

Comparative lignocellulosic profiling of tropical agro-industrial residues from Tarma, Perú, for sustainable bioenergy applications

Perfil comparativo de la composición lignocelulósica de residuos agroindustriales tropicales de Tarma, Perú, para aplicaciones de bioenergía sostenible

Nieto Apolinario,
Arthur Pool¹



Rosales Diaz,
Yareck Jesus¹



Bernaola Paucar,
Rosario Marilu¹



Rodriguez
Cangalaya, Nora¹



¹ Universidad Nacional Autónoma Altoandina de Tarma (UNAAAT), Carretera La Florida-Cochayoc, Huancucro 2092, Zip code: 12651, Junín, Perú.

Recibido:
12-02-2026

Publicado:
31-07-2026

Autor corresponsal:
Arthur Pool Nieto Apolinario
Correo:
72977475@unaat.edu.pe
Universidad Nacional Autónoma
Altoandina de Tarma, Junín, Perú

Para citar este artículo:
Nieto, A., Rosales, Y., Bernaola, R., y Rodriguez, N. (2026). Perfil comparativo de la composición lignocelulósica de residuos agroindustriales tropicales de Tarma, Perú, para aplicaciones de bioenergía sostenible. Revista Científica Kanyu, 4(1), p. 15-27.

<https://doi.org/10.61210/kanyu.v4i1.250>

ABSTRACT

This study evaluated the lignocellulosic composition of seven tropical agro-industrial residues generated in Tarma, Peru, to assess their potential for sustainable bioenergy applications. A Completely Randomized Design (CRD) comprising seven treatments and three replicates per treatment was employed. Biomass samples were oven-dried, milled, and chemically characterized to determine extractives, cellulose, hemicellulose, and acid-insoluble lignin using Soxhlet extraction, the Jayme–Wise, Kürschner–Hoffer, and Klason methods, respectively. Data were analyzed by one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) test ($p < 0.05$). Significant compositional variability was observed among the evaluated residues. Potato peel exhibited the highest cellulose content (53.15%), whereas corn cob presented the highest hemicellulose concentration (38.46%). In contrast, cocoa husk showed the highest lignin content (40.30%), while cocoa husk and banana peel exhibited the greatest extractive fractions ($>22\%$). ANOVA revealed highly significant differences among treatments for all evaluated variables ($p < 0.001$), and Tukey's HSD test confirmed distinct compositional groups. Overall, residues characterized by high structural carbohydrate contents and comparatively low lignin concentrations exhibited greater potential for biomass valorization and sustainable bioenergy applications. These findings provide baseline information for the selection of

agro-industrial feedstocks suitable for future renewable energy development in the Peruvian Andes.

Keywords: Lignocellulosic biomass; Agro-industrial residues; Structural carbohydrates; Biomass valorization; Sustainable bioenergy.

RESUMEN

El presente estudio evaluó la composición lignocelulósica de siete residuos agroindustriales tropicales generados en Tarma, Perú, con el propósito de determinar su potencial para aplicaciones de bioenergía sostenible. Se empleó un Diseño Completamente al Azar (DCA) conformado por siete tratamientos y tres repeticiones por tratamiento. Las muestras de biomasa fueron secadas en estufa, molidas y caracterizadas químicamente para determinar los contenidos de extractivos, celulosa, hemicelulosa y lignina insoluble en ácido mediante los métodos de extracción Soxhlet, Jayme–Wise, Kürschner–Hoffer y Klason, respectivamente. Los datos fueron analizados mediante un análisis de varianza de una vía (ANOVA), seguido de la prueba de diferencia honestamente significativa (HSD) de Tukey ($p < 0.05$). Se observó una variabilidad composicional significativa entre los residuos evaluados. La cáscara de papa presentó el mayor contenido de celulosa (53.15%), mientras que la tusa de maíz registró la mayor concentración de hemicelulosa (38.46%). En contraste, la cascarilla de cacao mostró el mayor contenido de lignina (40.30%), mientras que la cascarilla de cacao y la cáscara de plátano presentaron las mayores fracciones de extractivos (>22%). El ANOVA reveló diferencias altamente significativas entre tratamientos para todas las variables evaluadas ($p < 0.001$), y la prueba HSD de Tukey confirmó la existencia de grupos composicionales diferenciados. En conjunto, los residuos caracterizados por altos contenidos de carbohidratos estructurales y concentraciones comparativamente bajas de lignina exhibieron un mayor potencial para la valorización de biomasa y aplicaciones de bioenergía sostenible. Estos hallazgos proporcionan información de base para la selección de materias primas agroindustriales con potencial para el desarrollo futuro de energías renovables en los Andes peruanos.

Palabras clave: Biomasa lignocelulósica; residuos agroindustriales; carbohidratos estructurales; valorización de biomasa; bioenergía sostenible.

INTRODUCTION

The rapid expansion of agricultural and agro-industrial activities has substantially increased the generation of organic residues worldwide, creating significant environmental, economic, and technological challenges associated with their management and disposal. In many developing countries, including Peru, agro-industrial by-products are frequently discarded through open-air burning, uncontrolled decomposition, or direct disposal into natural ecosystems, practices that contribute to greenhouse gas emissions, soil degradation, water contamination, and the inefficient loss of potentially valuable biomass resources (Forero-Sandoval et al., 2026; Blasi et al., 2023). In the central Andean region of Peru, particularly in the province of Tarma, agricultural production constitutes one of the main economic activities, generating considerable amounts of lignocellulosic residues derived from crops such as maize, coffee, cocoa, banana, pineapple, potato, and coconut. Despite their abundance and continuous availability throughout the year, most of these residues remain underutilized and are rarely integrated into sustainable biomass valorization strategies or renewable energy production systems (Blasi et al., 2023; Forero-Sandoval et al., 2026).

In recent decades, growing concerns regarding fossil fuel depletion, climate change, and environmental sustainability have intensified scientific interest in the development of renewable energy alternatives derived from biomass resources. Among the different renewable feedstocks available, lignocellulosic biomass has emerged as one of the most promising raw materials for sustainable bioenergy production due to its wide availability, biodegradability, low economic cost, and high carbohydrate content (Blasi et al., 2023; Bele et al., 2026). Globally, lignocellulosic biomass is considered the largest renewable carbon reservoir on Earth, with annual production exceeding 180 billion tons, although only a small fraction is currently utilized for industrial or energetic purposes (Blasi et al., 2023). Structurally, lignocellulosic biomass consists primarily of cellulose, hemicellulose, lignin, and minor extractive compounds whose relative proportions directly influence biomass recalcitrance, biodegradability, and conversion efficiency during biochemical and thermochemical conversion processes (Bele et al., 2026; Schultz et al., 2025).

Cellulose constitutes the principal structural polysaccharide of plant cell walls and represents the major source of fermentable sugars for biological conversion technologies. Hemicellulose, composed mainly of short chain heteropolysaccharides, contributes additional carbohydrate fractions susceptible to hydrolysis and microbial degradation. In contrast, lignin is a highly complex aromatic polymer that forms a rigid structural network around cellulose and hemicellulose, limiting enzymatic accessibility and reducing biomass biodegradability (Lin & Dence, 1992; Schultz et al., 2025). Due to this structural complexity, lignin is considered one of the principal factors restricting the efficient conversion of lignocellulosic biomass into renewable biofuels and other value-added bioproducts (Brózda et al., 2026; Karthikeyan et al., 2025). Consequently, the structural composition of biomass plays a fundamental role in determining its suitability for anaerobic digestion, bioethanol production, thermochemical conversion, and integrated biorefinery systems (Blasi et al., 2023; Bele et al., 2026).

Several studies have demonstrated that the physicochemical composition of agro-industrial residues varies significantly depending on plant species, climatic conditions, crop maturity, agronomic management, and postharvest processing methods. Such compositional variability directly affects biomass structural stability, hydrolysis efficiency, and microbial degradation performance (Sánchez-Orozco et al., 2014; Schultz et al., 2025). Sánchez-Orozco et al. (2014) reported total sugar concentrations ranging from 0.487 to 0.591 g g⁻¹ dry biomass in lignocellulosic fruit residues derived from banana, mango, and orange processing, confirming their considerable potential as feedstocks for renewable bioenergy applications. Likewise, Schultz et al. (2025) and Karthikeyan et al. (2025) demonstrated that residues with higher cellulose and hemicellulose contents generally exhibit greater biodegradability and enhanced conversion efficiency, whereas elevated lignin concentrations negatively affect microbial accessibility and methane production.

The characterization of lignocellulosic biomass has therefore become an essential step in the identification and selection of suitable feedstocks for sustainable bioenergy systems. Previous investigations have emphasized the importance of evaluating structural carbohydrate fractions and lignin distribution to predict biomass performance during biological conversion processes (Brózda et al., 2026; Schultz et al., 2025). Brózda et al. (2026) demonstrated that increases in lignin concentration significantly reduced methane production efficiency in *Miscanthus × giganteus*, whereas Karthikeyan et al. (2025) reported that structural modification of lignocellulosic biomass considerably improved carbohydrate accessibility and overall conversion efficiency. These findings confirm that detailed compositional characterization is an indispensable step before selecting agricultural residues for bioenergy applications (Blasi et al., 2023; Bele et al., 2026).

Despite the increasing scientific interest in biomass valorization, information regarding the lignocellulosic composition of tropical agro-industrial residues generated in the Peruvian Andes remains scarce. In Tarma, agro-industrial residues are commonly regarded as low-value waste materials without prior physicochemical evaluation or systematic assessment of their suitability for sustainable bioenergy applications. Furthermore, most regional studies have focused primarily on residue generation, environmental impacts, or general waste management practices rather than on detailed structural characterization of cellulose, hemicellulose, lignin, and extractive fractions. This lack of scientific information limits the development of efficient biomass utilization strategies and restricts the implementation of technologies aimed at converting agricultural residues into renewable energy resources and value-added bioproducts.

Under this context, the present study was based on the hypothesis that tropical agro-industrial residues generated in Tarma, Peru, exhibit significant differences in lignocellulosic composition, and that residues with higher structural carbohydrate contents and lower lignin concentrations may possess greater suitability for sustainable bioenergy applications. Therefore, the main objective of this research was to perform a comparative lignocellulosic profiling of selected agro-industrial residues from Tarma, Peru, through the quantification of cellulose, hemicellulose, lignin, and extractive contents. Specifically, the study aimed to identify compositional differences among residues and evaluate their structural characteristics as potential feedstocks for biomass valorization and renewable energy production.

The relevance of this research lies in its contribution to the sustainable management and valorization of agro-industrial residues in tropical agricultural regions. The physicochemical characterization of lignocellulosic biomass provides fundamental information for the future implementation of bioconversion technologies, including anaerobic digestion, bioethanol production, pyrolysis, gasification, and integrated biorefinery systems (Blasi et al., 2023). Additionally, the utilization of agricultural residues for renewable energy applications may contribute to reducing environmental pollution, minimizing waste accumulation, decreasing dependence on fossil fuels, and promoting circular bioeconomy approaches based on renewable biomass resources (Forero-Sandoval et al., 2026). From a regional perspective, this study also represents one of the first comparative evaluations of lignocellulosic residues generated in Tarma, Peru, generating baseline scientific information for future research and technological development related to biomass conversion and sustainable bioenergy systems.

The scope of this work was limited to the structural and compositional characterization of untreated agro-industrial residues under controlled laboratory conditions. Although the study provides relevant information concerning lignocellulosic variability among residues, some limitations should be considered. Biomass composition may vary according to seasonal conditions, climatic factors, agricultural management practices, plant genotype, maturity stage, and postharvest handling, all of which may influence the reproducibility of lignocellulosic profiles and structural properties. Moreover, the study did not include direct biochemical conversion assays or experimental bioenergy production tests; therefore, the interpretation of bioenergy applicability was primarily based on structural composition and previously reported relationships between

lignocellulosic fractions and biomass conversion performance (Brózda et al., 2026; Schultz et al., 2025). Nevertheless, the findings obtained constitute a valuable contribution toward understanding the structural properties of tropical agro-industrial residues and their potential role in sustainable bioenergy applications within the Peruvian context.

METODOLOGY

Study Area

The study was conducted at the Universidad Autónoma Altoandina de Tarma, located in the district and province of Tarma, Junín Region, Peru. Tarma is an important agricultural area in the central Peruvian Andes, where the production and commercialization of Andean and tropical crops generate diverse lignocellulosic residues with potential applications in biomass valorization and sustainable bioenergy systems.

Experimental Design

A Completely Randomized Design (CRD) was used, with agro-industrial residue type considered as the only experimental factor. Seven treatments were evaluated, with three independent replicates per treatment, resulting in 21 experimental units. The treatments were defined as follows: T1, potato peel (*Solanum tuberosum* L.); T2, coffee husk (*Coffea arabica* L.); T3, pineapple peel (*Ananas comosus* L.); T4, corn cob (*Zea mays* L.); T5, coconut fiber (*Cocos nucifera* L.); T6, cocoa husk (*Theobroma cacao* L.); and T7, banana peel (*Musa paradisiaca* L.).

The response variables were cellulose, hemicellulose, acid-insoluble lignin, and extractive contents, all expressed as percentages on an oven-dry biomass basis. The statistical model was:

$$Y_{ij} = \mu + T_i + \varepsilon_{ij}$$

where Y_{ij} is the observed value of the response variable, μ is the overall mean, T_i is the fixed effect of the i -th agro-industrial residue, and ε_{ij} is the random experimental error associated with the j -th replicate.

Biomass Collection and Sample Preparation

The agro-industrial residues were collected from agricultural production and commercialization centers located in Tarma Province. Three independent samples were obtained for each residue type and treated as experimental replicates.

After collection, the samples were manually sorted to remove soil particles, stones, dust, and other foreign materials. The residues were then washed with distilled water and dried in a forced-air convection oven at 60 °C until constant mass was reached.

The dried materials were ground using a laboratory mill and sieved to obtain a homogeneous particle-size fraction suitable for chemical characterization. The processed samples were stored in airtight polyethylene containers under dry laboratory conditions until analysis.

Determination of Extractive Content

Extractive content was determined by Soxhlet extraction following the principles of TAPPI T204 cm-97 and the procedures described in the Forest Chemistry Laboratory Guide. This step was performed before structural carbohydrate and lignin analyses to remove soluble non-structural compounds, including pigments, oils, waxes, tannins, phenolic substances, and other low-molecular-weight constituents.

Approximately 3.00 ± 0.05 g of oven-dried biomass were placed in a cellulose extraction thimble. The sample was extracted with ethanol in a Soxhlet apparatus equipped with a round-bottom flask and reflux condenser. Extraction was maintained for 4 h under continuous reflux, or until the solvent in the extraction chamber became visibly colorless.

After extraction, the solid residue was removed from the thimble and dried at 105 °C until constant mass. Extractive content was calculated as:

$$\text{Extractives (\%)} = \frac{W_i - W_f}{W_i} \times 100$$

where W_i is the initial oven-dry mass of the sample and W_f is the oven-dry mass after extraction.

Determination of Holocellulose

Holocellulose content was determined using the Jayme-Wise method, based on the selective oxidative degradation of lignin by sodium chlorite in acidic medium. This procedure enabled the isolation of the structural carbohydrate fraction composed mainly of cellulose and hemicellulose.

For each determination, 1.0 g of extractive-free dry biomass was weighed into 250 mL Erlenmeyer flasks. Subsequently, 75 mL of 1.5% sodium chlorite (NaClO_2) solution and five drops of concentrated acetic acid were added. The mixture was heated in a thermostatically controlled water bath at 75 °C for 40 min with periodic agitation. After the first digestion stage, an additional 1.0 g of sodium chlorite and five additional drops of acetic acid were incorporated, and the reaction was maintained for another 40 min until a whitish fibrous residue was obtained.

The resulting suspension was filtered under vacuum using pre-weighed filter paper and washed repeatedly with cold distilled water to remove residual reagents. The holocellulose fraction was subsequently dried at 105 °C until constant mass.

Hemicellulose content was estimated from the structural carbohydrate balance obtained for each evaluated treatment.

Determination of Cellulose

Cellulose content was determined using the Kürschner–Hoffer method, based on the selective removal of hemicellulose from the holocellulose fraction through repeated digestion with a nitric acid–ethanol solution. Approximately 1.0 g of dried holocellulose was transferred to a digestion flask and treated with the nitric acid–ethanol reagent under controlled heating. The digestion was repeated until complete removal of hemicellulose was achieved, leaving purified cellulose fibers. The cellulose residue was filtered under vacuum, washed successively with ethanol and distilled water until neutral pH, dried at 105 °C to constant weight, cooled in a desiccator, and weighed. Cellulose content was calculated gravimetrically as the percentage of oven-dried biomass.

Determination of Acid-Insoluble Lignin

Acid-insoluble lignin was determined using the Klason method, following the principles of TAPPI T222 om-98. The method is based on the hydrolysis and solubilization of structural carbohydrates by concentrated sulfuric acid, leaving lignin as an insoluble residue.

Approximately 0.50 ± 0.01 g of extractive-free biomass was transferred to a 250 mL flask, and 5 mL of 72% sulfuric acid were added. The sample was mixed carefully to ensure complete wetting and allowed to stand for 15 min at room temperature.

The mixture was then diluted with 150 mL of distilled water and heated under reflux for 50 min. After hydrolysis, the suspension was cooled and filtered under vacuum through pre-weighed filter paper. The insoluble residue was washed repeatedly with hot distilled water until the filtrate reached neutral pH. The filter paper containing the lignin residue was dried at 100 °C until constant mass, cooled in a desiccator, and weighed. Acid-insoluble lignin was calculated as:

$$\text{Lignin (\%)} = \frac{W_r}{W_s} \times 100$$

Where W_r is the oven-dry mass of the acid-insoluble residue and W_s is the initial oven-dry mass of the extractive-free sample.

Statistical Analysis

Descriptive statistics were calculated for all evaluated variables, and results were expressed as mean $\pm$ standard deviation. Prior to inferential analyses, normality and homogeneity of variances were verified using the Shapiro–Wilk and Levene tests, respectively.

Differences among treatments were evaluated through one-way analysis of variance (ANOVA), considering agro-industrial residue type as the single experimental factor within the Completely Randomized Design. The ANOVA results revealed highly significant differences among treatments for cellulose, hemicellulose, lignin, and extractive contents ($p < 0.001$), indicating substantial structural variability among the evaluated residues.

When significant differences were detected, means were compared using Tukey's Honestly Significant Difference (HSD) test at a 95% confidence level. According to the Tukey analysis, T1 (potato peel) exhibited the highest cellulose content, while T6 (cocoa husk) showed the highest lignin concentration. Additionally, T4 (corn cob) presented the highest hemicellulose content among the evaluated treatments, whereas T6 and T7 exhibited the highest extractive fractions.

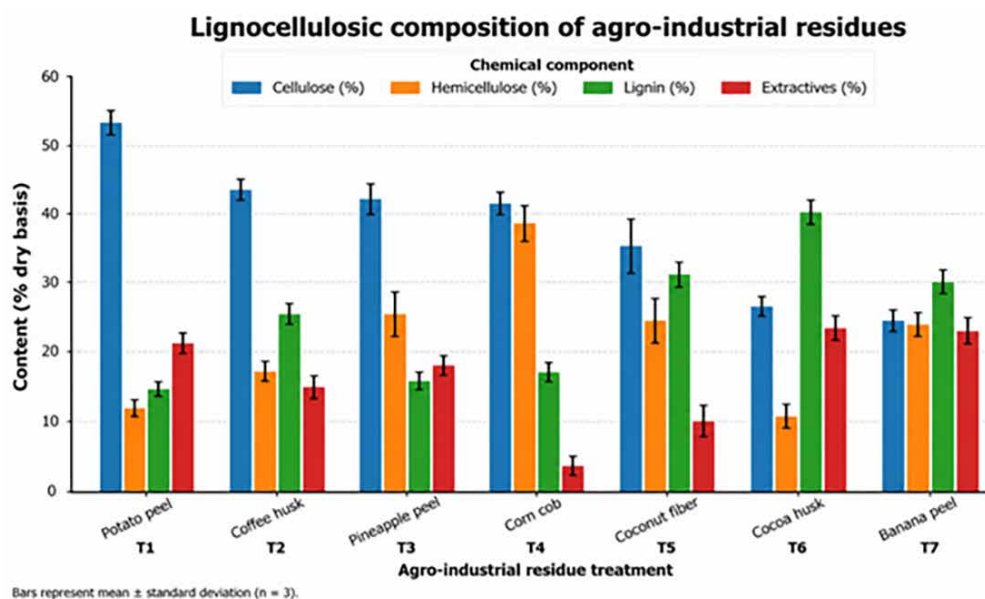
Statistical analyses were performed using IBM SPSS Statistics version 27.0 (IBM Corp., Armonk, NY, USA), considering a significance level of $p < 0.05$.

RESULTS

The lignocellulosic characterization of the evaluated agro-industrial residues revealed substantial compositional variability among treatments, demonstrating marked differences in structural carbohydrate distribution and lignin concentration according to the botanical origin of each biomass. The comparative composition of cellulose, hemicellulose, lignin, and extractive fractions is presented in Figure 1, where distinct structural profiles can be observed for each evaluated residue.

Figure 1

Comparative lignocellulosic composition of agro-industrial residues evaluated under a completely randomized design.



Extractive content exhibited pronounced differences among treatments. Banana peel (T7), cocoa husk (T6), and potato peel (T1) presented the highest extractive fractions, with average values above 20% on a dry basis. In contrast, corn cob (T4) showed the lowest extractive concentration, reaching values below 5%. Intermediate extractive contents were identified in pineapple peel (T3), coffee husk (T2), and coconut fiber (T5). The elevated extractive content observed in banana peel and cocoa husk suggests the presence of considerable quantities of soluble compounds such as pigments, oils, waxes, phenolic substances, and low-molecular-weight metabolites characteristic of tropical agro-industrial biomass. Conversely, the reduced extractive fraction identified in corn cob indicates a biomass composition dominated mainly by structural polysaccharides.

Regarding structural carbohydrates, cellulose content differed considerably among the evaluated treatments. Potato peel (T1) exhibited the highest cellulose concentration, with values exceeding 53%, followed by coffee husk (T2), pineapple peel (T3), and corn cob (T4), whose cellulose contents ranged between approximately 41 and 43%. Coconut fiber (T5) showed intermediate cellulose values close to 35%, whereas cocoa husk (T6) and banana peel (T7) presented the lowest cellulose concentrations, with values near 26 and 24%, respectively. The elevated cellulose content observed in potato peel indicates a high proportion of structural carbohydrates potentially available for future biomass conversion processes, while residues with lower cellulose fractions may present reduced carbohydrate availability for biological degradation.

Hemicellulose content also showed marked variation among residues. Corn cob (T4) exhibited the highest hemicellulose concentration among all treatments, reaching close to 39%, followed by pineapple peel (T3) and coconut fiber (T5). Coffee husk (T2) and banana peel (T7) showed intermediate hemicellulose concentrations, whereas cocoa husk (T6) and potato peel (T1) presented the lowest values, both close to 11%. The high hemicellulose content identified in corn cob suggests a greater abundance of amorphous polysaccharides susceptible to hydrolysis and microbial degradation, which may favor its future application in biomass valorization processes.

Lignin concentration exhibited the greatest structural variability among the evaluated residues. Cocoa husk (T6) showed the highest lignin content, with values approaching 40%, followed by coconut fiber (T5) and banana peel (T7), which exhibited lignin concentrations above 29%. In contrast, potato peel (T1), pineapple peel (T3), and corn cob (T4) presented substantially lower lignin

contents, ranging between approximately 14 and 17%. Coffee husk (T2) displayed intermediate lignin values close to 25%. The elevated lignin concentrations identified in cocoa husk and coconut fiber indicate a higher degree of structural recalcitrance, which may negatively influence biodegradability and microbial accessibility during future biomass conversion processes. Conversely, residues with reduced lignin content may exhibit more favorable characteristics for biological or thermochemical applications.

Significant differences were observed in the lignocellulosic composition of the seven agro-industrial residues evaluated. Cellulose content ranged from 24.13 to 53.15%, with potato peel (T1) exhibiting the highest concentration, whereas banana peel (T7) showed the lowest value. Corn cob (T4) presented the highest hemicellulose content (38.46%), while cocoa husk (T6) recorded the greatest lignin concentration (40.30%). Extractive contents varied considerably among residues, with cocoa husk (T6) and banana peel (T7) showing the highest values, whereas corn cob (T4) exhibited the lowest proportion. The Tukey HSD test identified significant differences among treatments for all evaluated variables, confirming the influence of residue type on lignocellulosic composition. In addition, the coefficients of variation ranged from 3.17% to 9.55%, indicating satisfactory analytical precision and good experimental repeatability. The complete mean values, standard deviations, Tukey groupings, and coefficients of variation are presented in Table 1.

Table 1

Mean ($\pm$ SD), Tukey HSD grouping, and coefficient of variation (CV) of cellulose, hemicellulose, lignin, and extractive contents in agro-industrial residues

Treatment	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Extractives (%)
T1 Potato peel	53.15 $\pm$ 1.08 a	11.86 $\pm$ 0.34 d	14.25 $\pm$ 0.59 e	20.72 $\pm$ 1.33 b
T2 Coffee husk	43.29 $\pm$ 0.66 b	17.00 $\pm$ 0.31 c	25.10 $\pm$ 0.17 c	14.93 $\pm$ 0.96 c
T3 Pineapple peel	41.74 $\pm$ 1.59 b	25.13 $\pm$ 3.04 b	15.57 $\pm$ 0.50 e	17.78 $\pm$ 1.34 c
T4 Corn cob	41.35 $\pm$ 0.34 b	38.46 $\pm$ 0.44 a	16.75 $\pm$ 0.22 d	3.57 $\pm$ 0.89 e
T5 Coconut fiber	35.00 $\pm$ 3.00 c	24.13 $\pm$ 2.93 b	31.00 $\pm$ 1.00 b	9.93 $\pm$ 1.90 d
T6 Cocoa husk	26.47 $\pm$ 0.55 d	10.00 $\pm$ 1.48 d	40.30 $\pm$ 1.55 a	23.03 $\pm$ 1.14 a
T7 Banana peel	24.13 $\pm$ 1.24 d	23.95 $\pm$ 0.50 b	29.55 $\pm$ 0.80 b	22.90 $\pm$ 1.55 a
CV (%)	3.89	7.32	3.17	9.55

* Values are presented as mean $\pm$ standard deviation (n = 3). Different lowercase letters within the same column indicate significant differences according to Tukey's HSD test ($p < 0.05$). CV = coefficient of variation.

The statistical analysis confirmed that the compositional differences observed among agro-industrial residues were highly significant for all evaluated variables. According to the analysis of variance presented in Table 2, cellulose content differed significantly among treatments, with an F value of 112.925 and a p-value of 4.8406×10^{-11} . Similarly, hemicellulose content exhibited significant variation among residues (F = 80.471; $p = 4.8317 \times 10^{-10}$), while lignin showed the highest statistical differentiation among treatments, reaching an F value of 381.414 and a p-value of 1.0944×10^{-14} . Extractive content also differed significantly among residues, with an F value of 77.088 and a p-value of 6.4558×10^{-10} . These results demonstrate that residue type exerted a strong influence on the lignocellulosic composition of the evaluated biomasses.

Table 2

Analysis of variance (ANOVA) of cellulose, hemicellulose, lignin, and extractive contents among agro-industrial residues

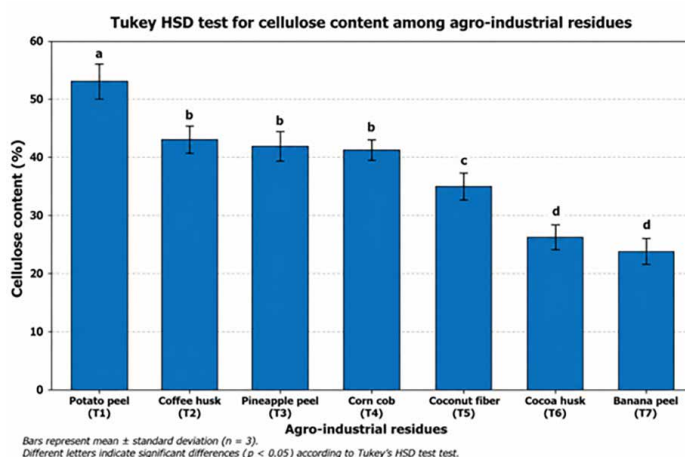
Variable	Sum Source of variation	squares	df	square	of F value	Mean p-value	Significance
Cellulose	Agro-industrial residues	1860.644	6	310.107	112.925	4.8406e ⁻¹¹	***
	Experimental error	38.446	14	2.746			
	Total	1899.090	20				
Hemicellulose	Agro-industrial residues	1639.079	6	273.180	80.471	4.8317e ⁻¹⁰	***
	Experimental error	47.527	14	3.395			
	Total	1686.606	20				
Lignin	Agro-industrial residues	1651.870	6	275.312	381.414	1.0944e ⁻¹⁴	***
	Experimental error	10.105	14	0.722			
	Total	1661.975	20				
Extractives	Agro-industrial residues	946.100	6	157.683	77.088	6.4558e ⁻¹⁰	***
	Experimental error	28.637	14	2.045			
	Total	974.737	20				

The low experimental error values obtained in the ANOVA indicate satisfactory analytical precision and good reproducibility of the chemical characterization procedures. Among the evaluated variables, lignin exhibited the lowest experimental error, suggesting high consistency during lignin quantification. Overall, the statistical analysis demonstrated that each agro-industrial residue possessed a distinct structural composition and a significantly differentiated lignocellulosic profile.

The post hoc comparison performed through Tukey's Honestly Significant Difference (HSD) test for cellulose content revealed the formation of statistically differentiated groups among treatments, as shown in Figure 2. Potato peel (T1) formed an independent statistical group characterized by the highest cellulose concentration among all evaluated residues. Coffee husk (T2), pineapple peel (T3), and corn cob (T4) formed a second statistical group with similarly elevated cellulose contents. Coconut fiber (T5) occupied an intermediate position, whereas cocoa husk (T6) and banana peel (T7) formed the group with the lowest cellulose concentrations.

Figure 2

Tukey HSD multiple comparison test for cellulose content among agro-industrial residues



The distribution pattern identified through the Tukey analysis confirms the existence of substantial structural variability among tropical agro-industrial residues generated in Tarma, Peru. In particular, residues characterized by elevated structural carbohydrate contents and reduced lignin concentrations may present greater suitability for future bioenergy-related applications due to their potentially enhanced biodegradability and carbohydrate accessibility. Conversely, residues with elevated lignin concentrations may require pretreatment strategies to facilitate structural disruption and improve biomass conversion efficiency. Collectively, the results obtained provide relevant baseline information regarding the compositional characteristics of tropical agro-industrial residues and their potential applicability within sustainable biomass valorization systems.

DISCUSSION

The compositional differences observed in Figure 1 and Table 1 demonstrate the pronounced structural variability among the tropical agro-industrial residues evaluated in Tarma, Peru. Potato peel (T1) exhibited the highest cellulose content ($53.15 \pm 1.08\%$), significantly differing from the remaining residues according to Tukey's HSD test, whereas cocoa husk (T6) and banana peel (T7) presented the lowest cellulose concentrations ($26.47 \pm 0.55\%$ and $24.13 \pm 1.24\%$, respectively). This variability is closely associated with the botanical origin of the biomass, the anatomical organization of plant tissues, environmental growth conditions, and postharvest processing characteristics. High cellulose concentrations indicate a greater proportion of structural carbohydrates available for biological conversion, thereby enhancing the suitability of biomass for renewable energy applications (Blasi et al., 2023; Schultz et al., 2025). Similar trends were reported by Sánchez-Orozco et al. (2014), who highlighted the importance of cellulose-rich agro-industrial residues as promising feedstocks for bioenergy production.

Corn cob (T4) exhibited the highest hemicellulose concentration ($38.46 \pm 0.44\%$), significantly exceeding the other evaluated residues, whereas potato peel (T1) and cocoa husk (T6) showed the lowest values. Hemicellulose is an amorphous polysaccharide with lower structural resistance than cellulose, making it more susceptible to hydrolysis and microbial degradation (Lin & Dence, 1992). The balanced cellulose–hemicellulose composition observed in corn cob suggests favorable structural characteristics for biomass conversion processes. Similar findings were reported by Schultz et al. (2025) and Karthikeyan et al. (2025), who demonstrated that lignocellulosic residues with high structural carbohydrate contents generally exhibit improved conversion efficiencies and greater suitability for biochemical processing.

Lignin concentration represented the principal structural constraint among the evaluated biomasses. Cocoa husk (T6) contained the highest lignin concentration ($40.30 \pm 1.55\%$), followed by coconut fiber (T5) ($31.00 \pm 1.00\%$) and banana peel (T7) ($29.55 \pm 0.80\%$), whereas potato peel (T1) and pineapple peel (T3) exhibited the lowest lignin contents. Because lignin forms a rigid three-dimensional matrix surrounding cellulose and hemicellulose, high lignin concentrations reduce enzymatic accessibility and microbial degradation, thereby decreasing biomass biodegradability (Lin & Dence, 1992; Guzmán Loayza, 2020). Comparable results have been reported by Brózda et al. (2026) and Bele et al. (2026), who demonstrated that lignin-rich biomasses generally show lower methane yields and require pretreatment strategies to improve carbohydrate accessibility.

Marked differences were also observed in extractive contents, with cocoa husk ($23.03 \pm 1.14\%$) and banana peel ($22.90 \pm 1.55\%$) presenting the highest concentrations, whereas corn cob contained only $3.57 \pm 0.89\%$. Extractives include soluble compounds such as waxes, oils, pigments, tannins, and phenolic substances that may influence biomass processing and microbial activity during biological conversion (Guzmán Loayza, 2020). According to Forero-Sandoval et al. (2026), tropical agro-industrial residues frequently accumulate considerable amounts of secondary metabolites, which may either inhibit or promote subsequent conversion processes depending on their chemical composition.

The statistical analysis presented in Table 2 confirmed that residue type significantly affected

cellulose, hemicellulose, lignin, and extractive contents ($p < 0.001$), demonstrating the existence of substantial structural heterogeneity among the evaluated biomasses. Lignin exhibited the highest F-value, indicating that this component represented the most discriminating structural characteristic among residues. Furthermore, the relatively low coefficients of variation reported in Table 1 (3.17–9.55%) indicate good analytical precision and high repeatability of the experimental procedures, supporting the reliability of the lignocellulosic characterization.

The highly significant statistical differentiation observed among treatments reinforces the importance of detailed physicochemical characterization before selecting biomass feedstocks for renewable energy applications. According to Blasi et al. (2023), biomass conversion efficiency is largely determined by the relative proportions of structural carbohydrates and lignin. Likewise, Bele et al. (2026) emphasized that residues combining high cellulose and hemicellulose contents with moderate lignin concentrations generally present greater technological potential for biomass valorization. Under this context, potato peel (T1), pineapple peel (T3), and corn cob (T4) exhibited the most favorable compositional profiles, whereas cocoa husk (T6) and coconut fiber (T5) may require pretreatment to overcome their greater structural recalcitrance.

The Tukey HSD analysis presented in Figure 2 further confirmed the existence of statistically distinct cellulose groups among treatments. Potato peel formed an independent group with the highest cellulose concentration, coffee husk, pineapple peel, and corn cob constituted an intermediate group, whereas cocoa husk and banana peel formed the lowest statistical group. This pattern highlights the considerable structural heterogeneity of tropical agro-industrial residues from Tarma and suggests that their technological performance in future bioenergy applications will depend largely on their intrinsic lignocellulosic composition. Future research should expand the present findings by evaluating the biochemical and energetic performance of the agro-industrial residues identified as the most promising feedstocks. In particular, residues with high cellulose and hemicellulose contents, such as potato peel and corn cob, should be assessed through anaerobic digestion experiments to determine methane yield and biodegradability under different operating conditions. Likewise, future studies should investigate the effects of biological, chemical, and physicochemical pretreatments on lignin removal and carbohydrate accessibility, especially for highly recalcitrant biomasses such as cocoa husk and coconut fiber. Integrating lignocellulosic characterization with biochemical conversion assays, life cycle assessment, and techno-economic analysis would provide a more comprehensive framework for selecting agro-industrial residues suitable for sustainable bioenergy production and circular bioeconomy development in the Peruvian Andes.

CONCLUSIONS

The present study demonstrated significant differences in the lignocellulosic composition of tropical agro-industrial residues generated in Tarma, Peru, confirming the strong influence of biomass type on cellulose, hemicellulose, lignin, and extractive contents. Potato peel, corn cob, pineapple peel, and coffee husk exhibited the most favorable structural profiles due to their elevated structural carbohydrate concentrations and comparatively lower lignin contents, whereas cocoa husk and coconut fiber showed high lignin levels associated with greater structural recalcitrance. Likewise, banana peel and cocoa husk presented the highest extractive fractions, indicating important compositional variability among the evaluated residues.

The statistical analyses confirmed highly significant differences among treatments for all evaluated variables, demonstrating the existence of differentiated lignocellulosic profiles among tropical agro-industrial biomasses. The results suggest that residues with high cellulose and hemicellulose contents combined with moderate lignin concentrations may possess greater potential for future sustainable bioenergy applications due to their potentially improved biodegradability and carbohydrate accessibility. Overall, the study provides relevant baseline information for biomass valorization strategies and future renewable energy research involving agro-industrial residues from the central Peruvian Andes.

REFERENCES

- Bele, V., Hassini, H., Rizzi, A., & Achouri, I. E. (2026). From biomass residues to syngas: Intensified biogas upgrading through nickel hydroxyapatite-catalysed dry reforming. *Biomass and Bioenergy*, 210, 108989. <https://doi.org/10.1016/j.biombioe.2026.108989>
- Blasi, A., Verardi, A., Lopresto, C. G., Siciliano, S., & Sangiorgio, P. (2023). Lignocellulosic agricultural waste valorization to obtain valuable products: An overview. *Recycling*, 8(4), 61. <https://doi.org/10.3390/recycling8040061>
- Brózda, A., Kazimierowicz, J., & Dębowski, M. (2026). Seasonal changes in biomass composition of giant miscanthus (*Miscanthus × giganteus*) and their impact on methane fermentation performance. *Energies*, 19(7), 1669. <https://doi.org/10.3390/en19071669>
- Forero-Sandoval, I. Y., Canché-Escamilla, G., & Duarte-Aranda, S. (2026). Estimación del potencial de residuos agroindustriales en la región sureste de México y su valorización. *Revista Internacional de Contaminación Ambiental*, 42, 111–127. <https://doi.org/10.20937/RICA.55675>
- Guzmán Loayza, D. (2020). Guía de prácticas de química forestal. Universidad Nacional Agraria La Molina, Facultad de Ciencias Forestales, Departamento de Industrias Forestales.
- Karthikeyan, P. K., Grbic, J., Iza, F., Bandulasena, H. C. H., & Radu, T. (2025). Microbubble plasma-assisted pretreatment of lignocellulosic biomass for biogas generation. *Waste and Biomass Valorization*, 16, 3987–4008. <https://doi.org/10.1007/s12649-025-03015-7>
- Lin, S. Y., & Dence, C. W. (1992). *Methods in lignin chemistry*. Springer-Verlag.
- Sánchez-Orozco, R., Balderas-Hernández, P., Roa-Morales, G., Ureña-Núñez, F., Orozco-Villafuerte, J., Lugo-Lugo, V., Flores-Ramírez, N., Barrera-Díaz, C. E., & Cajero-Vázquez, P. (2014). Characterization of lignocellulosic fruit waste as an alternative feedstock for bioethanol production. *BioResources*, 9(2), 1873–1885.
- Schultz, J., Scherzinger, M., Steinbrecher, T., Isci, A., & Kaltschmitt, M. (2025). Influence of vapo-thermal and hydrothermal pre-treatment on anaerobic degradability of lignocellulosic biomass. *Bioresource Technology*, 426, 132329. <https://doi.org/10.1016/j.biortech.2025.132329>
- Sosa, J. A., Laines, J. R., García, D. S., Hernández, R., Zappi, M., & Espinosa de los Monteros, A. E. (2023). Activated carbon: A review of residual precursors, synthesis processes, characterization techniques, and applications in the improvement of biogas. *Environmental Engineering Research*, 28(3), 220100. <https://doi.org/10.4491/eer.2022.100>
- Technical Association of the Pulp and Paper Industry. (1997). TAPPI T204 cm-97: Solvent extractives of wood and pulp. TAPPI Press.
- Technical Association of the Pulp and Paper Industry. (1998). TAPPI T222 om-98: Acid-insoluble lignin in wood and pulp. TAPPI Press.