

Article

Unlocking the Industrial Potential of Cambuci Peel: A Sustainable Approach Based on Its Physicochemical Profile

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Abstract

Cambuci is a native fruit from Brazil, and during the processing of this fruit, the peel is typically discarded due to limited knowledge of its physicochemical characteristics, which restricts its potential applications across various industries. Given the lack of detailed physicochemical characterization of this by-product in the literature, this study aimed to analyze key parameters to expand on our understanding of this raw material and stimulate interest from both academia and industry. The cambuci peel was found to have a moisture content of $9.41 \pm 1.69\%$ dw (dry weight), total solids of $90.59 \pm 1.69\%$ dw, and volatile solids of $87.41 \pm 1.69\%$. Its ash content was $3.18 \pm 0.41\%$, while the chemical oxygen demand (COD) reached $420.54 \pm 9.88 \text{ mg L}^{-1}$. The total protein content was $4.93 \pm 0.04 \text{ g/100 g dw}$, with reducing sugars at $108.22 \pm 3.71 \text{ mg g}^{-1}$ and non-reducing sugars at $30.58 \pm 3.16 \text{ mg g}^{-1}$. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were determined as $36.65 \pm 0.19\%$ dw and $18.91 \pm 0.05\%$ dw, respectively, with hemicellulose content of $17.74 \pm 0.20\%$ dw. Chromatographic analysis identified key bioactive compounds, including ellagic and gallic acid, which hold significant potential for pharmaceutical and food industry applications. Thermogravimetric analysis revealed three distinct decomposition zones, corresponding to physisorbed water, hemicellulose decomposition, and cellulose degradation, respectively. The results demonstrate the valuable physicochemical and biochemical properties of cambuci peel, supporting its potential for the development of new bioproducts aligned with circular economy principles. This study lays the foundation for further research into this underutilized by-product and its application in diverse industrial sectors.

Keywords: cambuci peel; physicochemical characterization; bioactive compounds; circular economy; by-product utilization



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1. Introduction

Brazil is considered one of the countries with the greatest biodiversity in the world, hosting 40,000 species, equivalent to 20% of the global flora [1]. Brazil's biodiversity richness

is largely attributed to its vast geographical expanse and diverse climatic conditions [2]. However, this potential remains largely underexplored [3]. Brazil's biodiversity could be harnessed to create new products to combat infections and diseases. This is due to the specimens' constituents, which have, for example, antidiabetic, digestive system regulatory, and antimicrobial properties [2,4]. Additionally, it is possible to find applications in various industries, including cosmetics and food [1].

The *Myrtaceae* family is one of the most prominent in the Brazilian flora, encompassing 121 genera comprising around 5800 species in tropical and subtropical regions [5]. This family is renowned for its diverse medicinal and aromatic plants [6]. Furthermore, their high nutritional potential allows them to be marketed in nature [7]. Plants in this family include eucalyptus (*Eucalyptus* spp.), guabiroba (*Campomanesia xanthocarpa* O. Berg), jambolan (*Syzygium cumini* (L.) Skeels), uvaia (*Eugenia pyriformis* Cambess), araçá (*Psidium cattleianum* Sabine), jabuticaba (*Myrciaria cauliflora* (Mart.) O. Berg), and cambuci (*Campomanesia phaea* Berg) [4,5].

The cambucizeiro, traditionally known as cambuci (*Campomanesia phaea* Berg.), is a native fruit tree in the Brazilian Atlantic Forest [8]. This fruit is distinguished by its fleshy pulp with few seeds, a sweet aroma, and an astringent flavor [9]. It is estimated that cambuci production can reach 100 kg of fruit per year per tree [10]. Nevertheless, this characteristic can vary due to the lack of uniformity in plantations, genetic and environmental influences, and cultivation practices [11]. Cambuci is rich in bioactive compounds, including ellagitannins and proanthocyanidins, which have been associated with beneficial effects such as modulation of HDL cholesterol, reduction of adipose tissue inflammation, and potential attenuation of postprandial glucose spikes [12,13].

Cambuci consists of approximately 80% pulp, 19% peel, and 1% seeds [14,15]. However, only the pulp is currently used in the production of food products such as ice cream, jellies, yogurt, and alcoholic beverages, among others [8,16,17]. This leads to the disposal of seeds and fruit peel, resulting in economic, environmental, and social problems [18]. Approximately 1.3 billion tons of food are lost and wasted annually, equivalent to about USD 936 billion [18,19]. Similarly, the losses and waste could meet the food needs of a portion of the population, considering that an estimated 12% suffer from hunger [20]. From an environmental perspective, in most cases, waste is disposed of in landfills without prior treatment, leading to the emission of greenhouse gases like methane, thereby exacerbating the issue of global warming [21].

To reduce waste and optimize natural resource utilization, it is crucial to leverage by-products from agro-industrial processing [22]. This approach allows for the revaluation and reintegration of these by-products into the industry, aligning with the principles of the circular economy [23]. Furthermore, these by-products, such as peels and seeds, represent a valuable source of bioactive compounds with potential biological activities, including the prevention and treatment of various diseases [24]. Prior to identifying potential applications for a by-product, comprehensive characterization of the corresponding matrix is essential. The detailed characterization of this material facilitates a better understanding of its physicochemical behavior, supporting its potential utilization in various industrial processes [25], while contributing to environmental sustainability and fostering economic development [26]. The objective of this study was to conduct a full and comprehensive characterization of cambuci peel, an underexplored agro-industrial by-product with potential interest in various industries. This work is particularly relevant, as it represents the first detailed analysis of cambuci peel, providing a foundational dataset for future research focused on exploring its properties and potential applications.

2. Materials and Methods

2.1. Raw Material

The cambuci peel, generously provided by Asmussen (Natividade da Serra, São Paulo, Brazil), was dried at 60 °C for 24 h in a drying oven (FANEM, 315 SE Mod) and crushed to obtain 1 mm particles. The resulting sample was stored in a bag and refrigerated until utilized for further analyses.

2.2. Sample Characterization

2.2.1. Physical Parameters

The analysis of moisture, total solids, and volatile solids was conducted following the methodology outlined by AOAC (2012) [27]. The sample color was determined using the CIELAB color space (with L* representing luminosity, a* corresponding to the green-red axis, and b* corresponding to the blue-yellow axis) through a portable colorimeter (CM-600d, Konica Minolta, Tokyo, Japan). The calibration data recorded by the equipment were used.

2.2.2. Chemical Parameters

Titrateable acidity and fat content were determined using the method described by AOAC (2012) [27]. The crude fiber content was determined according to the Weende method [28], while the neutral detergent fiber (NDF) and acid detergent fiber (ADF) fractions were analyzed following the Van Soest methodology [29]. The total nitrogen content was determined using the Kjeldahl method, following AOAC (2006) [28]. Total protein content was then calculated by multiplying the total nitrogen content by a conversion factor of 6.25. Total and reducing sugars were determined using the Somogyi–Nelson method [30]. The glucose calibration curve used for these analyses was ($Y = 500.36X - 41.108$; $R^2 = 0.9862$), and the results were expressed as mg glucose g^{−1} cambuci peel. Non-reducing sugars were calculated according to Equation (1):

$$\text{Non-reducing sugars} = (\text{Total sugars} - \text{reducing sugars}) \times 0.94 \quad (1)$$

The chemical oxygen demand (COD) was determined using method 5220, as described by APHA (2017) [31], with potassium dichromate (K₂Cr₂O₇) serving as the oxidizing agent. Absorbance measurements were taken at a wavelength of 610 nm using a spectrophotometer (Model UV-M51, Bell Photonics). A calibration curve was established with five points featuring concentrations of 0, 0.05, 0.1, 0.5, and 1.0 g L^{−1} of potassium hydrogen phthalate (KHP) ($Y = 0.2863X + 0.0116$, $R^2 = 0.9924$). The results were expressed as g O₂ L^{−1}.

2.2.3. Chromatographic Compound Identification

A tentative identification of metabolites was carried out in cambuci peel extracts. The extracts were prepared using 100% methanol, 50% methanol (methanol/water, 1:1), and 100% water as solvents. Each extract was prepared using 3 g of peel and 25 mL of solvent and then subjected to ultrasound treatment (Solidsteel, Piracicaba, SP, Brazil) for 20 min at 37 kHz and 25 °C. Cambuci extracts were diluted fivefold in water, filtered in a nylon filter of 0.22 µm, and further injected in an ultra-performance liquid chromatography coupled to a photodiode array and mass spectrometry (UPLC-PDA-MS) (Acquity, Waters Co., Milford, MA, USA). The separation system was performed in an Acquity UPLC BEH C18 50 × 2.1 mm, 1.7 µm analytical column, and the mobile phases consisted of water (A) and acetonitrile (B), both acidified with 0.1% acetic acid (*v/v*). The gradient elution was as follows: 2% B (0–1 min), 2–15% B (1–2 min), 15–35% B (2–8 min), 35–100% B (8–10 min), 100% B (10–12 min). The chromatography conditions were a flow rate of 0.5 mL/min,

a column oven at 40 °C, and an injection volume of 3 µL. UV spectra were recorded from 210 to 400 nm at λ_{max} of 254 nm. MS analysis was performed in positive and negative ionization mode (100–1000 Da) with cone voltage of 15 V and 30 V, respectively, capillary voltage of 0.8 kV, and probe at 600 °C. The software Empower 3.0 was applied for data processing (Waters Alliance, Milford, MA, USA).

The sugars present in cambuci peel were quantified using high-performance liquid chromatography (HPLC) coupled with a refractive index detector (RID), following the method described by Barroso et al., (2022) [32]. The concentrations of the sugars were determined using calibration curves from each corresponding standard, previously prepared by the research group. The results were expressed in mg g^{−1} of dry cambuci peel. The extracts used for sugar analysis were obtained through a semi-continuous flow hydrothermal pretreatment (HTP) unit described by Barroso et al. (2022) [32]. An amount of 10 g of previously dried and ground peel was used to extract the cambuci peel. The process was conducted at a constant pressure of 15 MPa, temperature of 160 °C, and flow rate of 5 mL min^{−1} for 16 min.

2.2.4. Thermal Parameters

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were performed on a Shimadzu thermobalance model TGA-50 (Kyoto, Japan). For the TGA analysis, 10.0 mg of dried cambuci peel were used. Nitrogen was used in a predefined flow range of 20.0 mL min^{−1} and heated from 28 to 900 °C at a heating rate of 20 °C min^{−1}. DSC was performed with a Mettler Toledo Calorimeter, Model DSC1 (Schwerzenbach, Switzerland). A total of 7 mg of sample was homogenized manually, transferred to an aluminum crucible (40 µL), and analyzed over a range of 20–250 °C. The tests were performed under standardized environmental conditions (25 ± 3 °C).

2.2.5. Morphological and Structural Parameters

The morphology of the cambuci peel was analyzed using scanning electron microscopy (SEM) (TM4000 SEM, Hitachi High-Tech, Tokyo, Japan) at an accelerating voltage of 10 kV. Samples were mounted on stubs using double-sided carbon tape. The material's structure was analyzed by Fourier-transform infrared (FTIR) spectroscopy using a spectrophotometer (model IRPrestige-21, Shimadzu, Japan) with IRSolution as the acquisition software (version 1.60). Spectra were obtained in the range of 400 to 4000 cm^{−1}, with a resolution of 4 cm^{−1} and 16 scans. KBr was used for equipment calibration. For every 200 mg of spectroscopic-grade KBr, 2 mg of the sample were used. The mixture was homogenized using an agate mortar and pestle and then transferred to a 13 mm diameter stainless steel mold and compressed using a hydraulic press (Shimadzu, model SSP-10A) connected to a vacuum pump. A force of 80 kN was applied for 10 min under a vacuum to form the tablet.

2.3. Statistical Analysis

The parameters were measured in triplicate (n = 3), and the values were expressed as the mean ± SEM (standard error of the mean). Data processing and statistical calculations were carried out using Statgraphics Centurion Version XIX (Statgraphics Technologies, Inc., The Plains, VA, USA), adopting a significance level of $p < 0.05$ where applicable.

3. Results

3.1. Sample Characterization

3.1.1. Physical Parameters

Table 1 presents the physical properties of cambuci peel. The moisture content measured for this residue was 9.41 ± 1.69%, which is higher than the value previously reported

for the same raw material [33], representing a percentage difference of 27.85%. This variation may be attributed to several factors related to cambuci, including climate, soil composition, and geographical location. These factors can significantly affect the quality of the fruit and, consequently, its properties [34]. The ash content of the cambuci peel was found to be 3.18%, a value comparable to those reported for various types of biomasses, including Virginia mallow (*Sida hermaphrodita* R.), Jerusalem artichoke (*Helianthus tuberosus* L.), and avocado peel [35,36]. Determining the ash content is important, as higher ash levels have been shown to enhance oxygen availability during composting, inhibit the formation of compounds such as hydrogen sulfide, and reduce unpleasant odors [37].

Table 1. Physical properties of dried cambuci peel.

Parameter	Experimental Value
Moisture content (%)	9.41 ± 1.69
Ash (%)	3.18 ± 0.41
Total solids (%)	90.59 ± 1.69
Volatile solids (%)	87.41 ± 1.69
L*	24.44 ± 0.37
a*	8.39 ± 0.12
b*	40.12 ± 0.37

The volatile solids (VSs) in the cambuci peel represent 87.41%, a characteristic value of by-products, indicating that this raw material can be a good co-substrate for anaerobic digestion [38]. Fröner-Lacerda et al. [39] demonstrated that cambuci peel can serve as a feedstock for biogas production, highlighting its potential in energy generation. Furthermore, the VS/TS ratio (where TS stands for total solids) of this by-product indicates a high suitability for biological treatment processes [40]. The moisture content of cambuci peel is higher than that reported for similar materials, which may be attributed to environmental and agronomic factors such as soil composition, climatic conditions, and geographic origin—all of which influence the fruit's physicochemical characteristics. Moisture content is a critical parameter in biomass storage and processing, as it directly affects material stability and the potential for microbial growth. The ash content ($3.18 \pm 0.41\%$) aligns with values found in other biomass sources, such as pineapple peel [41] and avocado peel [35], indicating the presence of inorganic components that can increase oxygen availability in composting and reduce undesirable odors. These attributes underscore the potential of cambuci peel for composting and other sustainable applications such as soil amendment. The high volatile solids content and VS/TS ratio indicate that cambuci peel is suitable for biological treatments, including anaerobic digestion. Additionally, the high organic matter content of the peel highlights its viability as a co-substrate for biogas production, aligning with previous studies that have demonstrated the bioenergetic potential of cambuci peel.

The parameter L* represents the luminosity of the sample, ranging from black ($L^* = 0$) to white ($L^* = 100$) [42]. For the dry cambuci peel, a luminosity of $L^* = 24.44 \pm 0.3$ was determined, indicating a tendency toward a dark color. Conversely, the a* parameter signifies the variation between green ($-a^*$) and red ($+a^*$), and the b* parameter represents the variation between blue ($-b^*$) and yellow ($+b^*$) [43]. For cambuci, these parameters were a* and b*, resulting in a dark green-brown coloration (Figure 1). Furthermore, colorimetric parameters reveal the dark color of the peel bark, characterized by a low luminosity value and a green-brown hue. These color characteristics are relevant for industrial applications where the visual appearance of the biomass can influence its usability, such as in the production of natural pigments or dyes. Together, these findings provide a fundamental understanding of the physical properties of cambuci peel and reinforce its potential for several industrial applications.



Figure 1. (a) Cambuci peel; (b) coloration of cambuci peel obtained in CIELAB color space.

3.1.2. Chemical Parameters

The total nitrogen content of cambuci peel was $0.79 \pm 0.01\%$, suggesting a low conversion of organic nitrogen into ammonium and nitrate during the analysis [44]. The total protein content was 4.93 ± 0.04 g/100 g, which is lower than values observed in other by-products such as jabuticaba peel (5.94 ± 0.4 g/100 g) [45], banana peel (7.17 ± 0.06 g/100 g) [46], mango (6.3 ± 0.1 g/100 g) [47], and umbu peel (6.08 ± 0.05 g/100 g) [48].

Table 2 shows the results for total, reducing, and non-reducing sugars. The sugar content in cambuci peel is composed of reducing sugars, including fructose and glucose [49]. Non-reducing sugars in this by-product constitute 21.72% of the total sugars. Notably, values for these parameters are unavailable in the literature due to the lack of studies specifically focused on cambuci peel. However, the results obtained in this study indicate that cambuci peel exhibits higher values compared to other fruits residues such as pomegranate peel (25.07 ± 0.4 mg g⁻¹ dry wt), citrus peel (22.53 ± 0.60 mg g⁻¹ dry wt), and apple peel (24.80 ± 0.61 mg g⁻¹ dry wt) [50].

Table 2. Composition of dried cambuci peel.

Parameter	Cambuci Peel
Titrateable acidity, g CA/100 g (d.w.)	0.1443 ± 0.0055
Fat content, g/100 g (d.w.)	7.27 ± 0.74
Reducing sugar (mg g ⁻¹)	108.22 ± 3.71
Non-reducing sugar (mg g ⁻¹)	30.58 ± 3.16
Crude fiber (%)	11.95 ± 0.30
Neutral detergent fiber (%)	36.65 ± 0.19
Acid detergent fiber (%)	18.91 ± 0.05
Cellulose (%)	11.47 ± 0.10
Lignin (%)	7.44 ± 0.06
Hemicellulose (%)	17.74 ± 0.20

Chemical oxygen demand refers to the amount of oxygen necessary to oxidize the organic matter present in a sample [51]. In the case of cambuci peel, the COD was 420.54 ± 9.88 mg L⁻¹, a value considered high. This result may be attributed to elevated levels of proteins and organic acids in this by-product [52]. The titrateable acidity of this by-product was 0.1443%, a low value compared to residues from other fruits such as blueberry pomace (5.63%), blackberry (2.18%), black currant (4.22%) [53], potato peel (0.80%), and mango peel (0.90%) [54]. The fat content of the cambuci peel was 7.27%, which is higher than the values reported for mango (6.26%) and apple peels (4.539) [55], as well as orange peel (1.88%) [47]. This distinctive chemical composition highlights the unique characteristics of cambuci peel and its potential for various applications. The total nitrogen

and protein content are lower than other fruit by-products such as jabuticaba and banana peels. These results suggest that cambuci peel may not be the richest by-product in protein, but it still has value in applications requiring moderate protein or energy. Furthermore, the sugar composition is dominated by reducing sugars over non-reducing sugars, with fructose, sorbitol, and glucose as the main components. These levels exceed those reported for other fruit peels, such as pomegranate and citrus, highlighting the potential of cambuci peel as a valuable source of sugars for bioenergy production and fermentation processes. The high chemical oxygen demand further reinforces its suitability for such applications, indicating a significant amount of organic matter.

This study determined the content of crude fiber, neutral detergent fiber (NDF), and acid detergent fiber (ADF). The crude fiber content was found to be comparable to values reported for other by-products such as pineapple peel [35,56]. The content of NDF in a sample estimates the amount of cellulose, hemicellulose, and lignin present. In contrast, ADF comprises cellulose and lignin [57,58]. NDF can estimate the amount of food an animal can consume, as it exhibits a negative correlation: higher NDF content corresponds to lower potential consumption. In the case of cambuci, the NDF content is 36.65%, which is higher than that reported for orange peel (30.4%) [59]. ADF, on the other hand, indicates the digestion capacity, meaning that higher ADF values correspond to reduced digestibility of the raw material. Cambuci peel has an ADF of 18.91%, which is lower than that reported for orange peel (10.94–13.52%) [60] and brewers' spent grains [25]. Given its NDF, particularly the significant proportion of hemicellulose, it can be inferred that cambuci peel may serve as a promising alternative source of emulsifiers, hydrogels, and biodegradable films, among other value-added materials. The analysis of fiber content highlights the structural value of cambuci peel. The high NDF and ADF content indicate a considerable presence of cellulose, hemicellulose, and lignin. While the high NDF suggests limited use as animal feed due to lower digestibility, the substantial hemicellulose content points to potential industrial applications such as the production of hydrogels, emulsifiers, and biodegradable films. The fat content of 7.27% exceeds that of mango and apple peels, making cambuci peel an interesting candidate for applications requiring lipid-based components. These findings highlight the versatility of cambuci peel and its potential to contribute to various industries, including food, pharmaceuticals, and sustainable materials, in alignment with circular economy principles.

3.1.3. Chromatographic Compound Identification

The extracts obtained by 100% MeOH, MeOH:H₂O (50:50, *v/v*), and 100% water were analyzed by UPLC-PDA-MS to identify the possible compounds. Considering previous reports in the literature about the metabolites already identified in *Campomanesia phaea* (*Myrtaceae* family), it was possible to point out the potential identifications related to the compounds presented in Table 3. Among the identified compounds, the only compound found in the water extract (C) was Methyl ellagic acid sulfate, with a retention time of 10.9 min and *m/z* 397.14. On the other hand, in the tentative identification of metabolites present in extracts, the MeOH (B) extract allowed for identifying more potential compounds in cambuci peel.

The UPLC-PDA-MS analysis of cambuci peel extracts revealed the presence of several bioactive compounds, highlighting their potential as a valuable raw material for various industries. The MeOH extract exhibited a greater capacity for compound identification compared to the 50% MeOH and water extracts, with compounds such as gallic acid, ellagic acid, and quercetin derivatives being predominant. Methyl ellagic acid sulfate, identified exclusively in the water extract, adds to the peel's value due to its reported antioxidant and anti-inflammatory properties. These findings underscore the influence of solvent

polarity on the extraction efficiency of specific compounds, which is critical for optimizing extraction processes for targeted applications. The compounds identified in cambuci peel are relevant to various industries. For example, ellagic acid has been used primarily for medicinal and nutritional purposes; however, in recent years, other applications have been explored, such as the synthesis of new materials for bioengineering [61]. Gallic acid, in particular, is of significant interest in the pharmaceutical industry due to its effectiveness in treating gastrointestinal diseases, attributed to its anti-inflammatory and antioxidant properties [62]. In addition, quercetin and its derivatives have gained recognition in recent decades as therapeutic agents for cardiovascular diseases due to their antihypertensive and cardioprotective effects [63]. Based on the above, the relevance of these compounds to various industrial sectors becomes evident, underscoring the need for diverse raw materials to enable their extraction and ensure a consistent supply.

Table 3. Identification of metabolites present in extracts of MeOH (A), 50% MeOH (B), and H₂O (C) by UPLC-PDA-MS.

Retention Time (min)	Name	<i>m/z</i>	Lamba (λ)	Fraction
1.0	Gallic acid	169.10 [M-H] ⁻	273	A, B
2.2	Bis-HHDP-hexoside (Pedunculagin)	783.29 [M-H] ⁻	258	A, B
3.3	Tetragalloyl hexoside	787.05 [M-H] ⁻	277	B
3.4	Ellagic acid	301.06 [M-H] ⁻	253, 356	A, B
3.6	Quercetin pentoside	433.22 [M-H] ⁻	255, 356	A, B
3.9	Quercetin- <i>O</i> -(<i>O</i> -galloyl)-pentoside	585.24 [M-H] ⁻	354, 346	B
5.6	Quercetin rhamnose	447.20 [M-H] ⁻	265, 348	A, B
10.9	Methyl ellagic acid sulfate	397.14 [M+H] ⁺	259	A, B, C

The presence of bioactive compounds like ellagic acid, gallic acid, and quercetin derivatives underscores the multifunctionality of cambuci peel. Ellagic acid, known for its role in bioengineering and cancer prevention, and gallic acid, widely used for its gastrointestinal benefits, demonstrates this by-product's pharmaceutical and nutraceutical potential. Additionally, the cardioprotective and antihypertensive effects of quercetin and its derivatives open opportunities for applications in functional foods and therapeutic agents. These compounds are in high demand across industries ranging from cosmetics to biotechnology, highlighting the economic and environmental benefits of valorizing cambuci peel. These results expand the knowledge of the chemical profile of cambuci peel and establish a foundation for its industrial utilization, promoting sustainable practices and circular economy principles.

The main sugars identified in the cambuci peel extracts under the specified conditions were glucose ($4.02 \pm 0.03 \text{ mg g}^{-1}$), fructose ($9.41 \pm 0.05 \text{ mg g}^{-1}$), and arabinose ($11.30 \pm 0.15 \text{ mg g}^{-1}$). The glucose content observed in cambuci peel under the described conditions is significantly lower than the values reported for other raw materials such as grape pomace (47.7 mg g^{-1}) [64] and jabuticaba peel (74.18 mg g^{-1}) [32]. Similarly, the fructose content found was also lower than that reported for other fruit by-products such as jabuticaba peel and grape pomace, containing 103.77 mg g^{-1} and 193.6 mg g^{-1} , respectively [32,64]. Similarly, the arabinose concentration in cambuci peel is also considerably lower than the values reported for grape pomace (34.5 mg g^{-1}) [64] and orange peel (50.03 mg g^{-1}) [65].

3.1.4. Thermal Parameters

Figure 2 shows the TGA and DTG curves for cambuci peel. The thermogravimetric analysis curve shows four well-defined mass loss zones. The first zone, between 36.22 and 215.58 °C, corresponds to a moisture loss of 10.21%, attributed to the elimination

of physisorbed water [66]. The second zone, observed between 219.78 and 286.11 °C, presents a mass loss of 18.03%, suggesting the decomposition of hemicellulose in the sample [67]. The third zone, ranging from 306.47 to 388.56 °C, exhibits a mass loss of 24.92%, characteristic of cellulose decomposition, as this compound typically degrades between 310 and 400 °C [68]. Two well-defined peaks are observed in the DTG curve. The first peak, at 273.11 °C, corresponds to the thermal degradation of hemicellulose, while the second peak, at 376.56 °C, is associated with the decomposition of cellulose [69]. The mass loss above 400 °C corresponds to the residue from the pyrolysis process [25], resulting in a final mass of 18.29% at the end of the analysis.

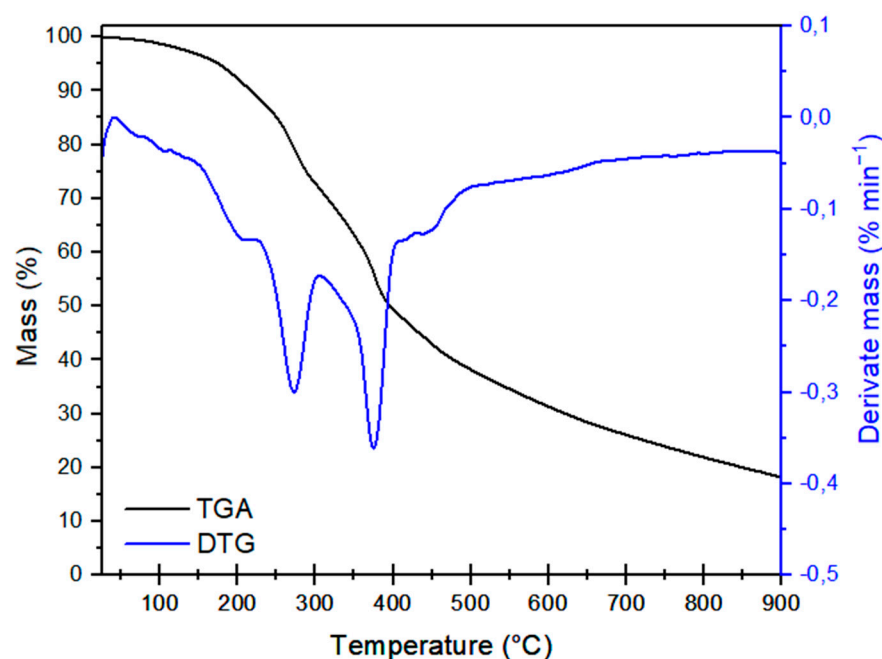


Figure 2. Thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG) of cambuci peel.

The differential scanning calorimetry (DSC) curve is shown in Figure 3. The endothermic peak observed at 116 °C can be attributed to moisture release from the feedstock, as reported by other authors for brewer's spent grain [25], barley, bagasse, rice husk, and corn-cob at different heating rates [66]. The subsequent peaks in the graph are associated with the decomposition of the structural components of the feedstock, including hemicellulose, cellulose, and lignin [70].

3.1.5. Morphological and Structural Parameters

Figure 4 presents the scanning electron microscopy (SEM) results for cambuci peel. The analysis, conducted at 800× magnification, revealed the presence of layered particles characterized by a rough surface and irregular geometry. The wrinkled appearance could be related to the slow drying process used to obtain the sample, as authors such as Hanan Taharuddin et al. (2023) [71] noted. Additionally, this appearance may also result from grinding during the sample preparation stage because shear and friction forces generated in this process could produce such particles, as suggested by Gan et al., (2019) [72]. The analysis of cambuci peel revealed structural characteristics that offer valuable insights into its physical behavior and potential applications. The observed wrinkled surface may be attributed to the slow drying process, which can induce internal stresses in the biomass as a result of uneven moisture removal. Such features are common in materials with high fiber content and complex structural arrangements, making cambuci peel suitable

for applications requiring mechanical robustness, such as biodegradable composites or fillers in biopolymers [73]. This textural complexity may enhance the functionality of the peel in applications such as adsorption, where a rough surface increase the available area for molecular interactions. The structural traits identified through SEM also suggest potential utility in bioengineering applications, such as scaffolding materials or controlled-release systems, where surface irregularities can influence material performance [74]. These findings provide a deeper understanding of the morphological properties of cambuci peel, reinforcing its potential for diverse industrial and environmental applications.

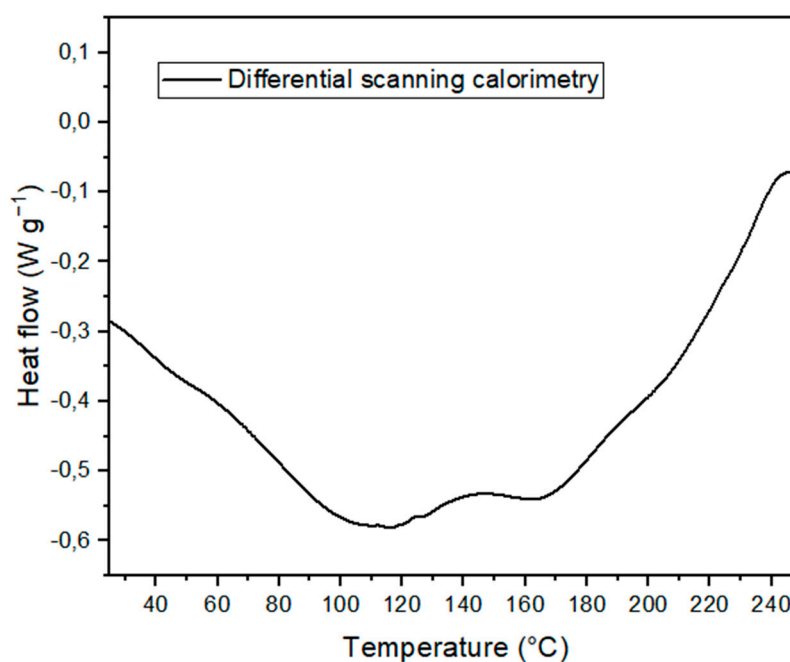


Figure 3. Differential scanning calorimetry (DSC) of cambuci peel.

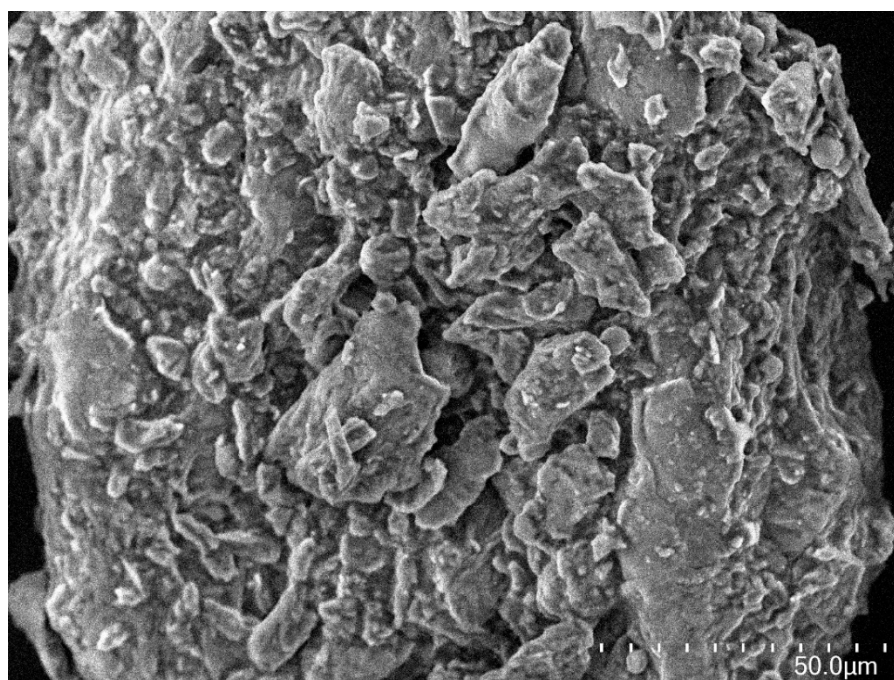


Figure 4. Scanning electron microscopy (SEM) for the cambuci peel.

The FTIR spectrum of cambuci peel is shown in Figure 5. A broad peak at 3381 cm^{-1} corresponds to the -OH stretching vibrations, indicating the presence of hydroxyl groups, such as those in alcohols or phenolic compounds, which are known for their antioxidant properties [75,76]. The bands at 2924 and 2853 cm^{-1} are associated with C-H stretching vibrations of alkanes, suggesting the presence of hydrophobic components that may contribute to the peel's structural integrity and potential for water-resistant material development [77,78]. Absorption in the range of 1744 to 1618 cm^{-1} is attributed to the stretching vibrations of carbonyl groups, particularly ketones and esters, indicating reactive sites suitable for polymer synthesis or bio-based material applications [79,80]. A peak near 1449 cm^{-1} is assigned to bending vibrations of methyl groups [81]. Additionally, bands at 1234 and 1103 cm^{-1} support the presence of esters, while the peak at 1034 cm^{-1} is related to the C-N stretching vibration of aliphatic amines [77,82]. Overall, the FTIR spectrum reveals a diverse array of functional groups in cambuci peel, offering valuable insights into its chemical composition and potential industrial applications.

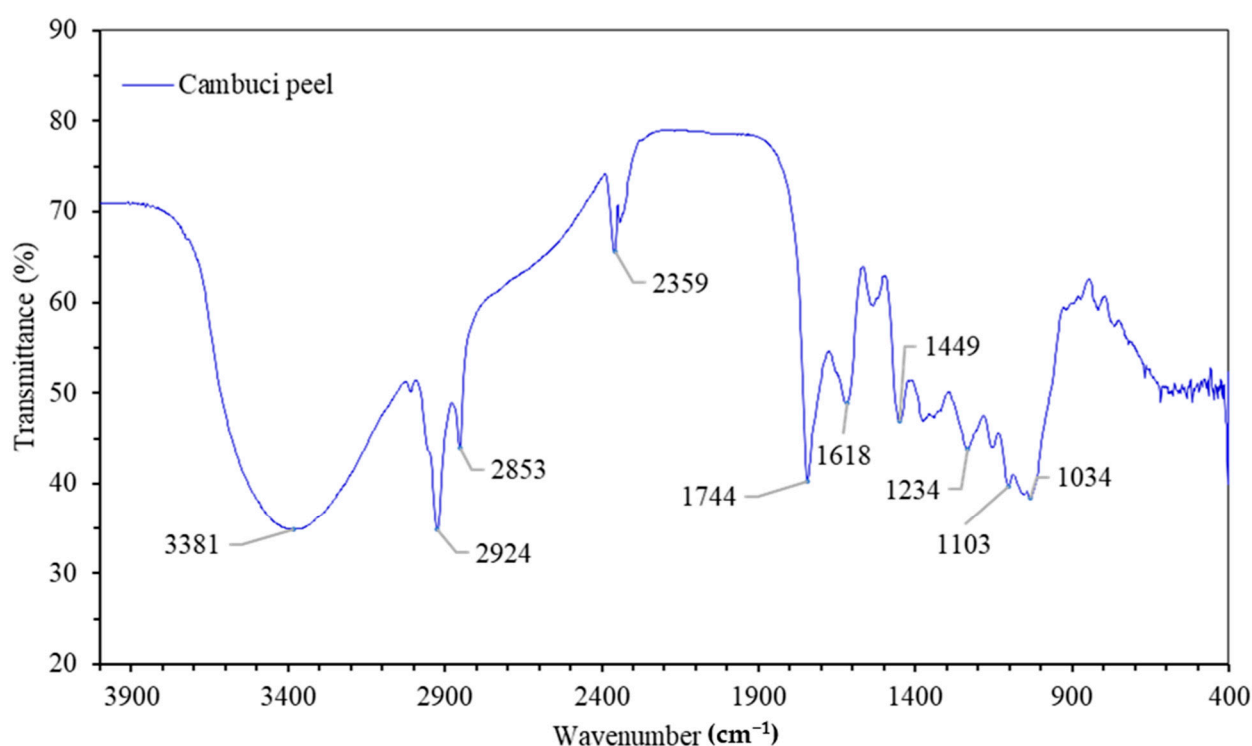


Figure 5. FTIR spectra of cambuci peel.

According to Refs. [75–79,82–84], the bands at 1234 and 1103 cm^{-1} , indicative of esters, and the peak at 1034 cm^{-1} related to C-N stretching vibrations of aliphatic amines, suggest the presence of complex organic compounds [85]. These functional groups could enhance the peel's applicability in industries like pharmaceuticals and cosmetics, where esters and amines are used for their solubility and reactive properties. Moreover, these findings align with the potential for cambuci peel to serve as a raw material for developing biodegradable films, adhesives, and other value-added products. The FTIR analysis provides a detailed understanding of the chemical complexity of cambuci peel, underscoring its versatility and reinforcing its role in sustainable material development and circular economy initiatives.

4. Conclusions

The characterization of cambuci peel revealed a high content of fiber, fermentable sugars, and phenolic compounds, highlighting its potential for applications in bioenergy, natural antioxidants, and functional ingredients. Thermal and structural analysis indicated

good stability at elevated temperatures, along with a notable presence of volatile solids, supporting its use in anaerobic digestion, biomaterials, and bioadsorbents. Its composition, rich in lignin and cellulose, also favors thermal and chemical conversion processes. These results underscore the importance of developing optimized extraction and fermentation methods to enhance both yield and economic feasibility. Cambuci peel thus emerges as a promising agro-industrial residue with versatile applications across sectors such as energy, cosmetics, and functional foods, contributing to circular economy strategies and environmental sustainability.

Future research will focus on evaluating the antimicrobial and antidiabetic properties of this residue, as well as exploring its potential as a raw material in green extraction techniques such as microwave-assisted and ultrasound-assisted extraction. These approaches aim to identify additional bioactive compounds and further highlight the value of cambuci peel as an agro-industrial by-product. Additionally, conducting technical and economic feasibility studies of these extraction methods would provide essential insights for scaling up from laboratory to pilot-scale applications.

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