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Effect of Pretreatment on the Profiling of Cassava Peels by Morphological and Chemical Characterization

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ABSTRACT

Cassava is mainly grown for its root, whereas the peels are mostly considered a byproduct. Cassava peels, a byproduct of cassava processing, have gained significant attention in recent years as a potential feedstock and other bioproduct. This study investigated the impact of pretreatment on the lignocellulose content, functional groups, morphological characteristics (SEM), chemical composition (XRF), and crystalline phases (XRD) of dried and autoclaved cassava peels. The Chemical analysis showed cellulose content increased from 42.80% to 45.51%, hemicellulose decreased from 25.33% to 19.66%, and lignin content decreased from 15.33% to 10.33% after autoclaving. The autoclaved cassava peels μXRF results also revealed the presence of high iron (Fe) and potassium, as well as traces of manganese at 0.52%, and an amorphous and semi-crystalline structure. Although the SEM images showed no morphological difference between the dried and autoclaved cassava peels. The Brunauer Emmette Teller (BET) analysis indicated a higher surface area of 2.713 m^2/g for autoclaved cassava compared to 2.097 m^2/g for dried cassava peels. Thermal pretreatment via the autoclave method improved the structural properties and increased the degradable cellulose content of cassava peels. Thus, the cassava peels can be biotechnologically converted into value-added products to maximize effective utilization.

1. INTRODUCTION

The agro-industrial sector generates large volumes of renewable lignocellulosic biomass annually, making it a suitable substrate for producing value-added products. Lignocellulosic materials and agricultural residues are the most attractive and abundant renewable biomass sources [1]. The Euphorbiaceae family's shrubby perennial cassava (*Manihot esculenta* Crantz) is sometimes known as tapioca or yuca. It is ranked fourth among food staples and is cultivated on various soil types. Cassava is a staple crop for over 800 million people in tropical and subtropical regions, with an annual global production of 263 million metric tons [2]. This frequently leads to the production of enormous amounts of residues. One such residue is the cassava peels, which typically account for 20 to 35% of the entire tuber with a starch content of up to 90% (dry weight) [3].

Cassava peels are the remnant that is produced by industry from the pre-cleaning process made of cracked bark (periderm), the inner peel found between the core cylinder and the cortex layer (sclerenchyma and cortical parenchyma cells) of the cassava root [4]. The peels are lignocellulosic waste containing polymeric structures such as cellulose, hemicellulose, and lignin, and are very rich in starch [5]. The proximate composition of cassava peels revealed a high carbohydrate content of 78.34%, fat of 3.70%, crude fibre of 5.32%, protein content of 5.25%, and ash of 4.07% [6]. Mineral content analysis reveals potassium predominates over other minerals, including calcium, sodium, magnesium, and zinc [7]. Cassava peels are typically discarded during the commercial production of cassava starch, and various biological and industrial processing-related factors influence their composition [8]. The more waste produced by an industry, the more capital, labour, materials, water, and energy are wasted in the process of

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producing agricultural products. The generated waste reveals the industry's inefficiencies and raises concerns about potential environmental impacts. The practical impossibility of achieving zero waste during manufacturing means that incinerating waste or converting it into energy is the only way to minimize losses and reduce harmful ecological effects.

In most rural regions, cassava peels are either fed to animals in minimal quantities or discarded with no value, considered an agricultural by-product. This underutilization is a missed opportunity, as several industries could use the peels from cassava plants as a good source of biomass. The textile, paper, and food sectors account for 7%, while the animal feed industries absorb almost 33% of it [9]. However, the potential for cassava peels to be utilized as starch-rich sources for animal feed, plastic bioproducts, and biorefinery products (formic acid, levulinic acid, glycolic acid, and vanillin) is indicated by their high residual carbohydrate and fiber content [4]. According to a study, sugars in the form of polysaccharides like starch and holocellulose are present in the peel of cassava [10]. [11] has revealed the viability of using cassava peel for anaerobic digestion to produce biogas. It was also studied for its ability to synthesize bioplastics with the addition of Kaffir lime (*Citrus hystrix* DC) [12] .

The biomass undergoes biological, chemical, and physical pretreatments to alter its lignocellulosic chemical structure. Chemical pretreatment can be performed using dilute or concentrated acid, alkali, ionic liquids, and organic solvents, which can lead to the formation of inhibitory compounds [13]. Disrupting lignocellulosic biomass's physical and chemical structure is essential to enhancing its susceptibility to enzyme and microbial degradation [14]. Few studies currently describe the thermal pretreatment of cassava peels via autoclaving as a useful and affordable component for bioproducts [13]. These processing techniques can potentially enhance the nutritional content of cassava peels, improve sugar recovery efficiency, reduce the formation of inhibitory compounds, and create a more cost-effective process. Despite the potential advantages, a significant knowledge gap remains concerning the combined effect of autoclaving and physical disruption (e.g., grinding) on the structural, chemical, and morphological properties of cassava peels. This study aimed to address this gap by examining the effects of physical disruption through grinding and autoclaving pretreatment using cassava peel as a substrate. It assessed the impact of pretreatment using elemental, chemical analysis, and morphological characterization techniques, including scanning electron microscopy (SEM), X-ray diffraction (XRD), micro-X-ray fluorescence (μXRF), and Fourier-transform infrared spectroscopy (FTIR). Thus, the present work also addresses cassava peel as a potential application and commercial prospect for agro-industrial waste materials, such as animal feed, enzymes, biofuels, and bioplastics.

2. MATERIALS AND METHODS

2.1 Sample Collection and Pretreatment

Cassava tubers were collected from Layang Food Industries SDN. BHD Layang-Layang, Johor, Malaysia. The samples were immediately washed to remove sand particles, then peeled, and dried at 50 °C in an oven for 48 h to avoid deterioration. It was then milled using a Warring commercial electric blender (Model 8011G, HGB2WTG4, assembled in the USA) to ensure uniform particle size and consistent sample preparation. It was sieved through a 1.00 mm mesh and stored in an airtight container before analysis. Thirty grams (30g) of the dried ground cassava peels were then sealed in an autoclave bag and

2.2 Analysis of Cassava Peel Composition

The cellulose, hemicellulose, and lignin content of cassava peels were determined before and after pretreatment. The percentage of hemicellulose was determined by dissolving 1.5 g of extractive-free cassava peel, which had been treated with 99.5% (v/v) acetone, in 60 mL of 0.5 M sodium hydroxide (NaOH) solution and incubating for 3.5 h at 80 °C. The weight reduction of treated cassava peel determines the amount of hemicellulose [15]. The determination of lignin involved mixing 1.5 g of the treated cassava peels with 45 mL of 98% (v/v) sulfuric acid (H2SO4) and subsequently heating the mixture at 100 °C for one hour to determine the lignin content. Afterward, it was left to stand for 24 h at room temperature [15]. After drying in an oven at 105°C, the weight of the lignin precipitated was determined by measuring the amount of lignin in the cassava peel sample. For the determination of cellulose, after reducing all of the components, the cellulose content was calculated by taking the difference between the weighted sum of extractives, hemicellulose, and lignin (lignocellulose structure) as 100% [15].

2.3 Determination of Total Reducing Sugar

The total reducing sugar concentration was determined using the dinitrosalicylic (DNS) method described by Miller (1959). The DNS technique can detect the free carbonyl group (C=O) in reducing sugar. This occurs by the oxidation of aldehydes or the ketone functional group, 3-5-dinitrosalicylic acid (DNS), which is converted to 3-amino-5-nitrosalicyclic acid [16]. Aliquots of 1 mL of the sample were mixed with 1 mL of DNS reagent and two (2) drops of 0.1 M NaOH. After 5 minutes of boiling and cooling to room temperature, 10 mL of distilled water was added, and the mixture was vortexed. The absorbance of the samples was taken at 540 nm using a UV-visible spectrophotometer (Jenway 7200).

2.4 Determination Of Protein Content

The Lowry method relies on a protein's reduction of copper, which is detected by the Folin-Ciocalteau reagent. One gram (1.0 g) of cassava (*tapioca*) peel substrate was weighed and mixed with 25.0 mL of cold pH 5.0 sodium acetate buffer (0.05 M). The mixture was vortexed for 2 minutes and then centrifuged at 4000 rpm for 20 minutes at 4 °C. Subsequently, 0.5 mL of the sample was added to 2.5 mL of Reagent C (comprising Na_2CO_3, NaOH, $CuSO_4 \cdot 5H_2O$, and Sodium Citrate) and allowed to stand for 10 minutes at ambient temperature. Then, Folin-Ciocalteu reagent (0.25 mL) was added, the mixture was vortexed, and it was kept at room temperature for 30 minutes. The absorbance was measured at 750 nm using a UV spectrophotometer with bovine serum albumin (BSA) as the standard.

2.5 X-Ray Diffraction

The crystalline phase of cassava peels (dried and autoclaved) was detected using X-ray diffraction analysis. The X-ray intensity was calculated using the angle formed by the diffracted beams and the incident beam, as determined by X-ray diffraction (XRD). Cu-kα (λ=1541 Â) was used as the

radiation source for the Bruker D2 Phaser X-ray diffraction (XRD) experiment, which was run at 40 mA and 45 kV to detect the crystalline patterns of the cassava peels. The patterns were analyzed using the X' pert high score plus software in the 20 range of 10-80º with a step size of 0.01º [17].

2.6 X-Ray Fluorescence

A M4 Tornado PLUS Micro X-Ray fluorescence spectrometer (μXRF) was used to identify the light elements present in the cassava (*tapioca*) peels (dried and autoclaved). The light element is a microfocus X-ray utilizing an aperture management system (AMS) and polycapillary X-ray optics. However, the X-ray tube features four-position collimator changers, ranging from 0.5 to 4.5 mm, and XFlash super-light-element silicon drift detectors with a 2 × 60 mm² sensitive area. The detectors offer an energy resolution of less than 145 eV at an input count rate of 600,000 counts per second (cps) and a throughput of 550,000 cps.

2.7 Scanning Electron Microscope

Employing a scanning electron microscope (SEM), the surface morphology of the sample was observed. The sample (dried and autoclaved cassava peel) was coated with gold plating and distributed onto the SEM stub mounted with conductive adhesive tapes. Observations were made using a scanning electron microscope (Hitachi, SU1510) at various magnifications.

2.8 BET

Using a Micromeritics 3Flex 3.01 device to standardize nitrogen absorption and desorption at 77 K, a BET analysis was conducted to explain the surface area of the cassava peels and provide pore volume and pore size data for them.

2.9 Fourier-Transformed Infrared Spectroscopy

A Thermo Scientific (USA) Nicolet iS5 FT-IR spectrophotometer with an iD5 attenuated total reflectance (ATR) accessory was used to detect functional groups. About 95 mg of finely ground potassium bromide (KBr) and 5 mg of powder from each sample were mixed to form pellets, which were then pressed into pellets with a thickness of approximately 1 mm. The crystal plate was covered with a small substrate, and the high-pressure clamp was tightened. The spectra were recorded between 4000 and 500 cm^{-1} using a Shimadzu Fourier transform spectrophotometer (IR Prestige 21 model), programmed in transmittance mode. The peak positioning of the obtained FTIR spectrum was performed using OMNIC software, and the identified peaks in the FTIR spectra were used to interpret the availability of functional groups within the studied peels [17].

3. RESULTS AND DISCUSSION

3.1 Effect of Pretreatment on Composition of Cassava (Tapioca) Peel

Cassava peels are lignocellulolytic biomass consisting of cellulose, hemicellulose, and lignin. The cassava peels used in this study undergo physical and thermal pretreatments (autoclaving). Cassava peels used in this study were analyzed for their cellulose, hemicellulose, and lignin content, and the results were compared to those of other cassava peels reported in the literature. The results show 42.80 ± 0.23% for cellulose, 25.33 ± 0.11% for hemicellulose, and 15.33 ± 0.33% for lignin in dried cassava peels, as presented in Table 1. At the same time, autoclaved cassava peels contain cellulose 45.51 ± 0.87 %, 19.66 ± 0.35 % hemicellulose, and 10.33 ± 0.42% lignin. The findings showed that dried and autoclaved cassava peels typically have high cellulose and hemicellulose fractions. The main lignocellulose content was significantly altered between dried and autoclaved cassava peels. The increase in cellulose content could result from the increased cellulose availability resulting from the hemicellulose solubilization process. Using thermal pretreatment techniques has been proven to impact the chemical composition of cassava peels. It shows less difference between the findings of [18] and this study, contrary to [19] and [20]. The difference may result from varietal differences, climatic variations, soil profiles, fertility levels, or variations in the methods of chemical analysis.

Table 1. Lignocellulose content of Cassava (Tapioca) peels in this study and previous report

Sample	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Dried cassava peel	42.80 ± 0.23	25.33 ± 0.11	15.33± 0.33	This Study
Autoclaved cassava peel	45.51 ± 0.87	19.66 ± 0.35	10.33 ± 0.42	This Study
Cassava peel	43.63	10.38	7.65	[23]
Dried cassava peel	40.5	21.4	11.7	[19]
Cassava peel	31.00	27.00	6.10	[24]
Cassava peel	37.9	23.9	7.5	[20]

Hemicellulose possesses a heteropolymer structure consisting of various sugar monomers, and cellulose is present in many plant fibers, significantly impacting their strength [5]. A study [21] reported that autoclaving cassava waste at 121°C for 15 minutes effectively decreased the concentration from 24.75% to 12.79%. High cellulose and hemicellulose content are crucial for microbial growth, as they provide a fermentation source [22] and are significant components in assessing the suitability of raw materials for pulp, bioethanol production, papermaking, and biodegradable food packaging [8].

In this study, the percentage of lignin after autoclaving decreased from 15.33 to 10.33%. The decrease in lignin content after the autoclaving suggests that the pretreatment technique on the cassava peel substrate greatly aided in breaking the bridges within the structure of the cassava peel biomass, which facilitates the exposure of the cellulose [25]. The lignin content of this study shows a highly significant difference between the studies of [26] and [19]. A study by [27] The reported use of micro-assisted hydrothermal treatment on cassava peel indicates a significant difference, with lower cellulose (11.30%) and lignin content (3.09%) than the hemicellulose content (22.39%). The chemical processes, pretreatment methods, and geographical location could be responsible for this. This research suggests that reducing the lignin level of the peel can

easily break down the cassava structure to release cellulose, which could be considered a good source of cellulose. The influence of autoclaved pretreatment on the composition of cassava peels can increase the cellulose content.

3.2 *Effect of Pretreatment on Total Reducing Sugar Content Analysis*

The reducing sugar determination (DNS) test uses spectrophotometric analysis. It depends on the change in absorbance in the reaction medium that signifies the presence of the reducing sugar. Cassava peels were subjected to simple physical pretreatment (grinding) and autoclaving pretreatment. The results of reducing sugar content are presented in Figure 1, which shows the most abundant sugar content at 16.49 mg/g for unwashed cassava peel, 12.34 mg/g for dried cassava, and 6.69 mg/g for autoclaved cassava peel. The significant difference between the three (3) samples, attributed to pretreatment processes (washing and autoclaving), has practical implications. The autoclaved cassava peels undergo washing with tap water and thermal treatment, reducing the substrate's sugar concentration. Heat was found to improve cellulose biodegradability by removing hemicellulose and lignin and reducing the degree of crystallinity and polymerization of the cellulose constituents, which can be applied in various industries [28, 29]. Pretreatment aims to maximize the conversion of glucan and xylan (polysaccharides) to glucose and xylose (monosaccharides) for fermentation [27]. A study by [13] recorded a reduced sugar content of 0.64 g/g from cassava peels using the soaking-assisted thermal pretreatment (SATP) method. Whereas a low sugar content may improve the absorption of vital nutrients from the feed, autoclaved, pretreated cassava peels are preferred for animal feed. However, as sugar is a necessary raw material for the synthesis of ethanol and other biochemicals, the significance of glucose cannot be overstated.

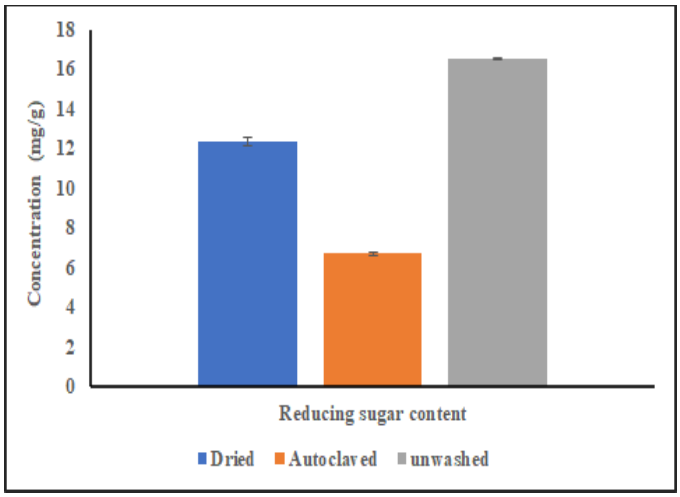

Fig. 1. Total reducing sugar of cassava peels (Dried, autoclaved, and unwashed). The data is presented as means and standard deviations (±) with n = 3

3.3 *Protein Content*

Pretreatments were used to assess the protein content of cassava peels. The autoclaved cassava peel had the highest protein content at 0.95 mg/mL, followed by the dried peel at 0.78 mg/mL. The unwashed sample displayed the lowest protein content at 0.72 mg/mL, as shown in Figure 2. This indicates that autoclaving significantly enhances protein availability compared to both drying pretreatments. The primary way that autoclaving might increase the amount of protein in cassava peels is by breaking down complex protein-polysaccharide complexes, thereby increasing the accessibility and potential digestibility of the proteins. However, a high protein concentration is vital since the microorganism requires protein to proliferate. Protein is necessary for the cellular processes that enable the cell to perform complex functions; thus, the organism requires it [30]. Increased protein availability after autoclaving may significantly influence animal nutrition, growth rates, and other health outcomes when cassava peels are added to feed.

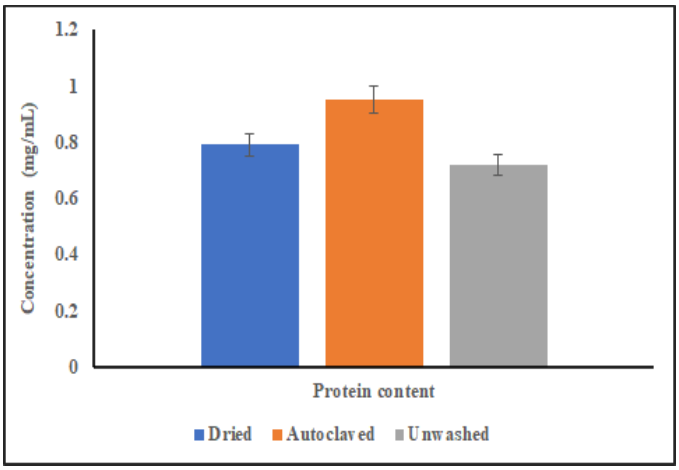

Fig. 2. Protein content of cassava peels (Dried, autoclaved, and unwashed). The data is presented as means and standard deviations (±) with n = 3

3.4 *Micro-X-ray fluorescence*

Micro-X-ray fluorescence (μXRF) is an analytical technique that uses the interaction of X-rays with a substance (liquid, solid, or powder) to determine its elemental composition. The results of the elemental composition, as shown in Figure 3(a), revealed that dried cassava peels contained abundant iron (Fe) at 58.78%, potassium (K) at 17.19%, and calcium (Ca) at 12.03%. Figure 3(b) revealed the elemental composition of autoclaved cassava peels with the presence of high potassium (K) at 62.65%, copper (Cu) at 9.76%, and manganese (Mn) at 0.52%. The results reveal that autoclaved cassava peel contains more potassium (62.66%) than dried cassava peel (17.91%). Iron and zinc are present in higher concentrations in dried cassava, with 58.78% and 11.27%, respectively. In contrast, their levels decreased to 19.31% and 7.74%, respectively, in autoclaved cassava peel. This could be attributed to the thermal pretreatment process involved. Nevertheless, other elemental compositions are found in trace amounts, such as copper, manganese, and zinc. Similar results for cassava peel powder indicated the presence of potassium, phosphorus, iron, and calcium [31]. Calcium, iron, and phosphorus are essential components of poultry nutrition. Iron is essential for DNA synthesis, oxygen, and electron

transport [32]. Also, minerals like Mg, Ca, and Na are found in cassava peel, making a stable, all-purpose organic fertilizer that is high in nutrients and less hazardous [33].

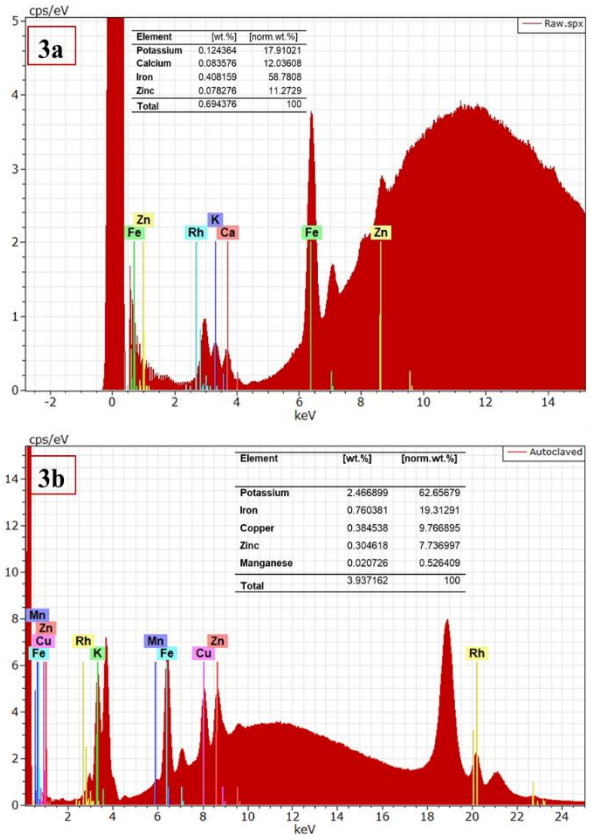

Fig. 3. (a) µXRF dried Cassava (*tapioca*) peel, **(b)** µXRF autoclaved Cassava (tapioca) peel

3.5 X-ray Diffraction

XRD analysis is the most reliable and robust non-destructive technique for qualitatively analyzing crystalline materials in powder or solid form. Figure 4 shows the X-ray diffractogram characterization of dried and autoclaved cassava peels measuring 1.00 mm. It indicates the presence of an amorphous phase and a semi-crystalline form in the dried and autoclaved cassava peel. This could be due to metallic impurities, such as copper, potassium, and manganese, which can alter the sample's crystallinity. The polysaccharides hemicellulose and cellulose possess crystalline and amorphous structures, along with branched and linear chains [34]. [8] detected a crystalline phase in cassava peel and bagasse by X-ray diffraction (XRD). However, [18] detected a low crystalline index but a high peak in the amorphous area. XRD indicated the presence of cellulose and carbon in the biomass. Physical and thermal pretreatment enhanced enzymatic activity on cassava peel, reduced amylose content, increased crystallinity, and improved mesoporous and hydrophilic properties. [34] stated that for a sample (cassava waste), peaks identified in the region 2θ between 15-27º represent the Van der Waal interaction among glucose molecules in cellulose and hemicellulose. XRD results correlated with the lignocellulose content, as cellulose is considered the primary component contributing to the crystalline region. In contrast, hemicellulose and lignin contribute to the amorphous region [35].

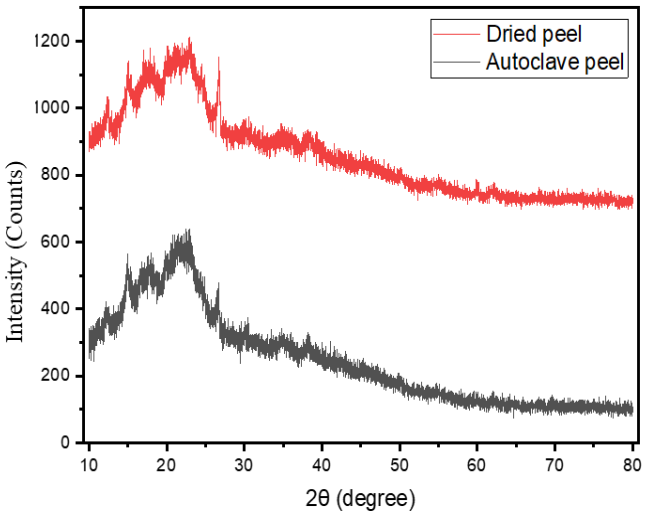

Fig. 4. XRD dried and autoclaved Cassava (*tapioca*) peel

3.6 FTIR

The Fourier transform infrared spectrophotometer (FTIR) is a spectroscopic method that reveals the presence of functional groups or chemical bonds in a substance based on the wavelength region of the infrared radiation peak. In this study, FTIR analysis was conducted to investigate the changes in the chemical structure of dried and autoclaved cassava peels. As shown in Figure 5, the absorbance spectra of the dried and autoclaved cassava peels exhibited minimal differences. Notably, the spectroscopy peaks revealed no significant bond alterations or elemental losses, indicating the absence of any chemical reactions that could lead to elemental degradation.

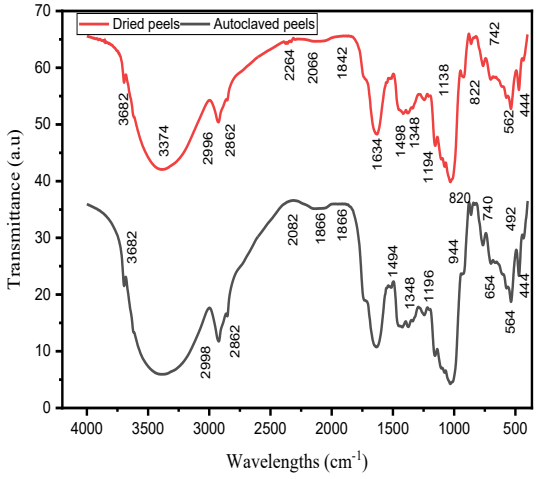

Fig. 5. FTIR spectra of dried and autoclaved cassava peels

A strong peak was detected at 3682–3200 cm^{-1}, representing the OH stretching vibration of cellulose molecules (hydroxyl group) [36]. This could be intramolecular or intermolecular hydrogen bonding. The subsequent sharp band at 2998–2865 cm-1 represents the CH stretching vibration of cellulose from methyl and methylene ester [8]. The 2303 and 2125 cm^{-1} present the O-H stretching of the hydrogen bond of amylose and amylopectin [13]. The peak in 1741–1643 cm^{-1} corresponds to the C=O stretching vibration with the bonding

of the acetyl unit in hemicellulose and lignin. A decrease in hemicellulose correlates with the intensity reduction associated with these peaks [37]. The peak at 1401–1397 cm^{-1} represents the CH_2 group in the crystalline form of cellulose in lignocellulose [38]. This finding is consistent with the results of the XRD analysis in this study. Based on the C-O-C stretching at β-glycosidic linkages of the glucose ring in cellulose, the peak at 890 cm^{-1} shows the presence of amorphous cellulose [39]. These functional groups are commonly associated with lignocellulose materials and are similar to those reported by other researchers from cassava peel [18, 31]. Table 2 summarizes the wave numbers and band assignments for each region. Moreover, the results obtained for the FTIR analysis also confirm the availability of cellulosic materials, which also cross-validate the SEM micrographic results.

Table 2. Characteristics of the band assignments and wavenumbers in FTIR analysis

Wavelength (cm^{-1})	Functional group	Characteristics
3570 – 3200	OH	Cellulose content rises, indicating free intermolecular bonds
2955 – 2903	C-H	CH_2 and CH_3 groups in the aromatic methoxyl group
1741 – 1643	C=O	Indicating hemicellulose from the acetyl carboxylic group
1401 – 1397	CH_2	Aromatic skeletal vibration (lignin) and C-H deformation in the plant (cellulose)
1075-1005	C-H	Deformation of various cellulose
994 and	C-H	Glycosidic bond β-(1-4) cellulose

3.7 Scanning Electron Microscope

The analysis of cassava peels using scanning electron microscopy (SEM) at different magnification levels was performed to evaluate the effectiveness of the pretreatment methods, including dried and autoclaved cassava peels. Figure 6 shows that the surface morphology of the granules exhibits a smooth texture with cluster bits, indicating that pretreatment may affect the lignocellulosic structure of cassava peels. Furthermore, the inclusion of inner-peel fractions was responsible for the observed higher fiber content in the peelings. The white region in the figures indicated the presence of impurities on the surface of cassava peels. Notably, the residual granules within the cassava peel exhibited diverse shapes, including round and irregular shapes, and varied in size [8]. The autoclaved pretreatment generally modified the cassava peels. In contrast, dried cassava peels showed less modification, as indicated by the micrograph of the substrate's intact structure, which had not undergone any chemical or biological pretreatment.

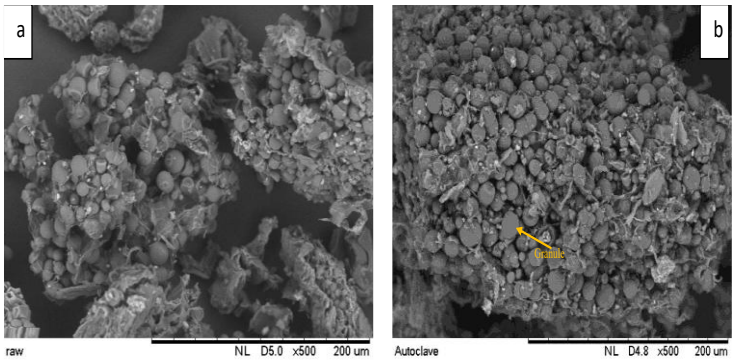

Fig. 6. SEM micrographs of cassava peel using 200µm magnification (a) Dried cassava peel, (b) Autoclaved cassava peel

3.8 Brunauer Emmette Teller

The surface area of the dried and autoclaved cassava peels was studied using the Brunauer-Emmett-Teller (BET) analysis. Table 3 presents the surface area, total pore area, and total pore volume of the dried and autoclaved cassava peels. The results show that the thermal treatment done on the cassava peels increased the surface area by (2.713 m^2/g), total pore area by (0.06298 m^2/g), and total pore volume by (0.0604 m^2/g). The structure of cellulose, lignocellulose, and lignin, which are characterized by their limited and blocked pores, is associated with low pore volume and area [40]. The findings of this research correlate with the report of [41], who reported a surface area of 2.0509 m^2/g, a pore volume of 0.002233 m^2/g, and a pore size of 4.35428 m^2/g of cassava peels [42]. [43] revealed the specific surface area at 2.497 m^2g and pore volume at 0.004 cm^3/g of cassava peel.

Table 3. Summary of BET Analysis of Dried and Autoclaved Cassava Peels

Sample	Surface area (m^2g^{-1})	Total pore area (m^2g^{-1})	Total pore volume (cm^3/g)
Dried cassava peel	2.097	0.03938	0.0370
Autoclaved cassava peel	2.713	0.06298	0.0604

4. APPLICATION AND COMMERCIALIZATION PROSPECTS OF CASSAVA PEELS

Cassava peels, a lignocellulosic biomass rich in starch, are a promising, abundant, and renewable energy source that is inexpensive and easy to process into bioproducts. Due to their ecological and environmental sustainability, crop wastes have long been a source of interest as feedstocks and industrial raw materials for producing bioplastics, biofuels, and organic acids [44, 45]. Table 4 lists potential industrial applications, uses of cassava peels, and their degree of technological readiness. The conversion of biomass to monosaccharides by chemical, enzymatic, or a combination of both processes is the first step needed to utilize these wastes in bioprocessing. Despite tremendous advancements, the efficiency of converting lignocellulosic biomass to monosaccharide sugars has remained poor, rendering the bioprocessing of this feedstock unsustainable. Cassava waste has been modified through various chemical, physical, biotechnological, enzymatic, and

dual/triple modification techniques to enhance its functional properties and expand its range of industrial applications. Additionally, incorporating cassava peel into the circular economy model aligns with the United Nations' Sustainable Development Goals (SDGs) by encouraging accessible and clean energy (SDG 7), enhancing sustainable industrial innovation (SDG 9), and supporting climate action through waste valorization (SDG 13). It would contribute to reducing greenhouse gas emissions [46]. The commercialization prospects of cassava peels are promising and would contribute to a greener future, without compromising food security, and present a sustainable solution to waste management. The impact categories of applications (High, Medium, Low) are determined by economic importance, scalability, and technological relevance, which refers to emerging ones. “Low" designates niche or early-stage applications with a minimal economic footprint or market presence.

Table 4. Prospect and Application of Cassava Peels

Application	Sector	Impact	References
• For animals, it can serve as a feed substitute for maize without impairing growth efficiency nutrient digestibility.	Animal Feed	High	[47], [48], [49], [50]
• Cassava plant peels are used for heavy metal bioleaching and wastewater treatment. They function by lowering the phenol content.	Wastewater treatment	Medium	[51]
• Cassava peels are extracted for their starch, which is utilized in biodegradable food packaging, paper production, and various industrial applications.	Plastic & Paper Industries	Medium	[52]
• Cassava peels can be used to produce poly-4-glutamic acid, which is utilized as a thickening agent, anti-freezing agent, and bitterness-relieving agent, as well as a biobattery that generates 0.563V and 0.014mA, exhibiting potential as an alternative energy source to replace batteries.	Industry	Low	[53], [54]
• Cassava peels, combined with animal manure or treated with potassium hydroxide (KOH) and potash, are used as a source of biogas. Biobutanol, bioethanol, biomethane, and biodiesel are used as substitutes for gasoline and diesel.	Biofuel Biogas	High	[55], [56], [57], [58]
• Its abundance of nutrients replenishes depleted soil fertility when it is decomposed into organic fertilizer. Biochar is produced through pyrolysis and serves as a soil enhancer, thereby enhancing soil fertility.	Agricultural Industry	High	[33], [59]
• Cassava peel utilizes sugar as an energy source and utilizes a biorefinery to transform it into organic acids, including citric, glycolic, levulinic, ferulic, lactic, and formic acid.	Industry	Medium	[60], [61]
• In the food industry, enzymes such as α-amylase, cellulase, and xylanase are utilized to modify starches, enhance texture, and improve flavor. Lipase and protease are used in the detergent industry to remove stains and improve cleaning efficiency. Cellulose effect on denim, stone-washed, pulp, and paper industry.	Enzyme Industrial	High	[55], [62]

5. CONCLUSION

This study revealed the impact of morphological and chemical characterization on dried and autoclaved cassava peels. The autoclave pretreatment resulted in notable changes in the lignocellulosic composition, primarily increasing cellulose content while decreasing hemicellulose and lignin content. While the functional groups and general morphological characteristics were alike in both treatments, XRD analysis indicated the presence of both amorphous and semi-crystalline phases in the dried and autoclaved samples. SEM and elemental analyses confirmed the presence of key functional groups (hydroxyl, carboxyl, amine) and minerals (Fe, K, Ca) in both peels, noting a reduction in chemical content after autoclaving. These findings highlight the potential of cassava peel as a sustainable feedstock for bio-based applications, including biofuels, animal feed, paper, and textiles. However, efficient pretreatment is still critical for enhancing its commercial viability. Future research should focus on optimizing autoclave parameters and integrating cost-effective pretreatment strategies for the large-scale conversion of cassava peels.

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