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Evaluation of Banana Pseudostem Fibres for Packaging Material Development

Sérgio Ambrósio Sangarote[1] | Antonio Gomes Soares[2] | Elen Beatriz Acordi Vasques Pacheco[3] | Otniel Freitas-Silva[1,2]

[1]Federal University of the Rio de Janeiro State (UNIRIO), Rio de Janeiro, Brazil | [2]Brazilian Agricultural Research Corporation–EMBRAPA, Embrapa Agroindústria de Alimentos, Rio de Janeiro, Brazil | [3]Institute of Macromolecules Professora Eloisa Mano (IMA), Universidade Federal do Rio de Janeiro (UFRJ), Cidade Universitária, Rio de Janeiro, Brazil

Correspondence: Elen Beatriz Acordi Vasques Pacheco (elen@ima.ufrj.br) | Otniel Freitas-Silva (otniel.freitas@embrapa.br)

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Keywords: banana fibre | composite | cushioning | gum arabic | moulded pulp | pressed boards

ABSTRACT

The present study investigated composites prepared from banana pseudostem fibres (BF) and gum arabic (GA), in different formulations (0, 5, 10, 15, 20, 25 and 30 wt% GA), as an innovative material for fruit packaging. Experimentally, the fibres were extracted using a thermomechanical method to produce pulp, which was then hot-pressed with GA to form composite boards with an average grammage of 461 g/m^2. Commercial packaging made from recycled paper pulp was used as a control. Assessment of the mechanical properties of the boards indicated superior performance by the 15 and 25 wt% GA composites, with respective tensile strength values of 2.7 and 3.1 MPa compared to the control (2.5 MPa), and flexural strength of 20.6 and 3.1 MPa concerning the control (4.6 MPa). Additionally, all the formulations exhibited low deformability, particularly the 100 wt% fibre composite, which showed only 0.4% deformation compared to 3.2% for the control. These results suggest that BF exhibits low deformability and that GA contributed to fibre bonding and cohesion, increasing the tensile modulus of the composites by up to tenfold. Thermogravimetric analysis of the boards showed thermal stability below 200°C, while the water absorption test showed significant absorption, with a maximum value of 358.3% compared to 130.5% for the control. Additionally, FTIR spectroscopy indicated no chemical interaction between GA and BF in the composites. The mechanical properties of the composites were superior to those of the recycled paper pulp packaging. Therefore, the composites show potential as an alternative cushioning material that may align with circular economy principles.

STATEMENT OF SIGNIFICANCE:

This work, 'Evaluation of Banana Pseudostem Fibers for Packaging Material Development,' investigates a novel biocomposite of banana pseudostem fibres and gum arabic as a packaging material, thereby enriching the portfolio of sustainable materials and contributing positively to scientific research and the packaging sector. This study is situated in a context where the production and use of fossil-based materials prevail, as well as the use of packaging materials lacking cushioning properties. Furthermore, the biocomposite was developed using chemical-free processes, which have a less negative impact on the environment, and aims to reduce postharvest losses in the fruit production chain. This research presents discoveries that explore the interconnection of packaging biomaterials, environmental factors and sustainability.

1 | INTRODUCTION

Moulded fibre pulp (MFP) can be formed into various shapes and is designed to cushion and immobilize packaged contents. Compared to expanded polystyrene (EPS) and corrugated cardboard, MFP offers suitable properties for cushioning applications [1], including higher flexural modulus and renewability relative to EPS [2]. Moreover, the resistance properties of MFP are comparable to those of corrugated cardboard, with a tensile modulus of 255.8 MPa compared to 145.8 MPa for corrugated cardboard [3]. Pinewood fibre, the primary raw material for packaging paper, has long been the main source of pulp in the paper industry [4]. However, the high cost of producing virgin wood fibre has prompted growing interest in using agricultural waste as an alternative for moulded pulp production [5]. A variety of agricultural residues have been investigated for this purpose, including waste from oil palm bunches [6], apple pomace fibres [7], pineapple peels and hemp leaves [8], banana pseudostem (BP) fibres [9], rapeseed stalks [4], sugarcane bagasse [10] and mixtures of BP fibres with pineapple leaves and rice straw [11]. These materials have been evaluated for their potential in producing packaging items such as fruit and vegetable trays [6], cups [8] and wrapping paper for butter [9]. Different methods are used to extract lignocellulosic fibres for pulp production, particularly mechanical [4,6] and chemical pulping [8,9]. The chemical composition and morphology of the resulting cellulose fibres vary depending on the extraction method used [12]. In some cases, additives such as chitosan, glycerol [7] and alkyl ketene dimer [10] are incorporated into the fibre pulp to improve specific properties of the final product, including hydrophobicity, fibre–fibre adhesion and mechanical strength.

After pulping, i.e., fibre extraction, the resulting pulp undergoes moulding, a process consisting of two main stages: forming and drying [12]. During the forming stage, moulds are immersed in a tank containing the fibre pulp, which is drawn into the mould using vacuum pressure. As the fibres accumulate on the mould surface to the desired thickness, the liquid phase is mechanically removed by the vacuum system. Once formed, the wet product is removed from the mould and transferred to the drying stage. Two primary drying methods are commonly used: simple and precision moulding. Although the forming process is identical in both methods, simple moulding involves oven drying, whereas precision moulding uses heated mould surfaces to accelerate water removal [13]. According to Zhang et al. [12], the choice between methods depends on the intended application of the final product. In addition to drying techniques and post-processing steps, the mechanical performance of moulded pulp products (MPPs) is significantly influenced by the type and origin of the fibre used [12]. In this study, BP was used as a raw material to assess its potential for postharvest packaging. Typically discarded as agricultural waste following banana harvests, the pseudostem poses a disposal challenge due to the large volume generated. However, several studies have demonstrated the feasibility of extracting BP fibres to produce various materials, including paper [14], polymer composites [15], wrapping paper [16], seedling pots [17], particle boards [18] and handicrafts [19].

Banana pseudostem fibres (BFs) were selected for this study due to their abundance and availability in the state of Rio de Janeiro, aligning with circular economy principles. Fibre extraction was carried out using a thermomechanical pulping method to obtain partially lignin-free fibres, as opposed to chemical pulping. Chemical pulping typically involves reagents such as sodium hydroxide, anthraquinone and sodium sulfide [9,11], which can lengthen the fibre extraction process and increase experimental costs. Gum arabic (GA), a natural and highly branched arabinogalactan polysaccharide [20], was also used as a raw material. GA is widely applied in the food industry as a stabilizer, emulsifier, thickener, humectant, firming agent, antioxidant [21] and auxiliary matrix-forming agent in food films and coatings [22]. Because of its excellent adhesive properties, GA has also been used as a binder for particle board production using wood sawdust [23] and in the textile industry to improve the tensile strength of yarns [24]. In this study, based on its water solubility and binding capacity, GA was used for the first time in combination with BP fibres to produce moulded and hot-pressed composite boards. The mechanical and physical properties of the resulting boards were assessed, along with their chemical structure, surface morphology and thermal stability. Additionally, the chemical composition of the fibres before and after delignification was analyzed. For comparison, the tensile strength, flexural strength, grammage and water absorption (Wa) of commercial recycled paper pulp packaging were also assessed as a control.

2 | EXPERIMENTAL SECTION

2.1 | Materials

Banana pseudostem (*Musa* spp.) was collected in the courtyard of the Professora Eloisa Mano Macromolecules Institute (IMA) at the Federal University of Rio de Janeiro (UFRJ), Brazil. Commercial-grade GA powder (*Acacia senegal L.*) of Senegalese origin was donated by NEXIRIA Brazil. For comparison with the hot-pressed fibreboards, recycled paper pulp (RPP) egg cartons commercially available on the domestic market were used.

2.2 | Experimental Activities

Figure 1 schematically summarizes the main experimental steps carried out in this study, from the collection of BP to the characterization of MPPs.

2.2.1 | Pulp Production (Pulping)

To extract and delignify the fibres, the BPs were washed, separated into sheaths and cut into pieces approximately 10 cm long and 5 cm wide [2,8,9]. The pieces were first sun-dried and then oven-dried at 60°C in a forced-air oven until reaching constant mass (m) [8]. Next, they were boiled in tap water at 100°C and atmospheric pressure for 30 min in 2-L Erlenmeyer flasks using a hotplate. After cooking, the softened pieces were cooled to room temperature and filtered through a metal mesh to separate the black liquor (lignin) [16]. The retained material was manually disintegrated, washed with tap water and dried again in a forced-air oven at 60°C until reaching constant mass (m_1) [16,25]. The dried fibres were weighed and blended in a domestic blender (Philips Walita-RI7761 750 W). Distilled water was added at a banana fibre to water (BF:H_2O)

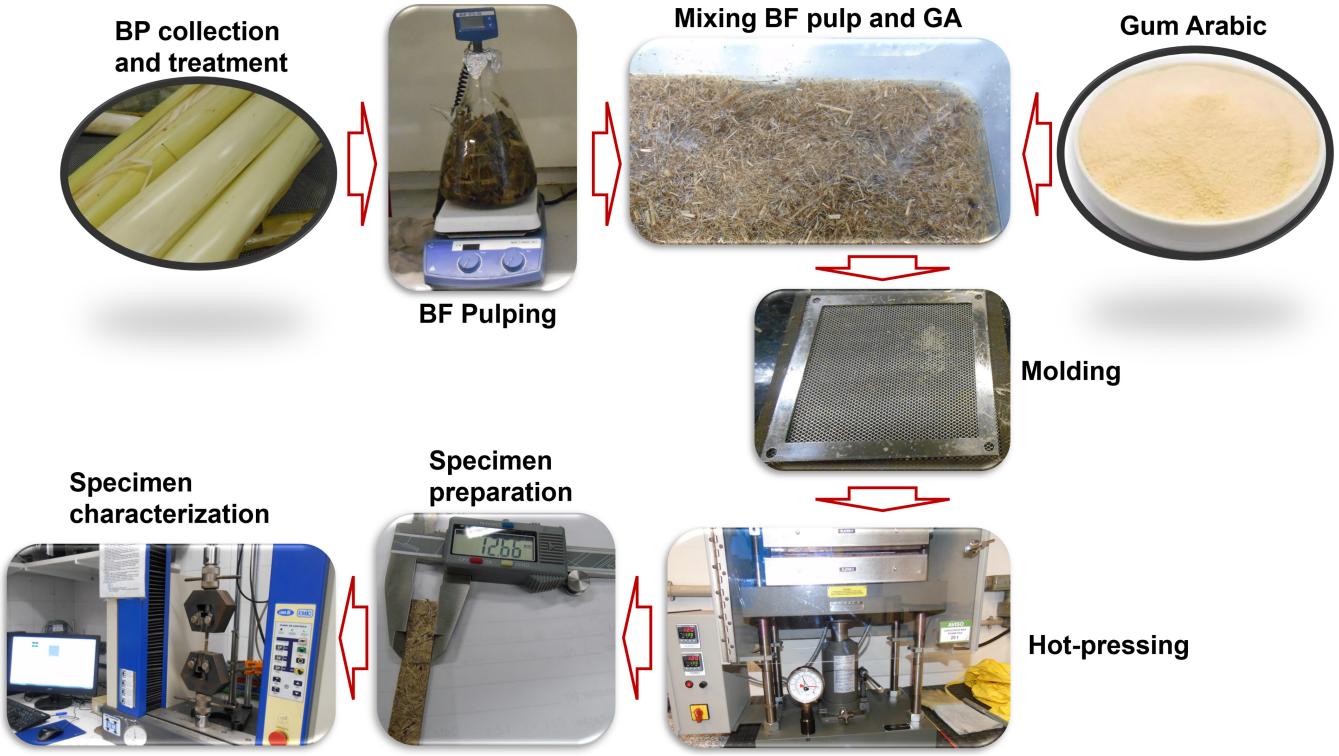

FIGURE 1 | General flowchart of the main experimental steps.

mass ratio of 1:78, yielding a fibre consistency of 1.3%, and the mixture was homogenized at 1500 rpm for 5 min [3]. To enhance fibre properties, GA was dissolved in distilled water at a GA:H_2O mass ratio of 1:13. The GA solution was then added to the fibre pulp in the blender at varying mass percentages (0%, 5%, 10%, 15%, 20%, 25% and 30%) relative to the dry mass of BF. Finally, the BF + GA composites were homogenized in a blender at 1500 rpm for 2 min to produce the final pulp formulations, as shown in Table 1.

2.2.2 | Fibre Chemical Characterization

Samples of BP were collected both before (BP) and after (BF) pulping to determine ash, holocellulose, hemicellulose, α-cellulose and lignin content. The analyses were performed in duplicate.

Ash content was determined using Method 'A,' ash in cellulose at 575°C, following the American Society for Testing and Materials (ASTM-D3516-89) [26]. The ash content was calculated using Equation 1.

$$C_{ash} = \frac{m_1 - m_2}{m_2} \times 100 \quad \text{(Eq.1)}$$

where C_{ash} is the ash content (%), and m_1 and m_2 are the masses (in grams) of the dry fibre before and after incineration, respectively.

The holocellulose content was determined according to Wise et al. [27]. Approximately 3 g of dry fibre were weighed and placed in a 500 mL conical flask with 120 mL of distilled water.

TABLE 1 | Formulation of BF and GA composites.

Fibre		Gum arabic		
Mass (g)	(wt/wt%)	Mass (g)	(wt/wt%)	Formulation code
25.32	100	0	0	BF100
24.05	95	1.27	5	BF/GA5
22.79	90	2.53	10	BF/GA10
21.52	85	3.80	15	BF/GA15
20.26	80	5.06	20	BF/GA20
18.99	75	6.33	25	BF/GA25
17.72	70	7.60	30	BF/GA30

The mixture was placed in an oil bath and heated to 70°C. Once this temperature was reached, 1 mL of glacial acetic acid and 2.5 g of sodium chlorite were added. This addition was repeated after 1 and 2 h. The reaction mixture was then maintained at 70°C for 6 h, filtered through a preweighed sintered funnel (n°3), washed with distilled water until neutral pH (7.0) and then rinsed with ethanol. The retained material was dried in a forced-air oven at 60°C. Finally, the funnel containing the dried material was weighed again to determine holocellulose content using Equation 2.

$$C_{ho} = \frac{m_{f2} - m_{f1}}{m_a} \times 100 \quad \text{(Eq 2)}$$

where C_{ho} is the holocellulose content (%), m_a is the mass of the sample (grams), and m_{f1} and m_{f2} are the masses of the funnel before and after filtering (grams), respectively.

The α-cellulose and hemicellulose contents were determined according to Wise et al. [27]. Approximately 1 g of the holocellulose obtained in the previous step was weighed and treated with 15 mL of 17.5 wt% NaOH solution for 2 min. The mixture was then ground for 8 min and allowed to stand for 20 min. After this period, the material was filtered through a previously weighed sintered funnel (n°3) and washed with distilled water until neutral pH (7.0). It was then rinsed with 200 mL of 20% (wt/vol) acetic acid and 200 mL of distilled water and dried in an oven at 60°C for 24 h. The funnel containing the dried material was then weighed again. The α-cellulose and hemicellulose contents were calculated using Equations 3 and 4, respectively.

$$C_{\alpha-\text{cellulose}} = \frac{m_{\alpha-\text{cellulose}}}{m_{\text{holloceluse}}} \times 100 \quad \text{(Eq 3)}$$

$$C_{\text{he}} = C_{\alpha-\text{cellulose}} - C_{\text{ho}} \quad \text{(Eq 4)}$$

where $C_{\alpha\text{-cellulose}}$ and C_{he} are the α-cellulose and hemicellulose content (%), respectively, $m_{\alpha\text{-cellulose}}$ is the mass of α-cellulose (grams), and $m_{\alpha\text{-holocellulose}}$ is the mass of holocellulose (grams).

Lignin content was determined according to the Technical Association of the Pulp and Paper Industry (TAPPI T13m-54) [28]. This procedure involves isolating lignin through hydrolysis of the polysaccharides using concentrated sulfuric acid (72%).

2.2.3 | Evaluation of the Pulping Process

After the BPs were cut into smaller sections, the material was dried to a constant mass, weighed and then subjected to pulping. Pulping yield was calculated using Equation 5. Additionally, the percentage of lignin removal was estimated by comparing the lignin content before and after pulping, as determined according to TAPPI T13m-54 [28].

$$\textit{Pulping yield}\,(\%) = \frac{m_1}{m} \times 100 \quad \text{(Eq 5)}$$

where m and m_1 are the dry masses (in grams) of the fibre before and after pulping, respectively [29].

2.2.4 | Production of Moulded Fibreboards

To produce the pressed fibreboards, the prepared pulps were poured into a plastic container, into which a metal mould (190 × 190 × 2 mm) with a metal filter mesh (30) attached to the bottom was submerged. This setup allowed the solid material to be retained in the mould cavity while the liquid phase drained through the mesh. Once the wet fibre mat was formed in the mould, it was transferred onto a stainless-steel plate and covered with a second plate. The assembly was then placed in a hydraulic press (CARVER model 3925) and hot-pressed at 120°C [7] for 30 min under a pressure of 10 metric tons. After pressing, the composites were removed and dried in an oven at 60°C until constant mass (typically > 24 h). Figure 2 illustrates the main stages of the fibreboard production process.

2.2.5 | Determination of Board Grammage

The grammage of the boards was determined by weighing each board using a digital scale and dividing the mass by the surface area of the respective board [30]. The same procedure was applied to the recycled paper pulp material for comparison.

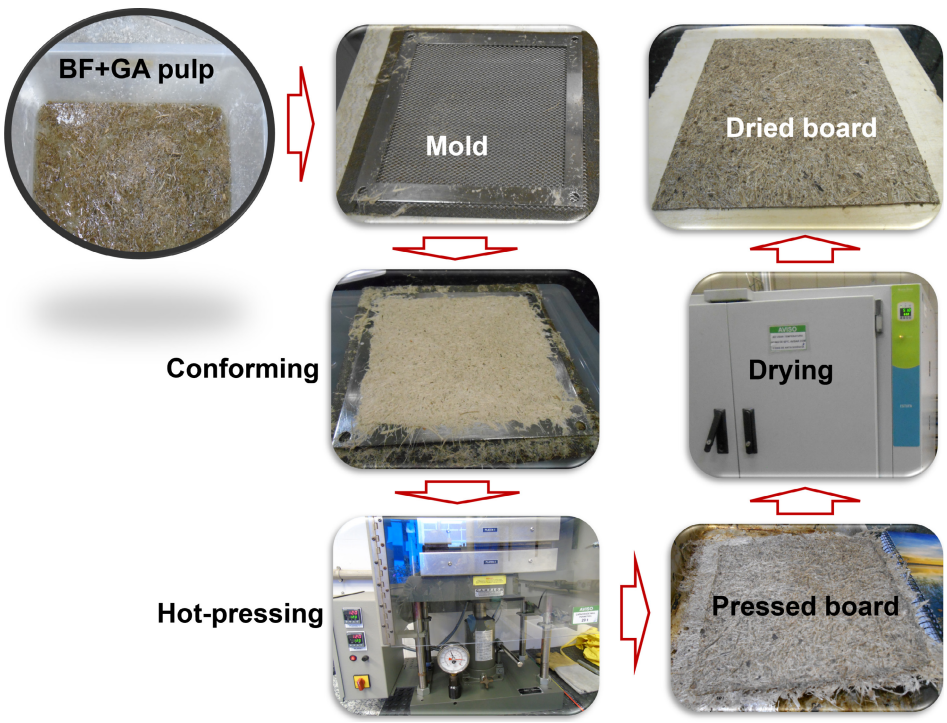

FIGURE 2 | Flowchart of the pressed board production process.

2.2.6 | Preparation of Specimens

Specimens were prepared from the pressed fibreboards (Figure 3a) and the recycled paper pulp packaging (Figure 3b) for comparative testing. The specimens were cut following ASTM D7264/D7264M [31] and TAPPI 494 [32] for flexural and tensile tests, respectively. Dimensions (length, width and thickness) were measured according to TAPPI 411 [33]. Before testing, all specimens were stored for 24 h in a controlled environment at 25°C and 50% relative humidity.

2.2.7 | Evaluation of Moulded Boards

According to Ek et al. [34], one of the most important properties of packaging material is toughness, defined as the ability of a material to absorb energy and plastically deform without fracturing. In this context, tensile and flexural tests were initially conducted on the pressed boards because their mechanical performance was a critical factor for the continuation of this study. For mechanical testing, five specimens per sample were tested using an EMIC DL-3000 universal testing machine equipped with a 5 kN load cell. Tensile properties were evaluated using specimens with dimensions of 15 × 80 mm, a gauge length of 50 mm and a test speed of 7 $mm.min^{-1}$, in line with TAPPI 494 [32]. Flexural properties were measured on specimens with dimensions of 12.7 × 100 mm, a gauge length of 32 mm and a test speed of 0.95 $mm.min^{-1}$, in accordance with ASTM D7264/D7264M [31].

Thermogravimetric analysis: thermal stability was assessed using a TGA Q500 V20.13 Build 39 thermogravimetric analyser. Accurately weighed samples were randomly distributed in crucibles and heated from 25 to 800°C at a constant rate of 10°$C.min^{-1}$ under an N_2 atmosphere at a flow rate of 40 $mL.min^{-1}$, following the procedure described by Li et al. [35] with some modifications.

Scanning electron microscopy (SEM): micrographs were obtained using SEM at an accelerating voltage of 5 keV with magnifications of 100 and 1000×. The samples were cut into small sections, sputter-coated with gold [4,36] and imaged more than three times for each sample type. The sharpest and clearest micrographs were selected for presentation.

Fourier transform infrared spectroscopy (FTIR) analysis was performed to investigate the interaction between BF and GA and detect possible chemical changes in the hot-pressed samples by identifying characteristic functional groups. The spectra were obtained using a PerkinElmer Spectrum Frontier FT-IR/FIR spectrometer (version 10.4.2), operating in attenuated total reflection (ATR) mode over a wavelength range of 600–4000 cm^{-1}, with a resolution of 4 cm^{-1} and an average of 60 scans [37,38].

Water absorption of the pressed boards and the control samples was analyzed according to ASTM D570-98 [39], with some modifications [7,25,40,41]. Specimens measuring 15 × 80 mm were weighed and then submerged in distilled water at 23°C for 2 h. After immersion, samples were suspended vertically for 1 min to allow the water to drain and then reweighed. Water absorption was calculated in triplicate as the percentage increase in mass of the sample relative to its initial dry mass.

2.3 | Statistical Analysis

After the dependent variables were determined, the data were submitted for analysis of variance (ANOVA). The ANOVA assumptions were analyzed using the Shapiro–Wilk test to assess the normality of residuals and Bartlett's test for homogeneity of variances. Differences between formulations and the control samples were compared using Fisher's least significant difference (LSD) test at a 5% significance level. All statistical analyses were performed in R software (version 4.1.3), using the GExpDes package (version 1.0.1).

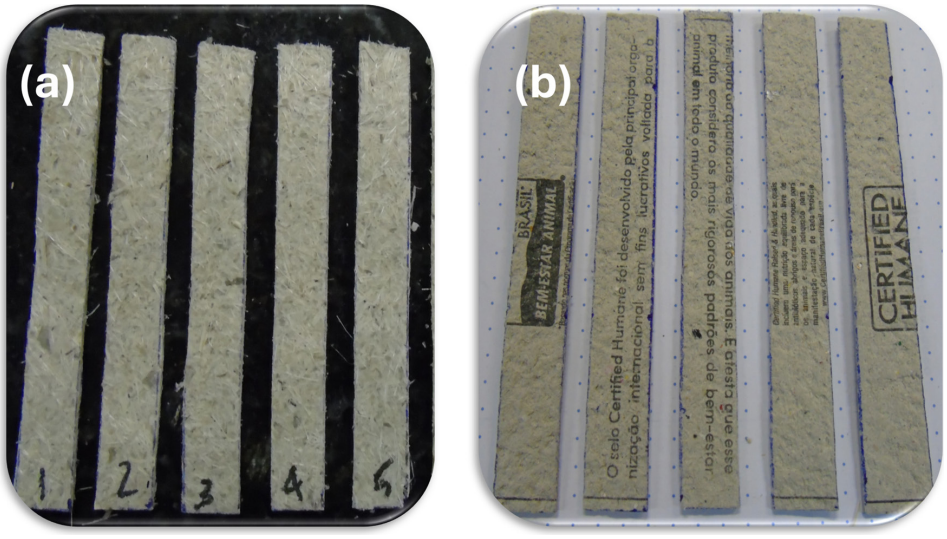

FIGURE 3 | Specimens prepared from: (a) experimentally pressed boards and (b) recycled paper pulp packaging.

3 | Results and Discussion

3.1 | Fibre Chemical Characterization

Table 2 presents the chemical composition of the banana pseudostem fibres used in this study, along with data from other studies for comparison.

The chemical composition of BP fibres can vary significantly, even among samples from the same or different varieties/species. This has been reported in several studies and is primarily attributed to soil and climate conditions [45,47], a common trait of natural fibres. Like other lignocellulosic fibres, banana fibres typically contain high proportions of cellulose, hemicellulose and lignin, with cellulose generally being the most abundant component. Other constituents such as pectin, fatty acids, extractives and ash are present in lower amounts [47]. The fibres analyzed in this study exhibited intermediate levels of cellulose, hemicellulose and lignin compared to values reported in the literature (Table 2). By contrast, Waliszewska et al. [48] reported 45% cellulose, 20% hemicellulose and 28% lignin in pine pulp. Similarly, another study found 49% cellulose and 27% lignin in the *Pinus contorta* and *Pinus sylvestris* species [49]. These results indicate that the chemical composition of BF is comparable to that of pine fibres, which are widely used as raw materials in the pulp and paper industry [4]. Therefore, BP fibres show promise as an alternative raw material for fibre pulp production and can potentially be used in sustainable packaging applications.

3.2 | Pulping Process Performance

The pulping yield obtained here was 63.1%, lower than the 90% yield reported by Moral et al. [4], who used a thermomechanical pulping method on rapeseed for packaging applications. Despite this lower yield, the 63.1% result suggests that a significant portion of lignin and other BP components was effectively removed during filtration and rinsing with tap water. The α-cellulose, hemicellulose and lignin contents before and after pulping were 48.3/61.9%, 4.7/19.9% and 22.8/10.9%, respectively. The lignin content was reduced by approximately half its initial percentage in the raw material, which can be considered significant. This is particularly relevant because fibre extraction for MPP production typically involves disintegration and washing steps that naturally remove a portion of the lignin. Depending on the pulping conditions, both lignin and a considerable fraction of hemicellulose may be dissolved and removed, which can reduce the pulping yield [50]. Therefore, optimizing pulping parameters, such as cooking temperature, time and the degree of fibre disintegration, is essential to ensure effective delignification of the raw material while maintaining the fibre characteristics necessary for the intended application.

TABLE 2 | Chemical composition of banana pseudostem fibres.

Main constituents (wt%)			
α-Cellulose	Hemicellulose	Lignin	References
48.3 ± 1.4	4.7 ± 2.7	22.8 ± 1.8	Present study
69.4 ± 0.7	8.8 ± 0.9	15.3 ± 0.1	Mohamad & Jai [42]
49.5 ± 2.3	27.8 ± 4.9	27.8 ± 4.3	Silva et al. [43]
46.3 ± 6.1	12.2 ± 3,9	15.0 ± 4,0	Jayaprabha et al. [44]
50.2 ± 1.1	0.8 ± 0.6	17.4 ± 0.2	Guimarães et al. [45]
37.4 ± 2.9	25.3 ± 0.3	12.4 ± 0.4	Cordeiro et al. [46]

3.3 | Boards Grammage

Figure 4 illustrates how the grammage of the fibreboards varies with the mass percentage of GA added to the different lignocellulosic formulations.

The 100 wt% fibreboard (i.e., the board without GA) exhibited a higher grammage when compared to the control, as shown in Figure 4. Unlike recycled paper fibres, which are chemically extracted and often fragmented, BP fibres were mechanically extracted, resulting in the presence of intact, nonfractured fibres in the pulp [34] and contributing to denser and more compact fibre pulps. When GA was incorporated into the pulp, the grammage of the pressed boards ranged from a minimum of 336 g/m^2 to a maximum of 554.9 g/m^2 (Figure 4). In general, an inverse relationship was observed between the GA content and the grammage of the composites, except for BF/GA15 and BF/GA25. This reduction in grammage with increasing GA content is primarily attributed to the partial replacement of high-density BF (1500 kg/m^3) with lower-density GA (405 kg/m^3), as well as the partial loss of dissolved GA during the draining step of the moulding process [51–53]. The deviations from this trend observed in BF/GA15 and BF/GA25 may be due to variability in manual handling during the moulding process, which may have affected the consistency of pulp retention across formulations.

The grammage of the fibreboards produced in this study is higher than the 40 g/m^2 and 60 g/m^2 reported in other studies [9,16] on MPPs developed from BP fibres. A higher grammage increases the mass of the final product, while a lower grammage

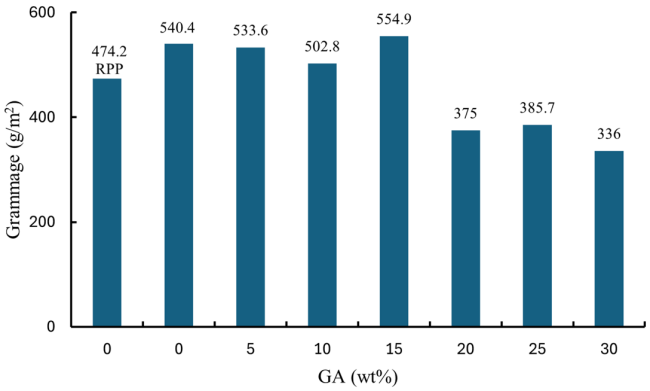

FIGURE 4 | Grammage of pressed boards and controls (RPP) as a function of GA.

results in a lighter material. In practical terms, the ideal scenario is to design packaging materials that optimize both weight and mechanical performance, thereby improving efficiency in supply chain logistics. However, the pulp and paper industry recommends a grammage range of 100– 400 g/m^2 for board-based packaging materials, such as cardboard and corrugated cardboard [34].

3.4 | Tensile and Flexural Properties

Table 3 presents the tensile and flexural properties of the pressed boards and recycled paper pulp packaging. Additionally, Figure 5 presents the stress–strain behaviour of 100% fibre-boards, fibre-GA composites and control samples. To the best of our knowledge, no published studies have simultaneously used BP fibres and the thermomechanical pulping method to produce pressed boards or sheets for mechanical assessment. As such, the results of this study are compared primarily to those of commercially available recycled paper pulp cartons, which serve as the control sample.

In general, the effect of increasing GA content on the tensile and flexural properties followed a nonlinear trend, making it possible to identify optimal BF/GA ratios for each property (Table 3). According to TAPPI 494 [32], tensile strength reflects factors such as fibre strength, fibre length and the quality of fibre–fibre and fibre–binder bonding. The 100 wt% fibre sample (i.e., 0% wt GA) exhibited lower tensile strength compared to that of the control. However, the incorporation of GA into the fibre pulp resulted in noticeable improvements, particularly at 15 and 25 wt% GA. These formulations (BF/GA15 and BF/GA25) outperformed both the 100 wt% fibre and control samples in terms of tensile strength, tensile modulus and tensile index (Table 3). As a natural resin, GA enhanced fibre bonding and cohesion, thereby contributing to increased material strength [40]. The tensile index also rose in tandem with tensile strength. This is consistent with the findings of Scheer et al. [36], who noted that the tensile index correlates with fibre mass, fibre–fibre and fibre–polymer bonds. Notably, at least one GA-containing formulation showed no statistically significant difference from the control in terms of tensile strength, tensile modulus and tensile index at a 5% significance level (Table 3).

Deformation under maximum force, or percentage elongation, is defined as the ratio between the increase in specimen length and its original length [32]. The pressed boards exhibited low deformation, particularly the 0 wt% GA sample, with an average elongation of 0.4% compared to 3.2% for the control. Upon incorporating 5% GA into the pulp, maximum deformation increased to 0.8% and then varied nonlinearly with further increases in GA content (Table 3). These results suggest that BF exhibited low deformation under tensile force and the inclusion of GA in the pulp only slightly increased the deformation of the samples. The slight increase in deformation may be attributed to the partial replacement of BF with GA, with a reduction in the fibre mass and fibre–fibre bond decreases, as discussed previously in the grammage analysis subsection. Although it contributes to fibre bonding, the interaction between GA and fibres may be

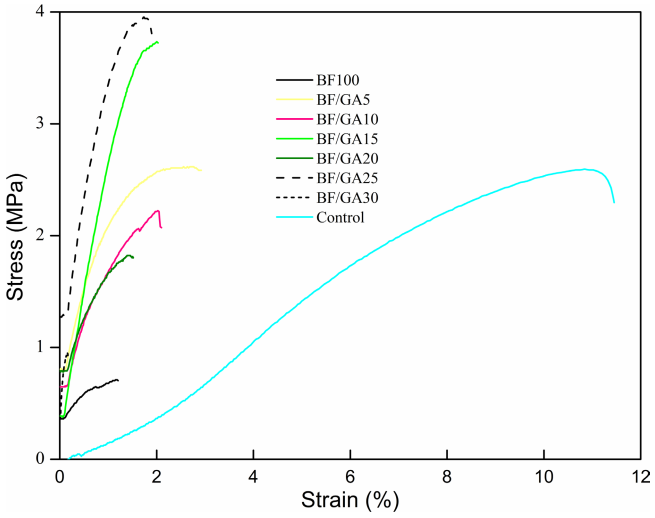

FIGURE 5 | Stress–strain curves of the pressed boards and control samples.

TABLE 3 | Mechanical properties of 100% fibreboard, fibre-GA composites and control samples.

	Tensile properties				Flexural properties	
GA added (wt%)	Tensile strength (MPa)	Tensile modulus (MPa)	Tensile index (N.m/g)	Deformation (%)	Flexural strength (MPa)	Flexural modulus (MPa)
0	0.5 ± 0.2	25.5 ± 8.5	1.8 ± 0.5	0.4 ± 0.1	7.0 ± 4.3^{d}	199.8 ± 160.1
5	2.0 ± 0.5^{a}	84.4 ± 39.6	3.3 ± 1.3^{c}	0.8 ± 0.2	15.2 ± 3.4	1196.4 ± 394.2
10	1.5 ± 0.5	57.0 ± 28.4	2.9 ± 2.1^{c}	0.7 ± 0.2	19.6 ± 9.5	1279.2 ± 255.4
15	2.7 ± 1.2^{a}	141.7 ± 32.7	4.6 ± 2.7^{c}	0.7 ± 0.6	20.6 ± 6.9	1155.4 ± 395.0
20	1.9 ± 0.5^{a}	95.5 ± 24.5	4.4 ± 1.3^{c}	0.6 ± 0.1	15.1 ± 3.3	1391.9 ± 506.4
25	3.1 ± 0.8^{a}	131.6 ± 72.4	6.3 ± 2.6^{c}	0.7 ± 0.2	3.1 ± 1.2^{d}	415.3 ± 166.7
30	0.5 ± 0.3	18.7 ± 3.9^{b}	2.5 ± 1.7	0.5 ± 0.2	3.4 ± 0.9^{d}	211.4 ± 79.4
Control	2.5 ± 0.1^{a}	12.8 ± 5.8^{b}	4.3 ± 0.4^{c}	3.2 ± 0.6	4.6 ± 0.5^{d}	97.3 ± 27.7

Note: Numbers with superscript letters (a, b, c, d) in the same column do not differ significantly from the control at a 5% significance level.

weaker than that of direct fibre–fibre bonding [36]. From a statistical perspective, all formulations showed significantly lower elongation ($p \leq 0.05$) compared to the control.

Figure 5 presents the stress–strain relationship, which reflects the stiffness of the boards and often provides a more accurate indication of their mechanical response to converting forces than failure criteria [32]. All curves exhibited different behaviours; however, within the elastic region, the composites with 15 and 25% GA showed similar performance and exhibited high tensile stress at break (Figure 5), which corroborates the tensile strength, tensile modulus and tensile index results shown in Table 3. On the other hand, the stress–strain curves of the pressed boards exhibited lower strain at break compared to the control (Figure 5), which supports the deformation results discussed previously.

Concerning flexural properties, the composite samples showed superior flexural strength when compared to the 100 wt% fibre and control samples, except for the 25 and 30 wt% GA formulations (Table 3). As previously reported, this enhancement is likely due to GA's contribution to fibre bonding and cohesion [40] and reduced fibre mobility, which improves both flexural strength and modulus. However, in applications where cushioning is important, packaging materials require greater flexibility, toughness and tensile strength. In this context, the 25 wt% GA sample obtained the lowest average flexural strength (3.1 MPa). This value indicates greater flexibility and is comparable to the 3.5 MPa reported by Gouw et al. [25] for pressed boards made from recycled newspaper pulp with glycerol as a plasticizer. In contrast to flexural strength, all formulations exhibited statistically significant differences ($p \leq 0.05$) in flexural modulus compared to the control.

3.5 | Water Absorption

Figure 6 illustrates the relationship between Wa and GA content (GA %wt) in different fibrous materials.

Water absorption is a parameter that quantitatively describes a material's ability to retain water after saturation [7]. Overall, the pressed fibreboard samples showed significantly higher Wa ($p \leq 0.05$) than the control (Figure 6). This difference is largely attributed to the composition of recycled paper pulp, which is derived from postconsumer materials such as recycled paper, cardboard and newspaper. These materials often contain residual fractions of synthetic plastics, coatings, adhesives and inks, which reduce their permeability when compared to virgin fibre pulp. Additionally, recycled paper fibres undergo chemical pulping and bleaching, which result in lower swelling capacity, Wa and retention compared to mechanically pulped fibre products [34,54,55]. Despite the presence of hydrophobic lignin in the pulp, the dominant components (cellulose and hemicellulose) are highly hydrophilic and therefore contribute more significantly to the increased Wa [56] of the pressed boards (Figure 6). Furthermore, the incorporation of GA into the pulp led to a general increase in Wa, with higher GA content resulting in higher Wa values. This is due to the intrinsic hydrophilicity and proteinaceous nature of GA, which promote water–matrix interaction [22]. Similar findings were reported by Ferreira et al. [40], who observed a 23% increase in Wa with up to 30 wt% of alkaline gum arabic (GA_b) added to bleached eucalyptus kraft pulp. Silva et al. [43] also reported comparable Wa values (344.2%) in pressed boards made from 100 wt% BF, aligning with several formulations presented in Figure 6.

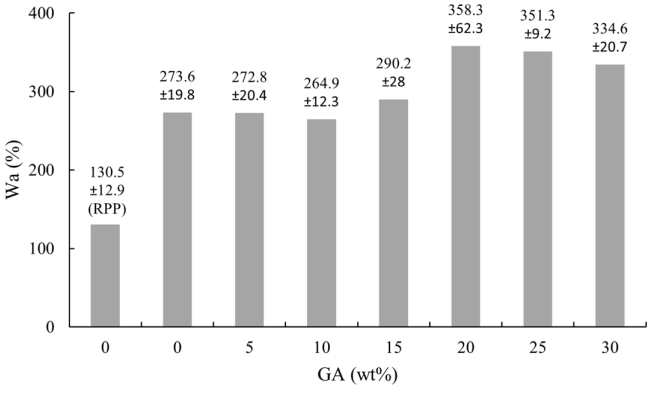

FIGURE 6 | Water absorption of the control (RPP) and pressed board samples as a function of gum arabic content.

3.6 | Thermal Stability

Thermogravimetric analysis (TGA) results are presented in Figure 7, illustrating the effect of high temperatures on the mass of the material constituents.

Moisture evaporation occurred primarily between 25°C and 150°C, corresponding to the first endothermic event and corroborating the findings of Li et al. [35] and Subramanya et al. [57]. This temperature range is typically associated with the loss of residual moisture and volatile extractives [58], with mass loss in this study ranging from 7% to 13%. The highest moisture loss was observed in the nondelignified fibre sample (BP), likely due to the absence of cooking, filtration and hot-pressing treatments, which are known to partially remove moisture and volatiles, as

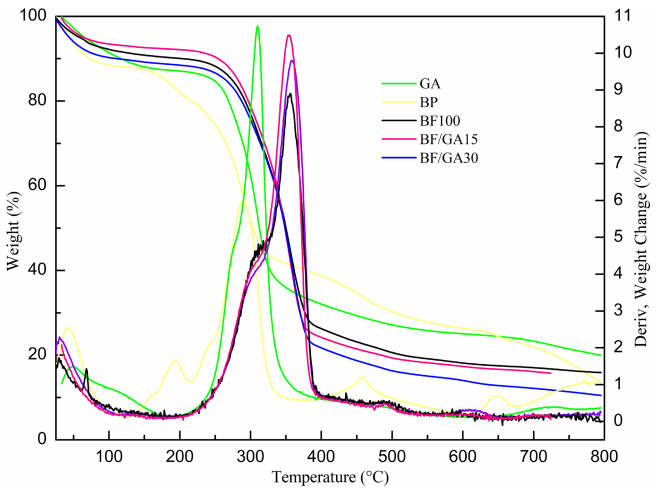

FIGURE 7 | TGA curves and their derivatives (DTG) for nondelignified fibres (BP), gum arabic, 100 wt% fibreboard (BF100) and composite boards containing 15 wt% (BF/GA15) and 30 wt% (BF/GA30) gum arabic.

observed in the remaining samples. Significant thermal degradation of the pressed boards began at temperatures exceeding 200°C, as shown in the TGA curves (Figure 7).

In general, the 200°C–400°C temperature range corresponds to the thermal degradation of hemicellulose (primarily between 206°C–326°C) and cellulose (between 320°C–400°C) in the fibres [59], as well as polysaccharides in the GA, which degrade between 260°C–300°C [22]. The mass loss curves of all samples followed a similar pattern, except BP (Figure 6), which did not undergo pulping. This difference is consistent with previous observations. Notably, the DTG shoulders around 200°C, 450°C and 650°C on the BP curve disappeared after pulping (as observed for BF100), indicating the partial removal of lignin, extractives, and other impurities from the raw material. In the 200 to 400°C heating range, the BP sample exhibited a lower maximum thermal degradation temperature (MTDT) of 300.8°C compared to the delignified and hot-pressed BF100 sample, which reached 355.9°C. This suggests that the presence of residual impurities in BP, due to the absence of pulping, may have compromised its thermal stability. The BF/GA15 and BF/GA30 composites displayed MTDTs of 353.7°C and 358.3°C, respectively. Compared to BF100, incorporating 15 wt% GA into the fibre pulp decreased the MTDT by 2.2°C, whereas 30 wt% GA increased it by 2.4°C. Because GA is generally less thermally stable than BF, the progressive substitution of BF by GA in the pulp was expected to reduce the MTDT of the composites (Figure 7). This contrasts with the findings of Ferreira et al. [40], who reported a linear MTDT decrease of up to 40°C with the addition of up to 30 wt% of alkaline gum arabic (GA_b) to bleached eucalyptus pulp. The authors attributed this decline to the plasticizing effect of GA_b, which reduced the thermal stability of the samples as their concentration increased.

Lignin degradation occurs between 400 and 800°C. Above 400°C, most of the C–C bonds in the lignin alkyl chains become unstable and reactive, causing further fragmentation and the release of functional groups such as -H, -OH, $-CH_3$ and -COOH [60]. After heating to 800°C, the residue content varied among samples, with 15.9% for BF100, 15.7% for BF/GA15 and 10.5% for BF/GA30. These differences can be attributed to the varying proportions of BF and GA, whereby samples with a higher fibre content yielded more residue since BF has a higher ash content (6.9%–15.7%) [16,61,62] compared to GA (2–4%) [63].

3.7 | Scanning Electronic Microscopy

Figure 8 presents the SEM micrographs of the surface morphology of the 100 wt% fibre and 15 wt% GA samples at 100× and 1000× magnification.

Figure 8 reveals variations in fibre size and suggests random dispersion of fibres throughout the pressed boards. At 1000× magnification, the BF displays fibrous cells (Figure 8C) and remnants of residual pulp (Figure 8D) not fully removed during pulping, as also described by Silva et al. [43]. Unlike the 100 wt% fibre sample (Figure 8A,C), the fibres in the GA-containing composite appear more randomly entangled (Figure 8D), because GA acts as a binding agent. This suggests that both GA and the hot-pressing process facilitated fibre bonding [11]. Similar results were reported by Ferreira et al. [40], who found that GA

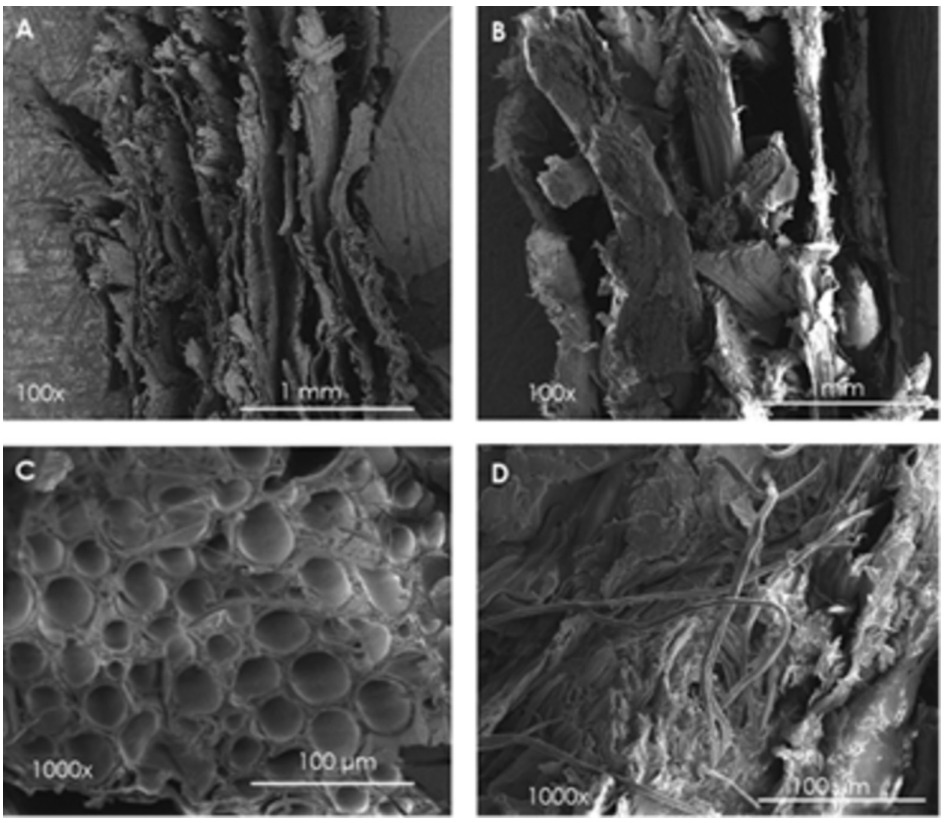

FIGURE 8 | SEM micrographs of the 100 wt% fibre (A, C) and 15 wt% GA pressed board samples (B, D).

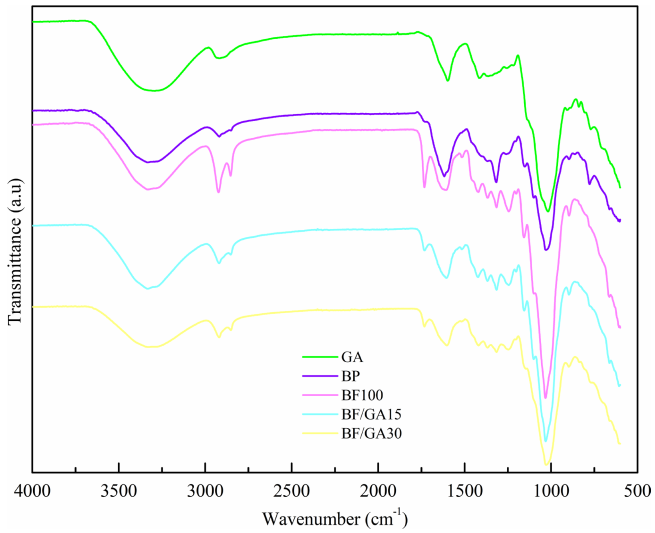

FIGURE 9 | FTIR spectra of nondelignified fibres (BP), gum arabic, the 100 wt% fibreboard (BF100) and BF/GA15 and BF/GA30 composites.

combined with pressing promoted material densification and reduced voids between fibres, thereby enhancing fibre cohesion. Likewise, Wang et al. [64] observed that lignocellulosic fibres were effectively bonded using adhesive substances (not identified by the authors for confidentiality reasons), which improved fibre bonding.

3.8 | Fourier Transform Infrared Spectroscopy

Figure 9 shows the FTIR spectra of GA, nondelignified fibre (BP) and the 100 wt% fibre (BF100), BF/GA15 and BF/GA30 samples.

The main objective of FTIR analysis was to investigate the interaction between BF and GA and predict possible chemical changes in the hot-pressed samples. However, as shown in Figure 9, the spectra of the composite samples show no new absorption peaks compared to BF100. This indicates that no molecular interactions occurred in the materials between the constituents of BF and GA. Therefore, the interaction between GA and BF was likely physical in nature (agglutination), as reported by Ferreira et al. [40].

In the spectrum of the nondelignified fibre (BP), the distinct peaks at around 1617 and 1317 cm^{-1} correspond to C=C stretching in the aromatic ring of lignin and C–O stretching in the syringyl unit, respectively [65,66]. However, these peaks appear with reduced intensity in the spectra of the pressed board samples (BF100, BF/GA15 and BF/GA30), likely due to the partial removal of lignin during the pulping process. Similar results were obtained by Mohamad and Jai [42] and Subramanya et al. [57].

Additionally, the peaks around 1733 and 2923 cm^{-1} in the BF/GA15 and BF/GA30 spectra exhibit lower intensity when compared to BF100 (Figure 8). The 1733 cm^{-1} peak corresponds to C=O stretching vibrations in aldehyde groups found in lignin and hemicellulose [15], while the 2923 cm^{-1} peak is attributed to the symmetric C–H stretching of methylene groups in cellulose and hemicellulose [65]. The decline observed in peak intensity with increasing GA content suggests that GA interfered with the fibrous matrix.

4 | Conclusions

Hot-pressed boards with an average grammage of 461 g/m^2 were produced and their mechanical properties were also evaluated. The results indicated that all formulations exhibited low deformation ($p \leq 0.05$), with the 100 wt% fibre sample performing best. These findings demonstrate that BP fibres display low deformation under tensile load, a desirable trait for applications in the supply chain. The addition of 15 and 25 wt% gum arabic improved both tensile strength and tensile modulus, likely due to enhanced fibre bonding and cohesion. Microstructural analysis further suggests that the fibres in the composites were randomly entangled, as a result of GA acting as a binder during the moulding.

All formulations demonstrated thermal stability; however, significant differences were observed in Wa ($p \leq 0.05$), which could limit their suitability for highly humid environments. This limitation could be mitigated in commercial applications through the use of additives, which have been shown to reduce Wa in MPPs. In summary, composites made from BP fibre and GA show potential as sustainable packaging materials for the fruit supply chain, aligning with circular economy principles.

Author Contributions

Sérgio Sangarote contributed to the conceptualization, literature review and analysis and writing of the original draft, as well as review and editing; Elen Pacheco contributed to supervision and manuscript revision; Antonio Soares was responsible for methodology and data curation; and Otniel Freitas-Silva contributed to the project conception, organization, supervision, writing (review and editing) and funding acquisition. All authors contributed to the manuscript and approved the final version.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interests

The authors declare no conflicts of interest.

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