

Exploring the biorefinery potential of *Acrocomia aculeata*: A native Mexican palm for sustainable resource valorization

Fidel Alejandro Aguilar-Aguilar

Instituto Politecnico Nacional <https://orcid.org/0000-0003-3021-1186>

Violeta Y. Mena-Cervantes

Instituto Politecnico Nacional <https://orcid.org/0000-0002-4403-8671>

Montserrat García-Solares

Instituto Politecnico Nacional

Raúl Hernández-Altamirano (✉ raulhaltamirano@gmail.com)

Instituto Politecnico Nacional <https://orcid.org/0000-0001-6685-2335>

Research Article

Keywords: *Acrocomia aculeata*, biorefinery, valorization, potential

Posted Date: June 29th, 2023

DOI: <https://doi.org/10.21203/rs.3.rs-3059939/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Version of Record: A version of this preprint was published at Waste and Biomass Valorization on January 11th, 2024. See the published version at <https://doi.org/10.1007/s12649-023-02385-0>.

Abstract

The coyol (*Acrocomia aculeata*) is a native plant of Mexico that holds great potential as a crop due to its high fruit yield and relatively unexplored. This study aims to contribute significant insights into the physicochemical properties, macro, and micro composition of two Mexican coyol (*Acrocomia aculeata*) varieties from Veracruz and Chiapas and their potential integration into biorefinery processes. The results of this study indicate that the *Acrocomia aculeata* (Chiapas) crop could potentially yield approximately 6.49 to 23.09 tons per hectare of fruits. The kernel and mesocarp of the coyol fruit show promise as viable alternatives, with high yields of 5.81–11.34 tons/ha and 0.89–1.75 tons/ha, respectively, and an oil yield of 11.51 net tons/ha. Furthermore, the epicarp and mesocarp could perform as significant reserves of sustainable energy, containing substantial amounts of lignocellulosic material ranging from 2.58–5.05 tons/ha and 3.51–6.85 tons/ha, respectively. Consequently, the coyol fruit, including its mesocarp, kernel, epicarp, and kernel shell, presents an extraordinary potential as an energy source, for biofuel production, food-related activities, and as a chemical resource within the framework of the biorefinery concept. Continued exploration of this species in Mexico and America is encouraged due to its promising and sustainable nature, which can yield numerous long-term benefits.

1 Introduction

The unsustainable utilization of natural resources has prompted the search for materials that can meet our needs in a sustainable manner. The global concerns surrounding climate change, reduction of greenhouse gas emissions, food security, affordable energy, rural development, and reindustrialization have led to a transition towards a bio-based economy [1–3]. The bio-based economy plays a crucial role in achieving sustainability by enabling efficient use of resources, particularly feedstocks. Through the integration of biomass in biorefinery processes, it becomes possible to generate products and services that fulfill societal needs [2].

Currently, there are industrial-scale biorefineries worldwide, as well as those in the developmental stage. These biorefineries can be utilized for the production of biofuels or industrial chemicals. They involve a range of processes, including chemical and thermal processes, and employ various raw material sources, ensuring the complete utilization of biomass [1, 4]. When constructing biorefineries, it is essential to consider environmental sustainability, economic viability, and social responsibility throughout the entire value chain, from raw material acquisition to transformation, production of bioproducts, and final disposal. This comprehensive life cycle analysis allows for effective competition with conventional refineries [5, 6].

In the biorefining process, raw materials can be separated into carbohydrates, lipids, proteins, and fibers. These components can then undergo physical, thermal, chemical, or biochemical treatments to obtain bioproducts or biofuels. Consequently, it is anticipated that the demand for biomass will increase in the short to medium term due to the growing demand for bioproducts. To adequately meet this demand for raw materials (biomass), it is crucial to identify and leverage bio-based production systems that provide biomass, particularly native species in each region. By promoting sustainable agricultural practices and exploring new species, we can ensure a sufficient supply of raw materials for biorefineries.

Currently, around the world, there are biorefineries on an industrial scale or biorefineries that are under development, that can be coupled for the generation of biofuels or chemical products of industrial interest [5, 7]; biorefineries that involve multiple processes (chemical and thermal processes); or biorefineries that use different sources of raw materials, where all the biomass is fully utilized. In the construction of biorefineries, in their value

chain, environmental sustainability, economic and social responsibility must be considered, with a life cycle analysis from obtaining the raw material, transformation, bioproducts, and their final disposal. This will make it possible to compete with conventional refineries [8].

The selection of plant species with the potential to generate valuable products while minimizing waste is crucial [2]. Native species offer promising alternatives as they possess advantages such as easy adaptability, no change in land use, and the potential to contribute to a social and solidarity-based economy, especially in developing countries. The coyol palm (*Acrocomia aculeata*) is a native species found in various countries across the American continent, ranging from South America to southeastern and central Mexico. It goes by numerous colloquial names, such as Macaúba in Brazil, Palma espinosa in Central America, and coyol, coyul, or cocoyol in Mexico [9–11]. The fruit of this palm has garnered significant interest worldwide due to its potential as a raw material in biorefinery processes. *Acrocomia aculeata* boasts a high fruit yield and a substantial oil content, making it suitable for the production of valuable products [10]. However, there is considerable variation among different varieties of *Acrocomia aculeata* in terms of fruit yield and physicochemical properties. Therefore, identifying the most suitable variety of *Acrocomia aculeata* becomes essential to address agricultural challenges, achieving higher yields, enhancing resistance to pests and climate change, and reducing the environmental impact of its cultivation [9, 12].

In this context, for the successful operation of an industrial-scale biorefinery and to meet the demand for products, careful consideration must be given to logistics, raw material availability, and fruit yield per hectare. Furthermore, this study aims to contribute significant insights into the physicochemical properties, macro, and micro composition of two Mexican coyol (*Acrocomia aculeata*) varieties from Veracruz and Chiapas and their potential integration into biorefinery processes. The results of this study will provide valuable knowledge and guidance for the development of effective strategies and processes that maximize the utilization and value creation of coyol, ultimately contributing to the advancement of sustainable and environmentally friendly practices in the biorefinery industry

2 Material and methods

2.1 Sample collection

In this study, two varieties of *Acrocomia aculeata* palm fruits were analyzed: the first variety was sourced from the Sierra Papanteca in the state of Veracruz (referred to as Coyol Veracruz), and the second variety was obtained from the Sierra Mariscal region in the state of Chiapas (referred to as Coyol Chiapas). For the study, a total of 5kg of ripe fruits were collected in January of the current year and stored at 4°C to preserve their characteristics until analysis. All reagents and solvents used in this study were of reagent grade. The reagents utilized for gas chromatography analysis had a minimum purity level of 99%.

2.2 Physicochemical characterization

At the Laboratorio Nacional de Desarrollo y Aseguramiento de la Calidad de Biocombustibles (LaNDACBio), the processing of coyol from Chiapas and Veracruz was conducted. The entire fruit was separated into its various parts, including the epicarp, mesocarp, kernel shell, and kernel. It is important to note that all analytical characterizations were performed in triplicate to ensure accuracy and reliability of the results.

2.3 Moisture Content

To determine the moisture content (%), 20g samples of the epicarp, mesocarp, kernel shell, and kernel were weighed in separate containers. These samples were then placed in a Memmert® drying oven set at $105 \pm 2^{\circ}\text{C}$ for a duration of 24 hours. After the drying period, the containers with the dried biomass were weighed again [13].

The moisture content (%) of the coyol parts from Chiapas and Veracruz was calculated using the following formula:

$$MC (\%) = \frac{\text{wetweight (g)} - \text{dryweight (g)}}{\text{wetweight (g)}} \times 100$$

2.4 Oil Content

To calculate the oil content of the mesocarp and kernel of the coyol from Chiapas and Veracruz, the following procedure was followed; weigh 20g of dry biomass and add it to extraction thimbles. Utilize the Soxhlet extraction method, recirculating for 8 hours at approximately $70 \pm 5^{\circ}\text{C}$, using hexane as the solvent. After the extraction period, separate the hexane from the oil using a rotary rotator from the Buchi® brand. Once the hexane has been separated, perform the necessary calculations to determine the oil content of the mesocarp and kernel of the coyol from Chiapas and Veracruz, employing the following formula:

$$\text{Oilcontent (\%)} = \frac{\text{Extractedoil (g)}}{\text{Mass (g)}} \times 100$$

2.5 Fatty acid profile

The identification and quantification of profile FAME (Fatty acid methyl ester) was carried out in a Clarus 580 chromatograph (Perkin Elmer USA) equipped with a flame ionization detector (FID), the column was Elite-5 (Crossbond 5%, diphenyl-95% dimethyl polysiloxane), 30 m long, 0.25 mm internal diameter, and 0.25 μm (Perkin Elmer E.U.). The equipment conditions were oven temperature: 100°C (3 min hold), $20^{\circ}\text{C min}^{-1}$ up to 280°C (8 min hold), inlet and detector temperature 260°C , split/spitless inlet mode with split injection, the ratio of 1:5, the carrier gas was nitrogen at 30 psi. Analyzes were performed in duplicate. For the identification of profile FAME, the samples were diluted with 98.5% HPLC grade hexane before performing the chromatographic analysis. FAME quantification was done by interpolation with a calibration curve for each analyte [14, 15, 16].

2.6 Fourier transform infrared (FTIR) analysis

The infrared spectra analysis was conducted using a Perkin-Elmer model Frontier FTIR spectrometer equipped with a diamond attenuated total reflectance (ATR) accessory, following the method described in reference [17]. The spectral data was collected by performing 32 scans with a resolution of 4 cm^{-1} over a range of $4000\text{--}600 \text{ cm}^{-1}$. To prepare the coyol palm (Chiapas and Veracruz) samples for analysis, the components were first crushed and then dried at 80°C for 8 hours. Subsequently, the dried samples were subjected to FTIR spectroscopy to obtain the spectral information and analyze the chemical composition.

2.7 Thermogravimetric analysis (TGA)

The TGA (Thermogravimetric Analysis) measurements were conducted using a Perkin-Elmer STA6000 instrument. A total of 30 milligrams of the sample (including epicarp, mesocarp, kernel shell, and kernel of coyol from Chiapas and Veracruz) was placed into a container. The TGA analysis was performed under a nitrogen atmosphere at a

flow rate of $10 \text{ ml} \cdot \text{min}^{-1}$, with the temperature ranging from 30 to 800°C . The heating rate used was $10^{\circ}\text{C} \cdot \text{min}^{-1}$. Before the TGA analysis, the samples were preheated at 105°C and kept at isothermal conditions for four minutes to eliminate any moisture content [17]. The dry samples were then subjected to the TGA process, and the data was continuously processed using the Pyris software (version 13.3.1.0014) provided by Perkin-Elmer. In addition to the TGA analysis, a derived thermogravimetric (DTG) analysis was performed. This analysis helps identify the temperature at which the maximum mass loss of the biomass occurs, providing valuable information about the thermal behavior of the samples [17].

3 Results and discussion

3.1 Description of coyol fruit

Acrocomia aculeata, also known as the coyol palm, is a perennial and fruitful palm native to rainforests. It can be found growing from South America to Mexico and exhibits exceptional resistance to drought, frost, and acidic soils [8, 11, 18]. In Mexico, coyol palms are found in various states including the Yucatan peninsula, Veracruz, Chiapas, Tabasco, Guerrero, and Sinaloa [10]. In Mexico, *Acrocomia aculeata* is cultivated for local consumption, particularly for the production of taberna, a fermented drink made from palm bark, and for the manufacturing of sweets from the fruit pulp [19]. However, research centers in Mexico have reported *Acrocomia aculeata* as one of the least studied species, and there is no record of its industrialization, suggesting an untapped opportunity for the coyol industry within the biorefinery concept [20].

Under natural conditions, coyol palms take up to 5 years to germinate. The productive period begins around the fourth or fifth year after germination and can last up to 100 years. Fruits reach maturity approximately 12 months after fertilization, typically between the months of January and May [10, 11]. Research conducted by Zardón [21] and Díaz-Fuentes et al. [10] indicates that coyol palms have a population density ranging from 150 to 200 palms per hectare. Each palm can produce 6 to 8 clusters, with each cluster yielding 250 to 500 fruits and 9.6 to 25 tons per hectare of coyol fruits [9–11]. Additionally, Berton et al. [22] suggest that the yield per hectare of coyol fruit could be further increased through the selection of optimal genotypes, fertilization, and proper palm management practices.

The performance and characteristics of coyol fruits vary depending on the variety. Therefore, this study evaluated two different varieties: I) Coyol Veracruz from the Sierra Papanteca region in the state of Veracruz and II) Coyol Chiapas from the Sierra Mariscal region in the state of Chiapas. Both varieties exhibit similar fruit morphology, with a hemispherical shape (Fig. 1). Coyol Chiapas measures approximately $4.16 \pm 0.52 \text{ cm}$ in height and $4.10 \pm 0.13 \text{ cm}$ in width, with an average wet weight of 28.8 g per fruit. On the other hand, Coyol Veracruz measures around $3.52 \pm 0.22 \text{ cm}$ in height and $3.79 \pm 0.29 \text{ cm}$ in width, with an approximate weight of 20.99 g per fruit. Therefore, Coyol Chiapas is larger and weighs approximately 23% more than Coyol Veracruz, as shown in Table 1.

The wet fruit of coyol is composed of different parts: the epicarp, mesocarp (pulp), kernel shell, and kernel. The epicarp makes up around 20.21–23.64% of the wet fruit, while the mesocarp accounts for 45.37–43.26%. The kernel shell constitutes approximately 27.43–24.93%, and the kernel itself represents 6.98–8.17% of the wet fruit. These proportions are illustrated in Fig. 1 and detailed in Table 1.

In terms of dry weight, the coyol Chiapas has an approximate weight of 12.83g (44.5% dry basis), while the coyol Veracruz has a dry weight of 8.20g (39%). Both fruits have a moisture content of over 50%, as indicated in Table 1.

Additionally, Table 1 shows that the mesocarp of the coyol Chiapas contains approximately 11.38% (w/w) oil, while the kernel contains 40.89% (w/w) oil. On the other hand, the coyol Veracruz has 9.80% (w/w) oil in the mesocarp and 34.02% (w/w) oil in the kernel. These results align with the results obtained in studies conducted by Vargas-Carpintero et al. [8], César, et al. [9], and Díaz-Fuentes et al. [10].

When comparing the coyol fruits from Veracruz and Chiapas, despite belonging to the same variety, it is important to consider that factors such as climate, altitude, soil type, geographical location, and management practices can influence the fruit weight and its content. Based on these factors, it can be inferred that Coyol Chiapas has the potential to generate a higher yield of fruits per hectare and a higher oil yield. Therefore, further in-depth agronomic studies under the biorefinery concept are warranted to explore the full potential of Coyol Chiapas.

Table 1
Physical characterization of Coyol Fruit (*Acrocomia Aculeata*) from Chiapas and Veracruz Varieties.

<i>Acrocomia aculeata</i> Chiapas					<i>Acrocomia aculeata</i> Veracruz			
	Wet (%)	Dry (%)	Oil (%)	Heat value (MJ/kg)	Wet (%)	Dry (%)	Oil (%)	Heat Value (MJ/kg)
Epicarp	20.21± 0.89	16.75± 0.10	-	20.41	23.64± 0.64	25.47±0.08	-	18.31
Mesocarp	45.37± 0.74	64.33± 0.31	11.38± 1.23	18.11	43.26± 0.94	23.54±0.17	9.80±1.56	16.92
Kernel shell	27.43± 0.48	10.80± 0.33	-	21.305	24.93± 0.65	47.12±0.33	-	19.66
Kernel	6.98± 0.35	8.12± 0.57	40.89± 2.42	22.48	8.17± 0.10	3.87±0.04	34.02±3.12	20.52
Fruit (g)	28.86± 2.45	12.83± 1.56	-	-	20.99± 1.33	8.20±0.95	-	-

3.2 Fatty acid composition of oil

Table 2 provides data on the fatty acid composition of coyol Chiapas and Veracruz kernel oil, revealing the presence of five main fatty acids and their respective concentrations. The predominant fatty acids identified are capric acid (30–34%), lauric acid (25–26%), myristoleic acid (18–22%), palmitoleic acid (16–17%), and oleic acid (7–9%). Particularly, coyol Chiapas exhibits a higher concentration of capric acid (34.73%) and 6.36% of oleic acid compared to coyol Veracruz.

These purified fatty acids hold significant potential for industrial and biotechnological applications. According to Mancini et al., capric acid has been found in some fruits such as African palm, coconut, and coyol [23]. For instance, capric acid is naturally present in coconut oil (around 10%) and African palm kernel oil (approximately 4%). The coyol kernel, as demonstrated in this study, contains a higher concentration of capric acid (30–34%). Capric acid is known for its beneficial properties as a fatty acid ester for controlling bacteria in humans [24].

Lauric acid, another prominent fatty acid, is primarily derived from plants such as coconut, palm, and coyol kernel oil (as indicated in Table 2). It is commonly utilized to provide consistency to cosmetic products and has also been evaluated for its effects on fermentation and milk production in dairy cows [25, 26].

The study also reveals the presence of palmitoleic acid (14–16%). According to Tang [18], only a few natural sources contain high concentrations of palmitoleic acid, such as fish oil (7%) and macadamia oil (30%).

Table 2
Comparative analysis of Fatty Acid Composition in Coyol Kernel from Chiapas and Veracruz Varieties.

		Coyol Veracruz		Coyol Chiapas
FAME*	Typical name	Average (%)		
Methyl Decanoate	Capric acid	C10:0	30.64 ±0.53	34.73 ±0.21
Methyl Laurate	Lauric acid	C12:0	26.85 ±0.58	25.67 ±0.09
Myristoleic acid methyl ester	Myristoleic acid	C14:1	22.71 ±0.12	18.48 ±0.16
Methyl palmitoleate	Palmitoleic acid	C16:1	16.57 ±0.28	14.76 ±0.15
cis- 9- oleic acid methyl ester	Oleic acid	C18:1	3.23 ±0.11	6.36 ±0.11
*Fatty Acid Methyl Ester				

Indeed, variations in the fatty acids and oil yield of coyol oil (*Acrocomia aculeata*) have been observed in this study as well as in studies conducted by César et al. [9], and Díaz-Fuentes et al. [10]. It is important to note that the oil content, fatty acid ester types, and bromatological composition of the fruit and its components depend on the maturity stage at which the fruits were harvested and characterized. According to Zavala- Hernández [28], fruit characteristics differ across three developmental phases: histodifferentiation, reserve accumulation, and drying. Additionally, most fruits exhibit varying degrees of physiological maturity, which can be challenging and impractical to measure directly in the field. Therefore, it is advisable to associate physiological maturity with other physical changes in the fruit, such as color and firmness.

Regarding the coyol kernel, its high oil yield, saturated (~ 58%) and unsaturated (~ 42%) fatty acids, and other characteristics make it highly suitable for the production of biofuels, particularly biodiesel, biokerosene, and green diesel, as well as chemical products [9, 10].

3.3 Relation between functional groups with FTIR

FTIR (Fourier Transform Infrared Spectroscopy) is a valuable analytical technique used to determine the molecular structure of compounds by analyzing their vibrational bands corresponding to specific functional groups such as C-N, C-H, C = O, and O-H [23]. In Fig. 2, the FTIR spectra of the epicarp, mesocarp (pulp), kernel shell, and kernel of both coyol Chiapas and coyol Veracruz samples are depicted. This analysis provides information about the wavelengths and indicates the presence of functional groups in the coyol samples. The FTIR spectra shown in

Fig. 2 consist of wavelength (cm^{-1}) on the x-axis and transmittance (%) on the y-axis. The presence of more than six peaks in the spectra indicates that the samples are chemically complex and composed of various compounds with different functional groups. FTIR analysis helps in identifying and characterizing these functional groups present in the different components of the coyol fruit.

In Fig. 2, the FTIR spectra analysis reveals specific functional groups present in the coyol Chiapas and coyol Veracruz samples. The C-H stretching bands are observed at wavelengths $2970 - 2950 \text{ cm}^{-1}$ and $2860 - 2880 \text{ cm}^{-1}$, indicating the presence of alkane functional groups. These peaks have a high intensity, suggesting a high concentration of alkane compounds in the samples. The largest and strongest peak observed at 1747 cm^{-1} in the kernel and mesocarp of both coyol samples indicates the presence of the C = O stretching carbonyl functional group [29]. This corresponds to the results in Table 1, where the mesocarp and endosperm were found to contain significant amounts of fatty acids (9–11% and 34–41%, respectively). The presence of this peak suggests the presence of long-chain fatty acid esters in the samples.

Furthermore, the presence of unsaturation fatty acids is indicated by the wavelength at 1642 cm^{-1} , which corresponds to the stretch of C = C olefinic bonds [30]. This confirms the presence of unsaturated fatty acids in the mesocarp and coyol kernel oil of both Chiapas and Veracruz samples.

The bands observed in the range of $1467 - 1380 \text{ cm}^{-1}$ correspond to the different bending modes of methylene and methyl functional groups in oils. These bands indicate the presence of these functional groups in the samples [31, 32]. Lastly, the wavelength range of $1700 - 1600 \text{ cm}^{-1}$ shows the presence of functional groups related to C = O, C-N, and N-H stretching, which are characteristic of the amide I band of proteins. This suggests the presence of protein functional groups in the samples. Overall, the FTIR spectra analysis provides valuable information about the functional groups present in the coyol Chiapas and coyol Veracruz samples, supporting the characterization of these components and their potential applications [33]. The FTIR spectra analysis of the coyol Chiapas and coyol Veracruz mesocarp (Fig. 2) reveals important functional groups present in these components. The bands observed at the wavelength range of $3550 - 3200 \text{ cm}^{-1}$ represent the stretching functional group -OH, specifically in alcoholic compounds [33]. These bands are broad and weak in intensity, indicating the presence of -OH groups in the mesocarp of both coyol samples. The bands between $1420 - 1350 \text{ cm}^{-1}$ correspond to the C-O and C-C stretching bonds, which are characteristic of carbohydrates. These peaks indicate the presence of carbohydrates in the mesocarp of Coyol Chiapas and Veracruz. Different peaks and bands are observed in the FTIR spectra of the epicarp and kernel shell at various wavelengths. This suggests the presence of a variety of polysaccharides in these components. In the wavelength range of $3800 - 2800 \text{ cm}^{-1}$, peaks related to the stretching of C-H and O-H functional groups are observed, which are present in lignin, hemicellulose, and cellulose. The wavelengths between 1600 and 1510 cm^{-1} show peaks assigned to the vibration of lignin aromatic rings and the presence of extractive compounds. The peak at $\sim 1730 \text{ cm}^{-1}$ corresponds to the C = O bond stretch in hemicellulose, while the peaks between $1446 - 1424 \text{ cm}^{-1}$ and 1380 cm^{-1} are assigned to functional groups of cellulose. In the kernel shell, a characteristic peak at 1508 cm^{-1} is observed, representing aromatic skeletal vibrations [34–36]. The wavelength range of $1372 - 1380 \text{ cm}^{-1}$ corresponds to the vibrations of O-H and C-H bonds, which are present in carbohydrates and lignin [37]. Additionally, peaks at 1036 cm^{-1} and 1032 cm^{-1} in the carbohydrate region indicate contributions from lignin bonds [13].

Based on the FTIR spectra analysis, it can be inferred that the endocarp and kernel shell of coyol Chiapas and coyol Veracruz are composed of lignocellulosic material. These components have significant potential for various

biotechnological applications within a biorefinery context.

3.4 Thermal stability of Coyol Chiapas and Veracruz

Biomass characterization is crucial for understanding its thermal behavior and degradation patterns, especially in the context of energy processes. The TGA/DTG method is commonly employed in studies involving various biomass sources, including organic wastes, lignocellulosic materials, energy crops, and biofuels [38].

The composition of biomass plays a significant role in its utilization, and thermal decomposition analysis is essential for accurately determining the characteristics and cost-effectiveness of different biomass sources. In this study, the TGA/DTG method was employed to analyze the thermal stability of the endocarp, mesocarp, kernel shell, and kernel of Coyol Chiapas and Veracruz, as shown in Fig. 3. The coyol components were heated at a rate of 10°C/min.

The results indicate that biomass degradation occurs in distinct phases. In the first phase (Phase I), which takes place within the temperature range of 26 to 260°C, the evaporation of water (dehydration) and light volatile materials occur, corresponding to the pyrolysis process [38, 39]. It is likely that below 260°C, the intramolecular water and low molecular weight materials such as organic acids, terpenes, and pigments are lost from the coyol samples [13, 39]. A study conducted by Yeo et al. [40] demonstrated that weight loss below 250°C can be attributed to the loss of water and light carbon from hemicellulose and cellulose. During this temperature range, cleavage of the lateral chains of hemicellulose is observed, while lignin remains relatively stable. Some polysaccharides undergo degradation, and lignin fusion may occur during this stage. Figure 3 illustrates the initial moisture loss, which ranged from 1.73 to 7.34%, with similar behavior observed for coyol from Chiapas and Veracruz, but with a greater weight loss in the kernel component.

During the second phase (Phase II) of the biomass degradation process, which occurs after 260°C and extends until approximately 580°C, a significant loss of mass is observed. The epicarp experiences a mass loss of around 64%, the mesocarp about 69%, the kernel shell between 67% and 74%, and the kernel approximately 72%, as shown in Fig. 3. Within this devolatilization process (Phase II), two peaks (DTG) can be observed for the epicarp, mesocarp, and endocarp. The first peak occurs between 240°C and 350°C, with the mesocarp exhibiting the largest peak and a maximum mass loss rate of 7.22%/min. The epicarp and kernel shell show maximum mass loss rates of 5.45%/min and 4.98%/min, respectively (Fig. 3). It is likely that during the first peak, around 280°C, the mesocarp experiences a mass loss of simple sugars (carbohydrates), while the epicarp and kernel shell undergo a mass loss of hemicellulose (Fig. 3). Yeo et al. [40] have reported decarboxylation and decarboxylation of hemicellulose occurring up to a temperature of 330°C. Fang et al., [41] have demonstrated that the decomposition of simple sugars and hemicellulose occurs below 300°C, whereas cellulose undergoes transglycosylation, resulting in the formation of oligosaccharides and levoglucosan [40]. In the second peak of the DTG (up to 350°C), the kernel shell exhibits a maximum mass loss rate of 5.84%/min, while the mesocarp and epicarp show maximum mass loss rates of 5.99%/min and 4.55%/min, respectively (as depicted in Fig. 3). Yeo et al. [40] have demonstrated that hemicellulose and cellulose decompose between 225 to 325°C and 325 to 375°C, respectively, both decomposing much faster than lignin, as lignin remains stable within that temperature range [41]. During this second stage, a significant fraction of lignin degrades through the cleavage of β -O-4 bonds [40]. Notably, in the DTG of the coyol kernel (Chiapas and Veracruz), the maximum mass loss occurs at a rate of 8.11%/min between 350 to 580°C, with a greater mass loss of 73%. This mass loss corresponds to the triglycerides present in the coyol kernel (Chiapas and Veracruz), as shown in Fig. 3. These TGA/DTG results align

with the high oil yields obtained from the Coyol (Chiapas and Veracruz) samples, as presented in Table 1. Del Río et al. [42] have mentioned that the decomposition of unsaturated triglycerides occurs between 350 to 480°C, leading to the generation of volatile compounds, and the residues disappear after reaching 600°C.

In the third phase (Phase III), which is the combustion phase (as shown in Fig. 3), weight loss occurs between 580°C to 680°C. The kernel shell exhibits the highest weight loss rate, with a maximum mass loss of 11.655%/min at a temperature of approximately 572°C. The epicarp, mesocarp, and kernel show weight loss rates of 3.8%/min at around 580°C. Figure 3 illustrates that at approximately 620°C, the epicarp experiences a weight loss of approximately 29%, the mesocarp around 19%, the kernel shell between 22–28%, and the kernel about 13%. As depicted in Fig. 3, during this third phase, significant weight loss is observed for the epicarp and the kernel shell, which could be attributed to the degradation of lignin. Chin et al. [43] mention that due to the complex structure of lignin, it is very difficult to degrade, as it contains numerous methoxy, hydroxyl, and ether groups.

These results highlight the complex thermal decomposition behavior of coyol components, with different biomass fractions undergoing distinct chemical transformations and mass losses at specific temperature ranges.

3.5 Industrial valorization of the *Acrocomia Aculeata*

Mexico possesses a rich diversity of native species and energy crops that hold significant potential for utilization within the biorefinery concept, taking advantage of the country's geographical location. Studies conducted by Morelos Gómez and Valdez-Vazquez et al. [44] Morelos Gómez and Valdez-Vazquez et al., [45] estimate that Mexico has the capacity to generate between 2.63 and 3.77 PJ (petajoules) of energy per year from residual biomass and energy crops. *Acrocomia aculeata*, commonly known as coyol, is one such species that has received limited research attention but offers a viable alternative for the production of food, chemicals, and biofuels within the biorefinery framework [9, 20].

Researchers have demonstrated that coyol cultivation holds significant potential for development in Mexico and across the American continent [46]. Studies by Zardón [21] and Díaz-Fuentes et al. [10] have revealed that coyol palms have a population density ranging from approximately 150 to 200 palms per hectare. Each palm produces around 6 to 8 clusters, with each cluster containing 250 to 500 fruits [9, 11]. Based on the results of this study (Table 1), crop yields could range from approximately 6.49 to 23.09 tons per hectare (Ton/Ha).

Indeed, numerous studies have focused on exploring various plant species with high fruit or seed yields for integration into biorefineries, particularly for the production of biofuels such as biodiesel or ethanol. Coyol, with its yield range of 6.49 to 23.09 tons per hectare (Ton/Ha), exhibits a higher yield compared to plants like *Jatropha curcas* and *Ricinus communis*. Furthermore, coyol yields are comparable to other high-yielding crops such as *Elaeis guineensis* (oil palm) with yields of 12.8 to 25 tons per hectare (Ton/Ha) and Sorghum bicolor with yields of 18.9 to 30 tons per hectare (Ton/Ha) (Table 3).

These results indicate that coyol possesses significant potential as a biomass feedstock for further investigation and development within the biorefinery concept. Its high yield and compatibility with other biofuel feedstocks make Coyol a promising candidate for sustainable bioenergy production.

Table 3
Comparative biomass yields for biorefinery potential.

Scientific Name	Yield (Ton/Ha)	Oil yield (Ton/Ha)	Reference
<i>Ricinus communis</i>	1.8- 3	1.188	[47]
<i>Jatropha curcas</i>	2–3	0.590–0.760	[48]
<i>Acrocomia aculeata</i>	6.49–23.09	115.1	This study
<i>Elaeis guineensis</i>	15–23	12	[49]

The study highlights that *Acrocomia aculeata* (coyol) exhibits great potential as an energy source, biofuel feedstock, food ingredient, and chemical product, as depicted in Fig. 4 [51]. This is attributed to its high content of carbohydrates, oils, proteins, and lignocellulosic material, as discussed earlier. Biodiesel production, typically derived from various edible vegetable oils [52], waste cooking oils, inedible vegetable oils, and microalgae, faces challenges related to the cost of raw materials [53, 54]. The demand for edible vegetable oils in the market and their competition with the food industry can significantly increase the feedstock cost by 60 to 70% [55]. However, the coyol kernel and mesocarp present a viable alternative due to their high yields of 5.81 to 1134 tons per hectare (Ton/Ha) and 0.89 to 1.75 Ton/Ha, respectively, as shown in Fig. 4. The coyol kernel can produce up to 10.22 tons of oil per hectare (Ton/Ha), while the mesocarp can yield 1.29 Ton/Ha. This means that approximately 11.51 net tons of coyol oil per hectare can be obtained, which is very close to the oil yield of 12 Ton/Ha from *Elaeis guineensis* (oil palm). It surpasses the oil yield of *Ricinus communis* (castor bean) at 1.18 Ton/Ha and *Jatropha curcas* at 0.590 to 0.760 Ton/Ha [28].

Moreover, both coyol kernel oil and mesocarp oil are considered high-quality oils based on their fatty acid profiles (Table 2). These oils present an opportunity for biodiesel production, as well as applications in the green diesel, cosmetic, and food industries. The kernel oil's composition comprises 57.49% unsaturated fatty acids and 42.51% saturated fatty acids, which are crucial factors influencing properties such as viscosity, heat of combustion, cloud point, pour point, cetane number, and oxidative stability—parameters important for biodiesel production [56].

In the vegetable oil industry, oil processing from raw materials often results in the production of solid byproducts called oilcake. In the case of coyol, this study estimates that the mesocarp and kernel could generate a significant amount of byproduct after oil extraction, with 10.04 tons per hectare (Ton/Ha) and 14.77 Ton/Ha, respectively, resulting in a total of 24.81 Ton/Ha. The kernel oil cake can be explored as animal feed and in the food industry due to its protein, mineral content, amino acids, carbohydrates, and energy content [57]. It represents an exceptional and cost-effective source with various benefits.

The mesocarp oil cake, on the other hand, is rich in fermentable sugars. According to the results of this study, it contains 40.70 g/kg of fermentable sugars, equivalent to 401.6 kg/Ha. This biomass has significant potential for ethanol production, with an estimated ethanol yield of 204.82 kg per hectare. Additionally, it can serve as a valuable energy source for biogas production. The mesocarp oil cake has a chemical oxygen demand (COD) of 147.20 g/kg, as reported by Filer et al. [58]. It is known that one gram of COD can generate up to 350 mL of biomethane. Therefore, one ton of mesocarp oil cake holds considerable potential, capable of producing up to 51.52 m³ of biomethane. Such utilization of byproducts under the biorefinery concept can yield economic and environmental benefits.

The epicarp and kernel shell of the coyol palm are significant sources of lignin, cellulose, and hemicellulose biomass, as observed in the FTIR results (Fig. 2) and thermograms (Fig. 3). These components are the three main biopolymers found in biomass. Cellulose is composed of linear polysaccharides linked by β -1,4-glycosidic bonds, primarily consisting of D-glucose units. Hemicellulose, on the other hand, is an amorphous and branched copolymer composed mainly of arabinose, galactose, glucose, and xylose [59]. The lignin shell, which surrounds the polysaccharide chains, is a biopolymer consisting of various phenyl propyl acids and alcohols such as coumarin, coniferyl, and sinapyllic acids [5,59].

In this study, the epicarp and mesocarp of the coyol palm are identified as important reserves of sustainable energy due to their high lignocellulosic material content, ranging from 2.58–5.05 Ton/Ha and 3.51–6.85 Ton/Ha, respectively. The utilization of this lignocellulosic material requires a fractionation process due to its complex nature, which may involve the integration and optimization of successive fractionation stages to achieve complete biomass utilization within a biorefinery concept [36]. Various hydrolysis methods exist for the solubilization of polysaccharides (hemicellulose and cellulose) and delignification (solubilization of lignin) [17, 36]. In the initial stage, the solubility of lignin can be targeted using organic solvents, which allows for the preservation of lignin, unlike alkaline processes. Once the lignin is recovered, the residual liquor may have industrial value as it contains sugars, oligomers, furfural, and acetic acid [28, 36]. Lignin offers several possibilities for use, as shown in Fig. 5, including applications as an absorbent, carbon fiber, activated carbon, or as a solid biofuel due to its high calorific value (> 20 MJ/kg) [60,62].

The sugar and oligomeric fractions obtained from the cellulose and hemicellulose of the coyol epicarp and kernel shell hold great potential for various applications. Cellulose, mainly composed of β -glucose molecules, can find utility in industries such as paper manufacturing, lubricants, chemical products, polymers, and chemical solvents (Fig. 5) [5,62]. Its unique characteristics make it suitable for a wide range of products.

Similarly, the hemicellulose of the coyol palm (epicarp and kernel shell) primarily consists of C5 sugars (pentoses) and C6 sugars (hexoses), linked by β bonds to form branched linear chains. This composition makes it a fermentable biomass with significant potential. The diverse monomers and oligomers present in hemicellulose open up opportunities for various applications, including the cosmetic industry, pharmaceuticals, animal and human food products. It can also be utilized in the synthesis of xylitol, acetic acid, furfural, polymeric products (furan resins), and nylon, among other bioproducts (Fig. 5) [63].

The results of this investigation support the notion that coyol fruits have immense potential for utilization within the biorefinery concept to produce clean fuels and chemical products. By employing a cycle of sustainable use and aiming for a balance of zero or near-zero carbon emissions, the development of an environmentally sustainable economy becomes feasible.

4 Conclusions

The results of this study highlight the promising potential of *Acrocomia aculeata* (coyol) as an energy crop native to Mexico and the American continent. Through the application of technological and biotechnological processes within the biorefinery concept, coyol can emerge as a viable alternative that competes directly with conventional biomass sources. This has the potential to drive the country's development, as well as the local and regional economy, by promoting sustainable agriculture, clean energy production, food sovereignty, and overall sustainable development in Mexico. By harnessing the high fruit yield of coyol, including the epicarp, mesocarp, kernel shell,

and kernel, the study suggests that this species can offer a competitive advantage over other biomass sources. Moreover, the aim is to reduce the environmental impact and carbon footprint associated with the production of bioproducts from vegetable biomass like coyol. This aligns with the broader objective of achieving sustainable and eco-friendly practices in various industries.

It is essential to continue exploring and studying *Acrocomia aculeata* in Mexico, America, and other countries, as it holds significant promise and can bring numerous benefits in the medium and long term. By capitalizing on its potential, we can foster a sustainable and prosperous future driven by renewable resources and environmentally conscious practices.

Declarations

Acknowledgments

This research was financially supported by Secretaría de Educación, Ciencia, Tecnología e Innovación de la Ciudad de México Project No. SECTEI-243-2020 "Mejorar los procesos de la planta de biodiésel". We give special acknowledgments to the Laboratorio Nacional de Desarrollo y Aseguramiento de la Calidad de Biocombustibles (LaNDACBio), for granting access to laboratory facilities, and the Consejo Nacional de Ciencia y Tecnología (COACyT).

References

1. Hingsamer, M., Jungmeier, G., Biorefineries, E.: ; [cited 2023 Mar 21]. p. 179–222. Available from: (2019). <https://linkinghub.elsevier.com/retrieve/pii/B9780128130568000054>
2. Jin, Q., Yang, L., Poe, N., et al.: Integrated processing of plant-derived waste to produce value-added products based on the biorefinery concept. *Trends Food Sci Technol.* **74**, 119–131 (2018)
3. Venkata Mohan, S., Dahiya, S., Amulya, K., et al.: Can circular bioeconomy be fueled by waste biorefineries – A closer look. *Bioresour Technol. Rep.* **7**, 100277 (2019)
4. Maity, S.K.: Opportunities, recent trends and challenges of integrated biorefinery: Part I. *Renew. Sustain. Energy Rev.* **43**, 1427–1445 (2015)
5. Ghosh, D., Dasgupta, D., Agrawal, D., et al.: Fuels and Chemicals from Lignocellulosic Biomass: An Integrated Biorefinery Approach. *Energy Fuels.* **29**, 3149–3157 (2015)
6. Hingsamer, M., Jungmeier, G., Biorefineries, E.: ; [cited 2023 Mar 22]. p. 179–222. Available from: (2019). <https://linkinghub.elsevier.com/retrieve/pii/B9780128130568000054>
7. Kumar, B., Verma, P.: Biomass-based biorefineries: An important archetype towards a circular economy. *Fuel.* **288**, 119622 (2021)
8. Vargas-Carpintero, R., Hilger, T., Tiede, K., et al.: A Collaborative, Systems Approach for the Development of Biomass-Based Value Webs: The Case of the *Acrocomia* Palm. *Land.* **11**, 1748 (2022)
9. César, A., Almeida, S., de Souza, F.: The prospects of using *Acrocomia aculeata* (macaúba) a non-edible biodiesel feedstock in Brazil. *Renew. Sustain. Energy Rev.* **49**, 1213–1220 (2015)
10. Díaz-Fuentes, V.H., Avendaño-Arrazate, C.H., Gálvez-Marroquín, L.A., et al.: Caracterización morfoagronómica de coyol (*Acrocomia aculeata* Jacq.) para determinar su potencial productivo de aceite para biodiesel. *Agro*

Product [Internet]. 2019 [cited 2023 Mar 21];12. Available from: <http://www.revista-agroproductividad.org/index.php/agroproductividad/article/view/1323>

11. Vianna, S.A., Colombo, C.A.: Distribuição geográfica de *Acrocomia aculeata* (Jacq.) Lodd ex. Mart. (Arecaceae) em sua região de ocorrência. 2013 [cited 2023 Mar 21]; Available from: <http://rgdoi.net/10.13140/RG.2.2.20079.33444>
12. Costa, J.M.C., Oliveira, D.M., Costa, L.E.C.: Macauba Palm— *Acrocomia aculeata*. Exot Fruits [Internet]. Elsevier; [cited 2023 Mar 22]. p. 297–304. Available from: (2018). <https://linkinghub.elsevier.com/retrieve/pii/B9780128031384000393>
13. Ramírez-Estrada, A., Mena-Cervantes, V.Y., Mederos-Nieto, F.S., et al.: Assessment and classification of lignocellulosic biomass recalcitrance by principal components analysis based on thermogravimetry and infrared spectroscopy. *Int. J. Environ. Sci. Technol.* **19**, 2529–2544 (2022)
14. Giraldo Montoya, S., Motoike, S.Y., Kuki, K.N., et al.: Registro da presença e danos causados por coleopteros em macaúba. *Pesqui Florest Bras.* **35**, 159 (2015)
15. Balick, M.J.: Production of coyol wine from *Acrocomia mexicana* (Arecaceae) in Honduras. *Econ. Bot.* **44**, 84–93 (1990)
16. Hernández, B.C.R., Hernández, J.Z.: Importancia agroecológica del coyul (*Acrocomia mexicana* Karw. ex Mart.). *Estud Soc.* ; (2013)
17. Zardón, A.F.H.: Cultivos Tropicales. Review Corajo palm, a natural resource for sustainable oil production. 2016 [cited 2023 Mar 21]; Available from: <http://rgdoi.net/10.13140/RG.2.2.30257.99687>
18. Mancini, A., Imperlini, E., Nigro, E., et al.: Biological and Nutritional Properties of Palm Oil and Palmitic Acid: Effects on Health. *Molecules.* **20**, 17339–17361 (2015)
19. Carta, G., Murru, E., Banni, S., et al.: Palmitic Acid: Physiological Role, Metabolism and Nutritional Implications. *Front. Physiol.* **8**, 902 (2017)
20. Becker, L.C., Bergfeld, W.F., Belsito, D.V., et al.: Final Report of the Amended Safety Assessment of Myristic Acid and Its Salts and Esters as Used in Cosmetics. *Int. J. Toxicol.* **29**, 162S–186S (2010)
21. Hristov, A.N., Lee, C., Cassidy, T., et al.: Effects of lauric and myristic acids on ruminal fermentation, production, and milk fatty acid composition in lactating dairy cows. *J. Dairy. Sci.* **94**, 382–395 (2011)
22. Zavala-Hernández, J.T., Córdova-Téllez, L., Martínez-Herrera, J., et al.: Desarrollo del fruto y semilla de *Jatropha curcas* L. e indicadores de madurez fisiológica de la semilla. *Rev. Fitotec Mex.* **38**, 275 (2015)
23. Cao, C., Yang, Z., Han, L., et al.: Study on in situ analysis of cellulose, hemicelluloses and lignin distribution linked to tissue structure of crop stalk internodal transverse section based on FTIR microspectroscopic imaging. *Cellulose.* **22**, 139–149 (2015)
24. Sari, F., Susanto, B.H., Bismo, S.: The potential utilization of coconut oil and palm oil as raw material of alkanolamide under alkaline conditions. *IOP Conf. Ser. Earth Environ. Sci.* **105**, 012035 (2018)
25. Chakrabarti, P.P., Prasad, R.B.N.: Biodiesel Production from *Jatropha curcas* Oil. In: Carels N, Sujatha M, Bahadur B, editors. *Jatropha Chall New Energy Crop* [Internet]. New York, NY: Springer New York; [cited 2023 Apr 17]. p. 463–490. Available from: <https://link.springer.com/> (2012). 10.1007/978-1-4614-4806-8_25
26. Alpandi, A.H., Husin, H., Sidek, A., et al.: Characterization of Malaysian *Jatropha* Seed Oil and Discovering the Process of Powdered *Jatropha* Leaves. *Processes.* **10**, 2577 (2022)

27. Lerma-García, M.J., Ramis-Ramos, G., Herrero-Martínez, J.M., et al.: Authentication of extra virgin olive oils by Fourier-transform infrared spectroscopy. *Food Chem.* **118**, 78–83 (2010)
28. Coates, J.: Interpretation of Infrared Spectra, A Practical Approach. In: Meyers RA, editor. *Encycl Anal Chem* [Internet]. Chichester, UK: John Wiley & Sons, Ltd; [cited 2023 Apr 26]. p. a5606. Available from: <https://onlinelibrary.wiley.com/doi/10.1002/9780470027318.a5606> (2006).
29. Fan, Y., Cai, Y., Li, X., et al.: Effects of the cellulose, xylan and lignin constituents on biomass pyrolysis characteristics and bio-oil composition using the Simplex Lattice Mixture Design method. *Energy Convers. Manag.* **138**, 106–118 (2017)
30. Singh, N., Singhanian, R.R., Nigam, P.S., et al.: Global status of lignocellulosic biorefinery: Challenges and perspectives. *Bioresour Technol.* **344**, 126415 (2022)
31. Horikawa, Y., Hirano, S., Mihashi, A., et al.: Prediction of Lignin Contents from Infrared Spectroscopy: Chemical Digestion and Lignin/Biomass Ratios of *Cryptomeria japonica*. *Appl. Biochem. Biotechnol.* **188**, 1066–1076 (2019)
32. Olatunji, O.O., Akinlabi, S.A., Mashinini, M.P., et al.: Thermo-gravimetric characterization of biomass properties: A review. *IOP Conf. Ser. Mater. Sci. Eng.* **423**, 012175 (2018)
33. Koshariya, A.K., Madhusudhanan, J., Anandaram, H., et al.: Thermochemical Recycling of Solid Biomass Materials for Achieving Sustainable Goal: A Complete Characterization Study on Liquid Yield Products. Ravindran B, editor. *J Chem.* ;2022:1–9. (2022)
34. Yeo, J.Y., Chin, B.L.F., Tan, J.K., et al.: Comparative studies on the pyrolysis of cellulose, hemicellulose, and lignin based on combined kinetics. *J. Energy Inst.* **92**, 27–37 (2019)
35. Fang, S., Yu, Z., Lin, Y., et al.: Thermogravimetric analysis of the co-pyrolysis of paper sludge and municipal solid waste. *Energy Convers. Manag.* **101**, 626–631 (2015)
36. Burhenne, L., Messmer, J., Aicher, T., et al.: The effect of the biomass components lignin, cellulose and hemicellulose on TGA and fixed bed pyrolysis. *J. Anal. Appl. Pyrolysis.* **101**, 177–184 (2013)
37. Del Río, J.C., Evaristo, A.B., Marques, G., et al.: Chemical composition and thermal behavior of the pulp and kernel oils from macauba palm (*Acrocomia aculeata*) fruit. *Ind. Crops Prod.* **84**, 294–304 (2016)
38. Chin, B.L.F., Yusup, S., Al Shoaibi, A., et al.: Comparative studies on catalytic and non-catalytic co-gasification of rubber seed shell and high density polyethylene mixtures. *J. Clean. Prod.* **70**, 303–314 (2014)
39. Morelos Gómez, J.: Análisis de la variación de la eficiencia en la producción de biocombustibles en América Latina. *Estud Gerenciales.* **32**, 120–126 (2016)
40. Valdez-Vazquez, I., Acevedo-Benítez, J.A., Hernández-Santiago, C.: Distribution and potential of bioenergy resources from agricultural activities in Mexico. *Renew. Sustain. Energy Rev.* **14**, 2147–2153 (2010)
41. Montoya, S.G., Motoike, S.Y., Kuki, K.N., et al.: Fruit development, growth, and stored reserves in macauba palm (*Acrocomia aculeata*), an alternative bioenergy crop. *Planta.* **244**, 927–938 (2016)
42. Koutroubas, S.D., Papakosta, D.K., Doitsinis, A.: Adaptation and yielding ability of castor plant (*Ricinus communis* L.) genotypes in a Mediterranean climate. *Eur. J. Agron.* **11**, 227–237 (1999)
43. Carels, N., Sujatha, M., Bahadur, B. (eds.): *Jatropha, Challenges for a New Energy Crop: Volume 1: Farming, Economics and Biofuel* [Internet]. New York, NY: Springer New York; [cited 2023 Apr 17]. Available from: <https://link.springer.com/> (2012). 10.1007/978-1-4614-4806-8

44. Aceves-Navarro, L.A., Rivera-Hernández, B., Arrieta-Rivera, A., et al.: Climate and soil effect on oil palm (*Elaeis guineensis* Jacq.) yield. *Agro Product* [Internet]. [cited 2023 May 12]; Available from: (2021). <http://www.revista-agroproductividad.org/index.php/agroproductividad/article/view/2005>
45. Aristizabal, C., Alvarado, P., Vargas, A.: Biorefinery Concept Applied to Phytochemical Extraction and Bio-Syngas Production using Agro-Industrial Waste Biomass: A Review. *Ing E Investig* [Internet]. [cited 2023 Apr 17];40. Available from: (2020). <https://revistas.unal.edu.co/index.php/ingeinv/article/view/82539>
46. Van Gerpen, J.: Biodiesel processing and production. *Fuel Process. Technol.* **86**, 1097–1107 (2005)
47. Demirbas, A.: Progress and recent trends in biodiesel fuels. *Energy Convers. Manag.* **50**, 14–34 (2009)
48. Mansir, N., Taufiq-Yap, Y.H., Rashid, U., et al.: Investigation of heterogeneous solid acid catalyst performance on low grade feedstocks for biodiesel production: A review. *Energy Convers. Manag.* Elsevier Ltd; p. 171–182. (2017)
49. Guo, M., Song, W., Buhain, J.: Bioenergy and biofuels: History, status, and perspective. *Renew. Sustain. Energy Rev.* Elsevier Ltd; p. 712–725. (2015)
50. Islam, M.A., Ayoko, G.A., Brown, R., et al.: Influence of Fatty Acid Structure on Fuel Properties of Algae Derived Biodiesel. *Procedia Eng.* **56**, 591–596 (2013)
51. Singh, R., Langyan, S., Sangwan, S., et al.: Protein for Human Consumption From Oilseed Cakes: A Review. *Front. Sustain. Food Syst.* **6**, 856401 (2022)
52. Filer, J., Ding, H.H., Chang, S.: Biochemical Methane Potential (BMP) Assay Method for Anaerobic Digestion Research. *Water.* **11**, 921 (2019)
53. Gellerstedt, G.: Softwood kraft lignin: Raw material for the future. *Ind. Crops Prod.* **77**, 845–854 (2015)
54. Chávez-Sifontes, M.: La biomasa: fuente alternativa de combustibles y compuestos químicos. *Quím. ;* (2019)
55. Bajwa, D.S., Pourhashem, G., Ullah, A.H., et al.: A concise review of current lignin production, applications, products and their environmental impact. *Ind. Crops Prod.* **139**, 111526 (2019)
56. Farhat, W., Venditti, R.A., Hubbe, M., et al.: A Review of Water-Resistant Hemicellulose-Based Materials: Processing and Applications. *ChemSusChem.* **10**, 305–323 (2017)
57. Chandra, R., Castillo-Zacarias, C., Delgado, P., et al.: A biorefinery approach for dairy wastewater treatment and product recovery towards establishing a biorefinery complexity index. *J. Clean. Prod.* **183**, 1184–1196 (2018)

Figures

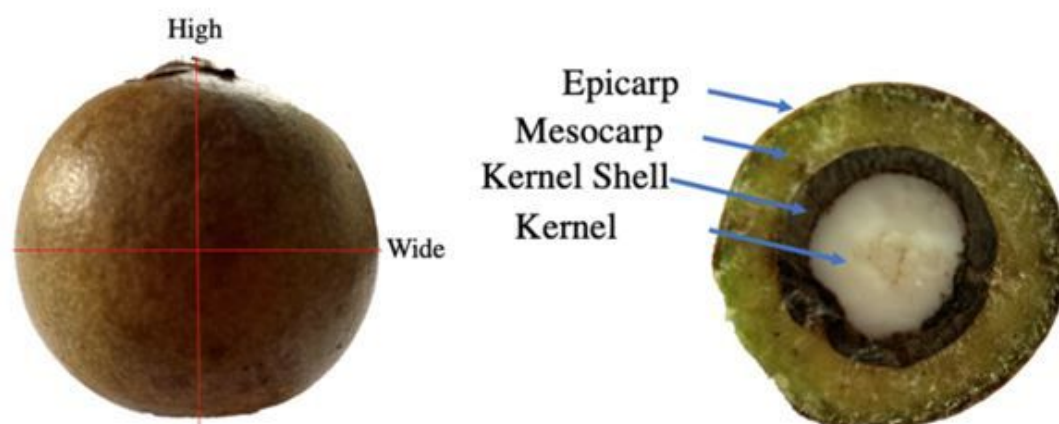


Figure 1

Morphology and composition of coyol fruit (*Acrocomia aculeata*)

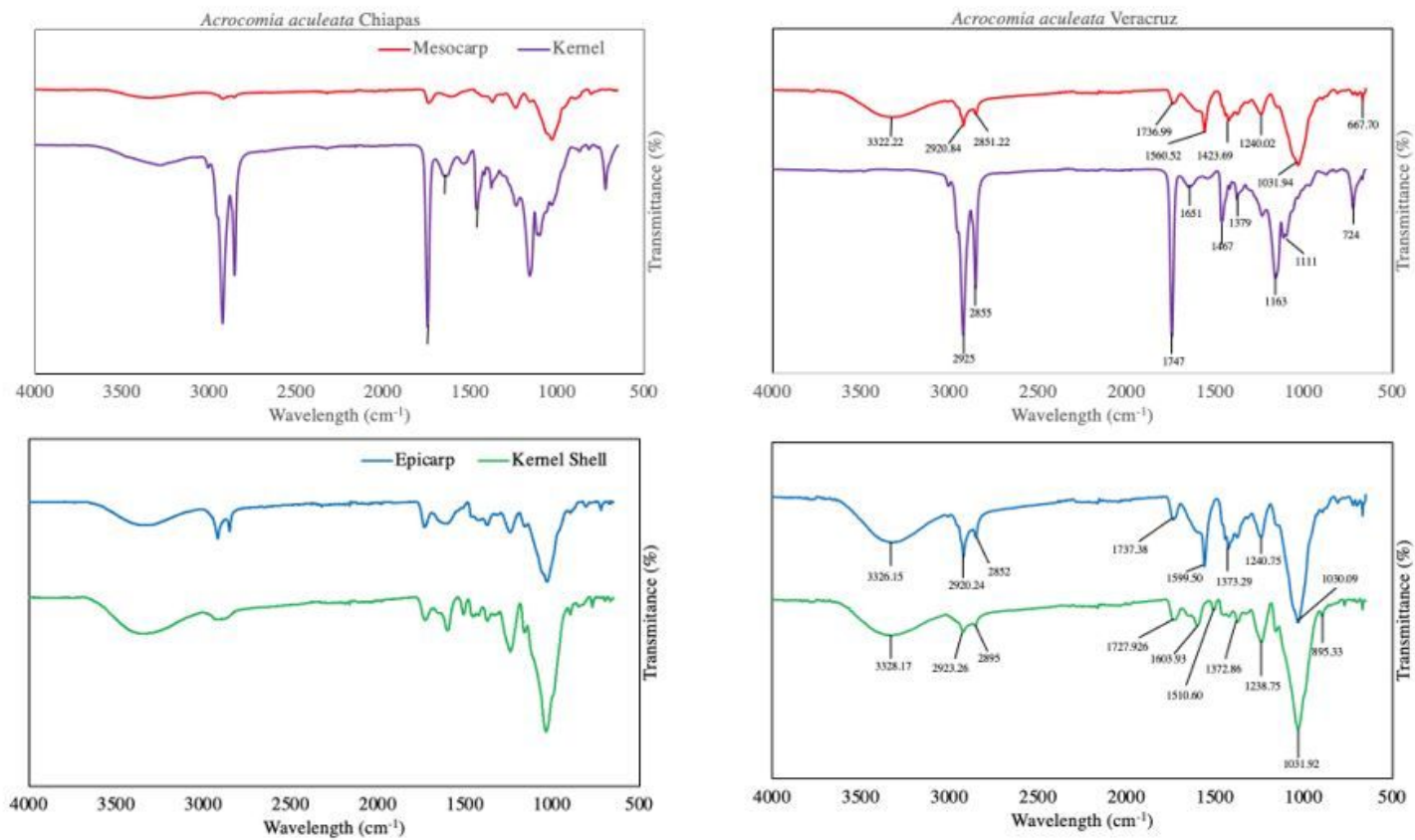


Figure 2

Comparative analysis of IR spectra from Coyol fruit components (Epicarp, Mesocarp, Kernel Shell, and Kernel) in Chiapas and Veracruz Varieties

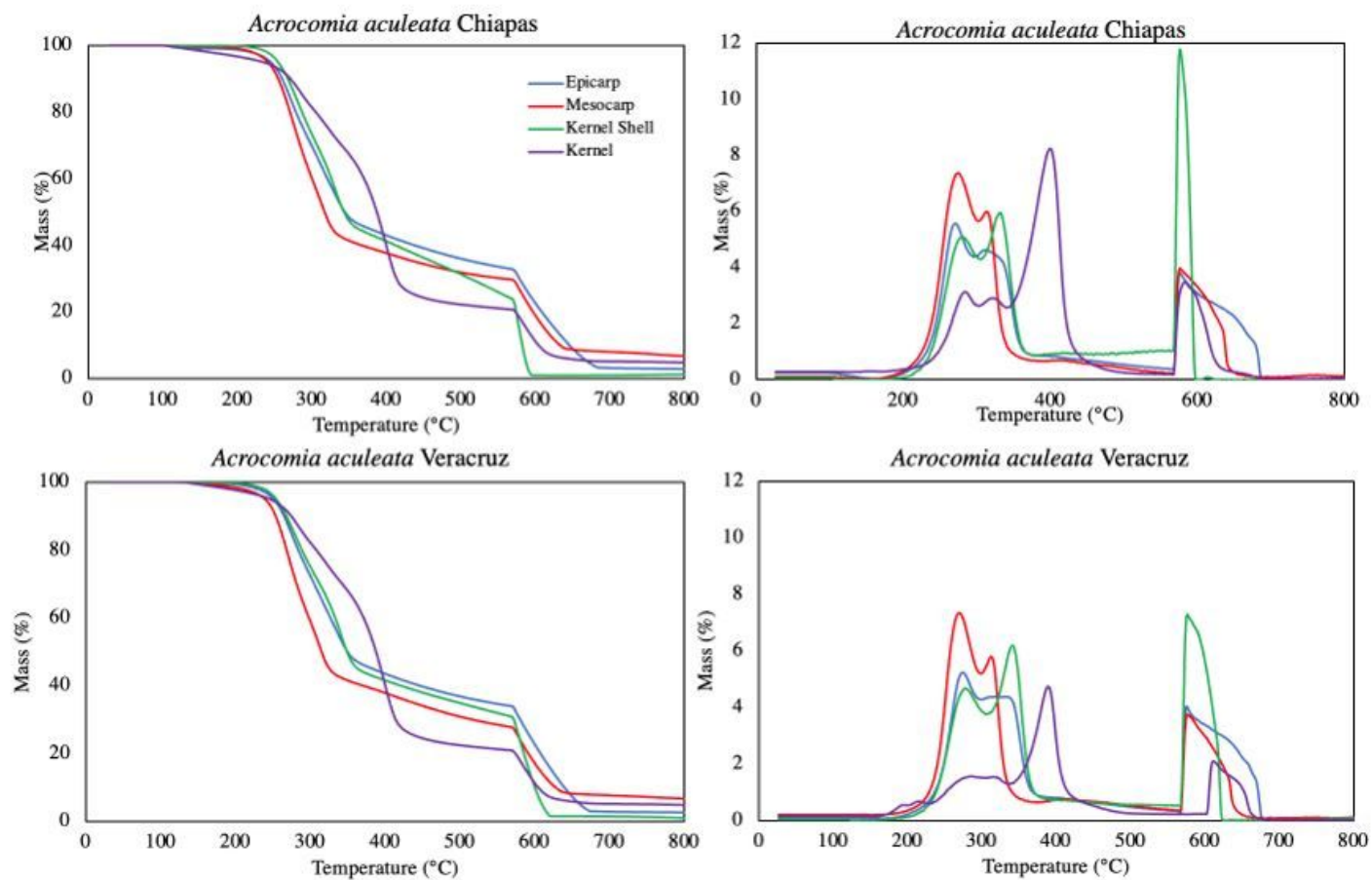


Figure 3

Comparative TGA analysis of Coyol Chiapas and Veracruz Components

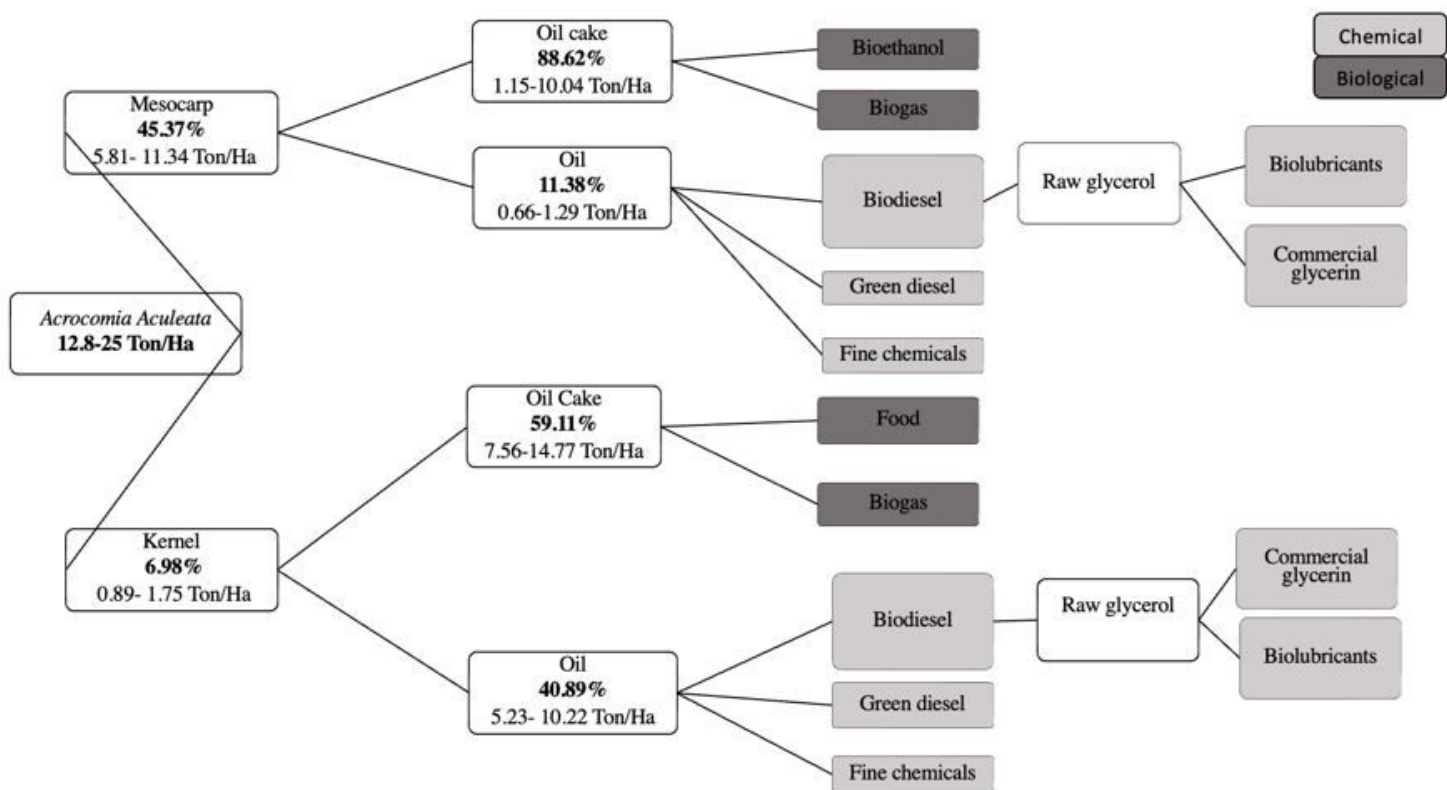


Figure 4

Block diagram of integrated mesocarp and kernel in the generation of bioproducts

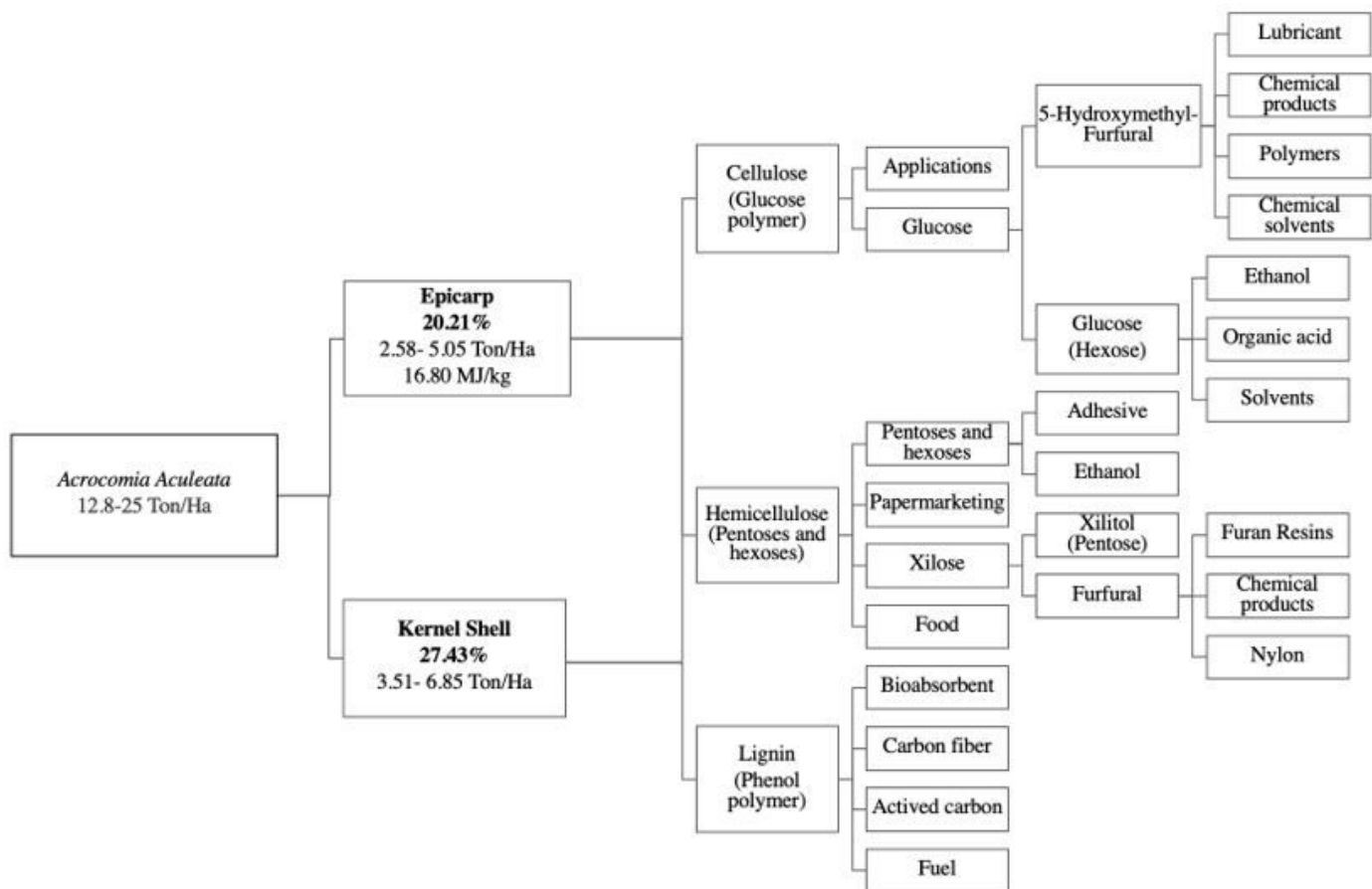


Figure 5

Integrated utilization of epicarp and kernel shell in bioproduct generation: A Block diagram approach