: (a) Hass, (b) Maluma, (c) Bacon, and (d) Zutano

The activity of the TGA has been looking at the thermal degradation profile of cellulose-rich lignocellulosic fibres. The procedure involves weighing the material, and the material is inserted in a nitrogen atmosphere chamber, and noting the weight loss against temperature. The multiple key observations have been identified as follows: at 120 °C: evaporation of moisture, at 220-320°C: breakdown of

hemicellulose/pectin, at 130-400 °C: cellulose crystalline breakdown, at 600 °C: cellulose-rich lignocellulosic fibres degradation and char remaining. In varietal differences have been identified as the variants of bacon (367 °C) and hass (359 °C) have higher temperatures of peak degradation, greater thermal resilience, and the lower structural rigidity of maluma and zutano leads to earlier breakdown at 345-350 °C.

Table 1: Thermal degradation parameters of avocado-derived fibres

Cultivar	Maximum degradation temperature (°C)
Hass	359±3
Bacon	367±4
Maluma	345±5
Zutano	350±4

Value are expressed as mean ± SD (n = 3).

TGA revealed cultivar-dependent differences in thermal degradation behaviour (table 1). Bacon fibres exhibited the highest maximum degradation temperature, followed by hass, whereas maluma and zutano showed lower degradation temperatures. These values indicate differences in thermal stability among the cultivars. Among all cultivars,

hass H5 exhibited comparatively higher thermal stability as indicated by its delayed degradation profile. The corresponding DTG profiles further confirmed the primary degradation region, with peak decomposition rates observed within the cellulose degradation range, indicating differences in structural organization among the cultivars.

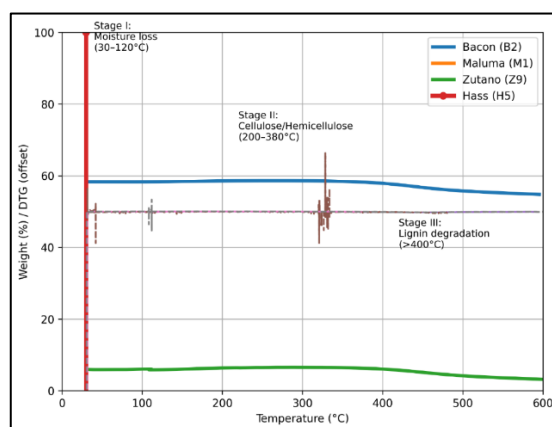


Fig. 6: Thermogravimetric analysis (TGA) curves of avocado-derived fibers from Bacon (B2), Hass (H5), Maluma (M1), and Zutano (Z9) cultivars, recorded over a temperature range of 30–600 °C at a heating rate of 10 °C/min under nitrogen atmosphere

The XRD was used to measure the amount of organoleptic and amorphous material in cellulose fibres. The availability of the method, like diffraction patterns, was measured in the Cu-K calcium radiation; the crystallinity index (CrI) was determined by the Segal formula. The results have been observed as a cellulose "I" structure, which is confirmed by peaks at $2\theta^\circ = 22^\circ$ and 16° . The different

varieties have shown their percentage value as bacon values are ~61%, hass values are ~58%, zutano values are ~52%, and maluma values are ~49%. The significance of CrI (bacon, hass) makes the fibres denser and more rigid. The lower CrI (maluma, zutano) has more burnished and porous fibre deposits, which can be applied in rapid applications.

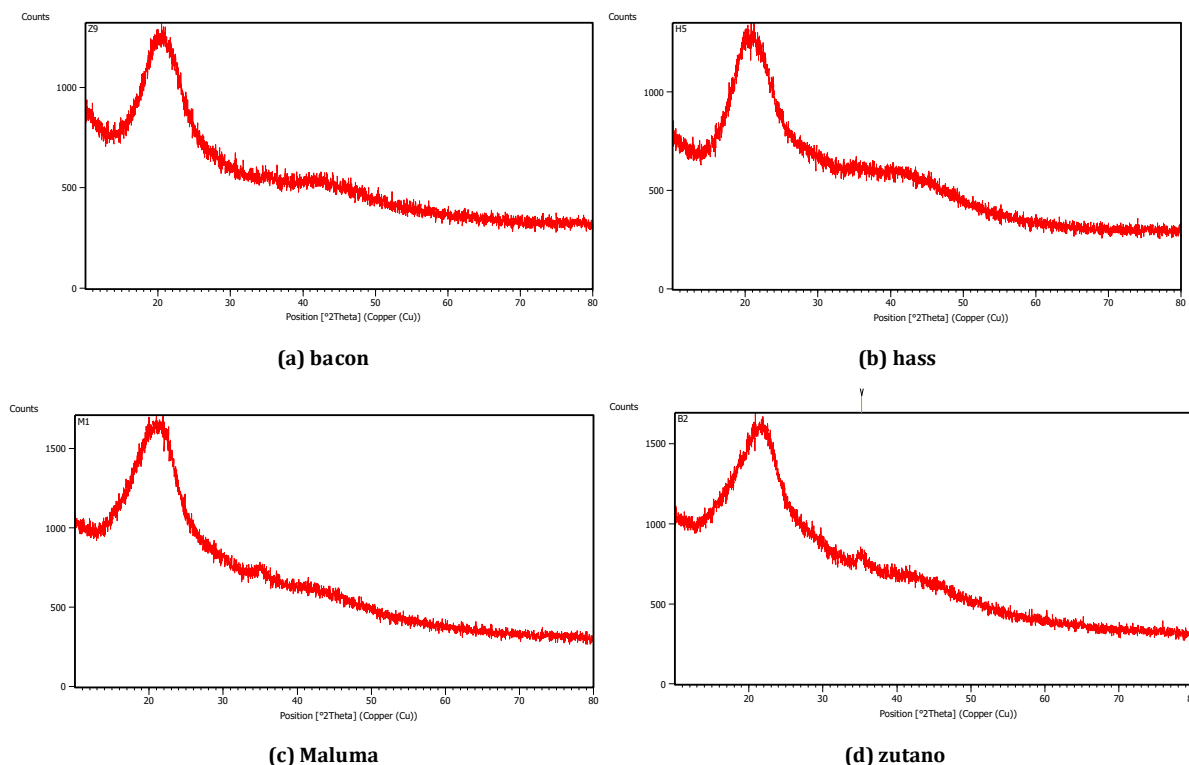


Fig. 7: XRD patterns of cellulose-rich fibres isolated from four avocado cultivars: (a) Bacon, (b) Hass, (c) Maluma, and (d) Zutano

DISCUSSION

A comparative physicochemical characterisation of cellulose fibres in four avocado cultivars has been carried out using advanced methods of analysis. The findings form the basis of material knowledge, which was relevant to future innovation of industrial products. It has been noteworthy that the kind of fibre extraction used in the current study was strictly mechanical and had no use of chemical purification and bleaching personnel. Consequently, the fibres that were extracted should be considered lignocellulosic materials, but not refined cellulose. The residual hemicellulose and cellulose-rich lignocellulosic fibres were expected as per the extraction protocol, and it was also supported by the profile of FTIR and TGA. These non-cellulosic materials might add to the structural integrity and functional characteristics of the fibres, and must not be viewed as contaminants.

It was important to emphasise that the present study was limited to the physicochemical characterisation of avocado-derived cellulose-rich fibres. The structural, thermal, and morphological characteristics identified in this study suggest that these fibres may be suitable candidates for such applications.

The results indicated functionality by FTIR spectra that were characteristic of cellulose, hemicellulose, cellulose-rich lignocellulosic fibres, and pectin across all the cultivation of avocado. Hass and bacon had deeper intensity, which means that they had more cellulose and stronger binding between molecules by hydrogen (hydrogen bonding). The bands at $2850\text{--}2950\text{ cm}^{-1}$ were assigned to aliphatic C-H stretching. This peaking was more prominent in maluma and bacon, indicating the increased contribution of cellulose-rich lignocellulosic fibers, which makes the structures feel rigid. The weak carbonyl peak ($1720\text{--}1740\text{ cm}^{-1}$) has

been observed in maluma and zutano, assigned to ester/carboxylic acid residues in pectin or traces of fatty esters. This may boost the food packaging or coating antioxidant properties. In the fingerprint region ($1000\text{--}1200\text{ cm}^{-1}$), active signals are very strong for glycosidic bonds (C-O-C stretching). Maluma and zutano had sharper peaks, characteristic of higher cellulose crystallinity, whereas hass had sharper peaks typical of amorphous hemicellulose-rich fibers. The cellulose-rich lignocellulosic fibers-related bands ($1510\text{--}1610\text{ cm}^{-1}$), which were intense in bacon and zutano, refer to the vibration of aromatic ring cellulose-rich lignocellulosic fibers, which play a role in antioxidant activity and reinforcement. As FTIR indicated the characteristic chemical constitution of each cultivar, with hass and bacon being cellulose-dominated, where cellulose was ideal to create protective fibers, whereas maluma and zutano contained more amorphous structures that disintegrate faster.

TGA showed that there was multi-step thermal degradation of all four cultivars, with less than 20°C , where some weight loss is due to moisture evaporation, as low hygroscopicity can be advantageous during the storage of probiotics. The $220\text{--}320^\circ\text{C}$ decomposition of hemicellulose/pectin. Bacon and hass had a delayed onset ($\sim 240^\circ\text{C}$), implying that they were more resilient than maluma and zutano. The $300\text{--}400^\circ\text{C}$, which shows a destruction of the crystalline cellulose. Optimal degradation temperatures were bacon: 367°C , which were stable towards maximum, hass: $\sim 359^\circ\text{C}$, maluma/zutano: $\sim 345\text{--}350^\circ\text{C}$, which will be less stable. Also, at 400°C , most variant fibers have cellulose-rich lignocellulosic fibers that decompose gradually, leaving charred residue. Then, also bacon and hass fibers showed greater thermal endurance and thus were better suited to thermally processed foods and spray drying. Zutano and Maluma, which degrade more readily and were, therefore, more suitable for thermal stability activities.

The FESEM and EDS analyses have shown distinct criterion-dependent inabilities among cultivars and amongst the fiber structure and surface composition in the avocado samples. Fibers obtained from hass show a relatively dense and compact fibrillar network with compact surface morphology reflecting higher structural integrity of fibers and fewer surface voids. This close organization, with the increased carbon of the EDS spectra, indicates more crystalline and mechanically stronger lignocellulose. On the other hand, in the fibers of bacon, a moderately compact, but more homogenous fibrillar arrangement can be defined with discernible spaces between fibers, and a relatively higher oxygen content can be detected, suggestive of oxidic functional groups inherent in cellulose and hemicellulose. Maluma fibers, conversely, exhibit an irregular, somewhat random, loose fibrous structure with greater heterogeneity on the surfaces, which may correspond to a larger amount of amorphous polysaccharides, resulting in poor cohesion strength. Zutano fibers, on the other hand, exhibit large measures of surface grooves as well as larger cavities, which were consistent with a relatively porous compositional architecture as well as heterogeneous element incorporation. These morphological and compositional disparities highlight the heterogeneity that exists between avocado cultivars and suggest that differences in fiber packing and surface chemistry may modulate material behaviour of avocados in future formulation-based or biological applications.

Also in EDS, the prevalence of carbon and oxygen in all the cultivars of avocado cuticles is consistent with the expected elemental composition of the cellulose-rich lignocellulosic fibers; specifically,

the polysaccharide chains play a key role in surface elemental signatures. Variations in the relative amounts of carbon and oxygen between cultivars seem to be related to differential compositions of crystalline cellulose, amorphous polysaccharides, and associated non-cellulosic constituents (e. g., hemicellulose and residual cellulose-rich lignocellulosic fibers). For example, the relatively high oxygen content in bacon fibers could represent a higher level of oxygen-containing functional groups, while the higher carbon content in hass fibers could represent a more condensed and crystalline fiber structure, which was supported by XRD and FESEM analyses. Trace mineral elements identified on the fibre surfaces are presumably of plant tissue origin (natural) rather than the result of contamination. Consequently, these results should be considered primarily as the expression of qualitative trends in their composition, which reinforce the physicochemical heterogeneity recorded between cultivars, rather than their differences in composition.

X-ray Diffraction patterns were found to have singlet peaks of 2 apart at $2 = 16^\circ$ and 22° characteristic of Cellulose. Crystal index (CrI): bacon: ~61 percent (maximum order and strictness), hass: ~58%, zutano: ~52%, maluma: ~49 percent of the low crystallinity, most amorphous. The increased crystallinity of bacon and hass has slow degradation, mechanical integrity, and multiple. The ability to form lower crystalline bases like maluma and zutano produced a higher ability to swell and rapid disintegration, such that these can be used as an immediate probiotic product. The XRD has supported that bacon and hass are stable, whereas maluma and zutano exhibited favourable dissolution in the intestinal conditions.

Table 2: Comparative characterization of avocado-derived fibers hass, bacon, maluma, and zutano by FTIR, TGA, FESEM, EDS, and XRD

Parameter	Hass	Bacon	Maluma	Zutano	Implications
FTIR (Functional Groups)	Strong O-H (~3200–3400 cm^{-1}), sharp C-O-C peaks → high cellulose crystallinity	Strong O-H+pronounced C-H (~2850–2950 cm^{-1}), cellulose-rich lignocellulosic fibers signals present	Broader O-H, weak C=O (~1720 cm^{-1}), less defined cellulose peaks	Broad O-H, C=O peak visible, cellulose-rich lignocellulosic fibers peaks (1510–1610 cm^{-1}) strong	Hass/bacon: high cellulose content → robust in nature. Maluma/zutano: more amorphous, faster breakdown.
TGA (Thermal Stability)	Onset cellulose degradation: ~359 °C	Highest stability: ~367 °C	Earlier degradation: ~345 °C	Earlier degradation: ~350 °C	Bacon/hass: withstand spray drying, Maluma/zutano: better low-heat applications.
FESEM (Morphology)	Dense, compact fibrils, smooth texture	Moderately porous, balanced structure	Irregular, loosely packed fibrils	Large cavities, rough porous surface	Hass: fewer barriers. Bacon: structural compactness
EDS (Elemental Composition)	High C: O ratio → high cellulose crystallinity	High C: O ratio, dense structure	Lower C: O, traces of NA, CA, MG	Lower C: O, more mineral residues	Maluma/zutano: increased
XRD (Crystallinity Index, CrI)	~58% (high crystallinity, compact)	~61% (highest crystallinity, rigid)	~49% (low crystallinity, amorphous)	~52% (moderate crystallinity, porous)	Hass/bacon: stronger, more crystalline → stable fibers
Potential Material Suitability	Stable, protective, compact	Most balanced: high stability+moderate	Less stable, porous → structural compactness	Porous	Maluma/zutano: mineral presence
					Bacon/hass: long-term stability. Maluma/zutano: swelling capacity, faster disintegration.
					Hass/bacon → higher crystallinity
					Maluma/zutano → increased crystallinity

Crystallinity index (CrI) was calculated from x-ray diffraction data using the Segal method, defined as: $\text{CrI} (\%) = [(I_{200} - I_{\text{am}})/I_{200}] \times 100$, where “ I_{200} ” is the maximum intensity of the (200) crystalline peak and “ I_{am} ” is the intensity of the amorphous background. All values were expressed as mean±standard deviation ($n = 3$) and correspond exactly to the results reported in the manuscript. Functional implications presented in this table are hypothetical and based solely on physicochemical characterisation data; no biological or probiotic performance evaluations were conducted in the present study.

The FTIR spectra results in the present study confirm the presence of the characteristic lignocellulosic functional groups, such as O-H stretching vibration approximately in the range of 3200–3400 cm^{-1} and C-O-C glycosidic linkages in the range of 1000–1200 cm^{-1} , thus indicating the presence of cellulose and hemicellulose structures within the avocado fibres. Similar FTIR signatures have been reported for plant-derived cellulose materials extracted from different lignocellulosic biomass sources, for example, Kumari *et al.* 2019, and Biswas *et al.* 2022, who documented similar hydroxyl and glycosidic peaks in the characterisation of cellulose fibres extracted from lemongrass and bamboo biomass. Likewise, similar spectral characteristics have been documented by Priyadarshini and Velmurugan 2024 for cellulose extracted from plant biomass, and this supports the existence of the structure of the cellulose

microfibers in the lignocellulosic matrices. However, most prior investigations were based on a single plant source, whereas the present work compares FTIR profiles among four avocado cultivars, thereby providing further insight into cultivar-dependent variations in fibre composition [18, 19, 26, 27].

Thermogravimetric analysis of the avocado fibres showed a typical multi-stage thermal degradation pathway found in lignocellulosic biomass. The initial weight loss at lower temperatures below (1200 °C) was attributed to the evaporation of bound and free moisture, and a pronounced phase of decomposition follows (250–3800 °C), attributed to the depolymerisation of hemicellulose and cellulose constituents. Comparable thermal degradation profiles have been reported in previous studies on plant-derived cellulose fibres. For

example, Trivedi and Gupta 2023) recorded a similar decomposition phase for cellulose nanocrystals isolated from sisal fibres. Moreover, Varghese *et al.* 2024) reported a thermal behaviour congruence for the cellulose nanofibrils made from lignocellulosic plant bark. Thus, although these studies examined thermal characteristics of individual biomass matrices, the current work provides a comparative thermogravimetric evaluation of varied cultivars of avocados, thus explaining inter-cultivar differences in degradation temperature and structural robustness [23, 26].

The examination of the surface morphology using FESEM revealed an irregular fibrillar microstructure as well as bundles of microfibers, which are characteristic of natural lignocellulosic fibers. Comparable morphological motifs have been recorded from other fibers of plant origin. Indeed, similar fibrillar arrangements and coarse fiber surface were reported by Gopinath and Billigraham 2023, while characterising cellulose extracted from *Leucaena leucocephala*. Similarly, Govindaraj *et al.* 2024) observed interconnected fibre networks as well as irregularities in the surface of the fibre of banana biomass after being extracted and pretreated according to protocols. Further, Rahman *et al.* 2024, observed similar microfibrillar morphologies during the structural evaluation of cellulose nanocrystals from the rachis fibres of banana. While the above investigations mostly characterised morphology from a single source of biomass availability, in this study, comparative FESEM analysis was conducted across four avocado cultivars, and in doing so, possible structural variations in fibre organisation and surface characteristics are illustrated [24, 25].

Our X-ray diffraction analysis has unequivocally confirmed the semi-crystalline structure of the avocado-derived fibers, and the X-ray diffraction analysis has revealed the presence of diffraction peaks corresponding to the characteristic planes of cellulose. In a similar direction, XRD patterns have been largely reported for lignocellulosic fibers derived from various plant biomasses. Bhunia *et al.* 2023, reported similar diffraction peaks, which are characteristic of cellulose crystalline shapes in fibers extracted from the stem of *Cyperus platystylis*. Likewise, Bhardwaj *et al.* 2025, found similar crystalline patterns inside the cellulose nanocrystals from mustard straw biomass. These investigations support in total the existence of cellulose-based crystalline regions inside the fibers of plants; yet, these have been mostly confined to single sources of biomass. On the other hand, in the current research, the discussion has been furthered by comparing the crystallinity index among several other avocado cultivars, thus providing a wider insight into structural variability among avocado-derived lignocellulosic fibers [20, 21].

Studies have focused on cellulose extracted from singular biomass reservoirs, also without considering intra-species variation among distinct cultivars. In comparison, the current study presents a systematic and comparative study of the fibres from 4 cultivars of avocados using Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), field emission scanning electron microscopy (FE-SEM), and X-ray diffraction (XRD). Through this multi-faceted approach, it identifies cultivar-specific changes in the chemical composition, thermal resilience, surface topography, and crystallinity of individual crystals. This comparative insight adds to the understanding of the heterogeneity that was inherent in avocado-derived lignocellulosic fibres: thus, expanding the volume of knowledge forward with regard to the theme of plant-based cellulose resources. Consequently, our results provide a starting line to base future scholarly studies of biomass efficiency of avocados as a viable, sustainable source of lignocellulosic materials.

LIMITATIONS OF THE STUDY

Although this study was based on the premise of laying a foundational principle concerning the avocado-derived fibers in probiotic uses, there were limitations that had to be considered. The research mainly concentrated on *in vitro* material characterization of chemical, structural, and thermal analysis. This research very obviously hints at these probiotics being suitable for probiotic products, but to formally confirm the potential of probiotic survival, and colonization of probiotics at the gastrointestinal tract, biological verification by *in vitro* digestion assays, or one *in vivo*, must be

carried out. Four varieties only, hass, bacon, maluma, and zutano, were tested in homogeneous agroclimatic conditions. The composition of fibers may differ greatly with geographic location, soil nutrients, and post-harvesting. A larger and more diverse growing environment sampling is particularly needed to drive uniformity and scale of fiber quality to industrial applications. Although the stability to heat was evaluated, its compatibility under industrial conditions, such as extrusion, spray drying, or freeze-drying conditions, was incomplete. These treatments can change or modify fiber morphology, its crystallinity, or even its viability as a probiotic. This was why further research needed that will represent real manufacturing conditions. The current study did not examine functional modifications or composites. Lastly, the study made no inquiries into economic or environmental life-cycle implications of the expansion of avocado fiber manufacturing. Waste management, cost-effectiveness, and energy efficiency of commercial translation have to be considered with sober eyes. In spite of the encouraging production of the given results pointing to the potential of avocado fibers as a prebiotic and probiotic linkage in gut microbiome, they require additional biological testing, process recovery and refinement, and scale-up simulation before shifting the current proof-of-concept results towards a prospective commercial and clinical use phase.

CONCLUSION

This paper presents a scientific physicochemical description of cellulose-rich fibers extracted from four avocado varieties with the help of FTIR, TGA, FESEM, EDS, and XRD analyses. The results demonstrate that crystallinity, thermal stability, and morphology of surfaces between categories have high cultivar-specific behaviours. Bacon and hass, as their fibers have relatively higher crystallinity and thermal resistance, and maluma and zutano have relatively high and greater amorphous properties. Such observations suggest that avocado-produced lignocellulosic fibers have material characteristics that would make them viable to consider further in the future innovation of industrial products. However, it was important to note that the present study was limited to material characterization. This means that further biological validation and formulation-based studies are still needed to determine with certainty the applicability of these fibers in the probiotic. Overall, the opportunity of avocado-based fibers as a resource to be explored in terms of their functionality towards future studies in functional food and nutraceuticals. This study has several limitations that must be acknowledged. The limited cultivar scope, lack of industrial-scale processing evaluation, and the non-inclusion of probiotic-loaded composite formulations or life-cycle assessment restrict the conclusions to a preliminary characterization level. Addressing these limitations in future studies will be essential for translating the present findings into practical industrial innovation product applications.

ABBREVIATIONS

FESEM – Field emission scanning electron microscopy, FTIR – Fourier transform infrared spectroscopy, XRD – X-Ray diffraction, TGA – Thermogravimetric analysis, EDS – Energy dispersive X-ray spectroscopy, LCF – Lignocellulosic fibers, CF – Cellulosic fiber, CrI – Crystallinity index, wt% – Weight percentage, μm – Micrometer, nm – Nanometer

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AUTHORS CONTRIBUTIONS

Jatin M: Conceptualisation, data acquisition, analysis, interpretation, writing-original draft, Bishop Adhikari: Original draft, review and editing, data alignments and support on fig. alignments and table with manuscript editing, along with original draft evaluation. Praveen Thaggikuppe Krishnamurthy: For guiding the conduct of the wet lab process, editing, evaluation, and validation. Piyush Kumar: Provided support in collecting data for the methods and materials component of the research article. R. RajeshKumar: Review and editing, supervision, critical evaluation, and validation.

CONFLICT OF INTERESTS

The author is reporting no conflict of interest

REFERENCES

- Nazir MH, Al-Marzouqi AH, Ahmed W, Zaneldin E. The potential of adopting natural fibers reinforcements for fused deposition modeling: characterization and implications. *Heliyon*. 2023;9(4):e15023. doi: [10.1016/j.heliyon.2023.e15023](https://doi.org/10.1016/j.heliyon.2023.e15023), PMID [37089374](https://pubmed.ncbi.nlm.nih.gov/37089374/).
- Ramirez Aguirre MD, Montiel Lopez RJ, Tejeda Miramontes JP, Garcia Cayuela T, Tejada Ortigoza V, Rodriguez Martinez V. Preserving bioactive compounds in avocado peel through convective drying: RSM-based optimization and multivariate modeling. *Applied Food Research*. 2026;6(1):101818. doi: [10.1016/j.afres.2026.101818](https://doi.org/10.1016/j.afres.2026.101818).
- Cunningham M, Azcarate Peril MA, Barnard A, Benoit V, Grimaldi R, Guyonnet D. Shaping the future of probiotics and prebiotics. *Trends Microbiol*. 2021;29(8):667-85. doi: [10.1016/j.tim.2021.01.003](https://doi.org/10.1016/j.tim.2021.01.003), PMID [33551269](https://pubmed.ncbi.nlm.nih.gov/33551269/).
- Thakkar B, Arham M, Verma N. Extraction & sustainable valorization of avocado seed and banana peel-based waste biomass. *Sustain Chem One World*. 2025;8:100118. doi: [10.1016/j.scowo.2025.100118](https://doi.org/10.1016/j.scowo.2025.100118).
- Martinez Zamora L, Bueso MC, Kessler M, Zapata R, Aguayo E, Artes Hernandez F. β -glucanase vs cellulase for enzymatic-assisted extraction of phenolic compounds in avocado peels by-products. *Food Biosci*. 2025;68:106777. doi: [10.1016/j.fbio.2025.106777](https://doi.org/10.1016/j.fbio.2025.106777).
- Salazar Irrazabal MD, Ramirez Tixe EE, Velasquez Barreto FF, Bello Perez LA. Avocado seed starch: effect of the variety on molecular physicochemical and digestibility characteristics. *Int J Biol Macromol*. 2023;247:125746. doi: [10.1016/j.ijbiomac.2023.125746](https://doi.org/10.1016/j.ijbiomac.2023.125746), PMID [37437674](https://pubmed.ncbi.nlm.nih.gov/37437674/).
- Liu A, Wu H, Naeem A, Du Q, Ni B, Liu H. Cellulose nanocrystalline from biomass wastes: an overview of extraction, functionalization and applications in drug delivery. *Int J Biol Macromol*. 2023;241:124557. doi: [10.1016/j.ijbiomac.2023.124557](https://doi.org/10.1016/j.ijbiomac.2023.124557), PMID [37094644](https://pubmed.ncbi.nlm.nih.gov/37094644/).
- MJ, Adhikari B, JAB, Kumar P, Rajeshkumar R. Unlocking avocado's potential: exploring prebiotic-infused cellulose matrices for probiotic stability enhancement. *Int J Appl Pharm*. 2025;17(6):9-24. doi: [10.22159/ijap.2025v17i6.54285](https://doi.org/10.22159/ijap.2025v17i6.54285).
- Kim SK, Guevarra RB, Kim YT, Kwon J, Kim H, Cho JH. Role of probiotics in human gut microbiome-associated diseases. *J Microbiol Biotechnol*. 2019;29(9):1335-40. doi: [10.4014/jmb.1906.06064](https://doi.org/10.4014/jmb.1906.06064), PMID [31434172](https://pubmed.ncbi.nlm.nih.gov/31434172/).
- MJ, Adhikari B, JAB, Kumar P, Kumar RR. Innovative strategies for improving probiotic viability using avocado-based prebiotics and nanotechnology. *Int J Appl Pharm*. 2025;17(4):51-65. doi: [10.22159/ijap.2025v17i4.54336](https://doi.org/10.22159/ijap.2025v17i4.54336).
- Berru SQ, Aguirre E, Garcia-Siu MW, Arias-Nunuvero JO, Cordova Chang A, Rodriguez G. Nutritional and functional properties of defatted avocado (*Persea americana*) pulp cake and its application in the manufacture of cookies. *Food Hum*. 2026;6:101032. doi: [10.1016/j.foohum.2026.101032](https://doi.org/10.1016/j.foohum.2026.101032).
- Rojas Garcia A, Fuentes E, Cadiz Gurra ML, Rodriguez L, Villegas Aguilar MD, Palomo I. Biological evaluation of avocado residues as a potential source of bioactive compounds. *Antioxidants (Basel)*. 2022;11(6):1049. doi: [10.3390/antiox11061049](https://doi.org/10.3390/antiox11061049), PMID [35739946](https://pubmed.ncbi.nlm.nih.gov/35739946/).
- Cai F, Aaqil M, Zhuang L, Shi Z, Cheng R, Zi Y. Comparative study of thermal and non-thermal sterilization on the physicochemical properties microstructure texture and flavor quality of avocado puree. *Food Chem X*. 2026;35:103733. doi: [10.1016/j.fochx.2026.103733](https://doi.org/10.1016/j.fochx.2026.103733), PMID [41853596](https://pubmed.ncbi.nlm.nih.gov/41853596/).
- Chaiyasut C, Kesika P, Sirilun S, Makhmrueng N, Peerajan S, Sivamaruthi BS. Influence of extraction process on yield total phenolic content and antioxidant properties of avocado (*Persea americana Mill.*) oil and stability assessment. *Asian J Pharm Clin Res*. 2019;12(2):391-6. doi: [10.22159/ajpcr.2019.v12i2.30017](https://doi.org/10.22159/ajpcr.2019.v12i2.30017).
- Pantoja KR, Aires GC, Oppata SA, Carvalho JP, Cordeiro RM, Carvalho Junior RN. High-quality Margarida avocado oil obtained by supercritical CO₂ compared to commercial Hass avocado oil from cold pressing: comparative lipid profile analysis by UPC² and GC/MS. *J Supercrit Fluids*. 2026;229:106819. doi: [10.1016/j.supflu.2025.106819](https://doi.org/10.1016/j.supflu.2025.106819).
- Mali P, Sherje AP. Cellulose nanocrystals: fundamentals and biomedical applications. *Carbohydr Polym*. 2022;275:118668. doi: [10.1016/j.carbpol.2021.118668](https://doi.org/10.1016/j.carbpol.2021.118668), PMID [34742407](https://pubmed.ncbi.nlm.nih.gov/34742407/).
- Ponphaiboon J, Krongrwa W, Aung WW, Chinatankul N, Limmatvapirat S, Limmatvapirat C. Advances in natural product extraction techniques, electrosun fiber fabrication and the integration of experimental design: a comprehensive review. *Molecules*. 2023;28(13):5163. doi: [10.3390/molecules28135163](https://doi.org/10.3390/molecules28135163), PMID [37446825](https://pubmed.ncbi.nlm.nih.gov/37446825/).
- Kumari P, Pathak G, Gupta R, Sharma D, Meena A. Cellulose nanofibers from lignocellulosic biomass of lemongrass using enzymatic hydrolysis: characterization and cytotoxicity assessment. *Daru*. 2019;27(2):683-93. doi: [10.1007/s40199-019-00303-1](https://doi.org/10.1007/s40199-019-00303-1), PMID [31654377](https://pubmed.ncbi.nlm.nih.gov/31654377/).
- Biswas S, Rahaman T, Gupta P, Mitra R, Dutta S, Kharlyngdoh E. Cellulose and lignin profiling in seven, economically important bamboo species of India by anatomical biochemical FTIR spectroscopy and thermogravimetric analysis. *Biomass Bioenergy*. 2022;158:106362. doi: [10.1016/j.biombioe.2022.106362](https://doi.org/10.1016/j.biombioe.2022.106362).
- Bhunja AK, Mondal D, Parui SM, Mondal AK. Characterization of a new natural novel lignocellulose fiber resource from the stem of *Cyperus platystylis* R.Br. *Sci Rep*. 2023;13(1):9699. doi: [10.1038/s41598-023-35888-w](https://doi.org/10.1038/s41598-023-35888-w), PMID [37322033](https://pubmed.ncbi.nlm.nih.gov/37322033/).
- Bhardwaj S, Singh S, Meda RS, Jain S, Maji PK. Structural and morphological exploration of cellulose nanocrystals extracted from lignocellulosic waste biomass of *Brassica nigra* (mustard straw). *Biomass Conv Bioref*. 2025;15(17):23753-66. doi: [10.1007/s13399-023-03970-y](https://doi.org/10.1007/s13399-023-03970-y).
- Govindaraj O, Olaganathan GN, Asm R, Uthandi S. An eco-friendly EnZolv pretreatment optimization in banana fiber biomass using response surface methodology (RSM) and its structural characterization. *Biomass Conv Bioref*. 2023;14(1):1329-42. doi: [10.1007/s13399-023-04829-y](https://doi.org/10.1007/s13399-023-04829-y).
- Trivedi AK, Gupta MK. An efficient approach to extract nanocrystalline cellulose from sisal fibers: structural, morphological, thermal and antibacterial analysis. *Int J Biol Macromol*. 2023;233:123496. doi: [10.1016/j.ijbiomac.2023.123496](https://doi.org/10.1016/j.ijbiomac.2023.123496), PMID [36731698](https://pubmed.ncbi.nlm.nih.gov/36731698/).
- Gopinath R, Billigraham P, Sathishkumar TP. Characterization studies on new cellulosic fiber extracted from *Leucaena leucocephala* tree. *J Nat Fibers*. 2023;20(1):2157922. doi: [10.1080/15440478.2022.2157922](https://doi.org/10.1080/15440478.2022.2157922).
- Rahman MM, Pk ME, Waliullah M, Hossain MI, Maniruzzaman M, Ghos BC. Production of cellulose nanocrystals from the waste banana (*M. oranta*) tree rachis fiber as a reinforcement to fabricate useful bionanocomposite. *Carbohydrate Polymer Technologies and Applications*. 2024;8:100607. doi: [10.1016/j.carpta.2024.100607](https://doi.org/10.1016/j.carpta.2024.100607).
- Karupuchamy A, Ramya K, Siva R. Novel banana core stem fiber from agricultural biomass for lightweight textile applications. *Inds crops Prod*. 2024;209:117985. doi: [10.1016/j.indcrop.2023.117985](https://doi.org/10.1016/j.indcrop.2023.117985).
- Velmurugan T, Suganya Priyadarshini G, Suyambulingam I, Siengchin S. Extraction and characterization of *Thespesia populnea* leaf cellulose: a biomass to biomaterial conversion. *Biomass Conv Bioref*. 2024;14(23):30833-44. doi: [10.1007/s13399-024-06018-x](https://doi.org/10.1007/s13399-024-06018-x).