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Acrocomia aculeata fruits from three regions in Costa Rica: an assessment of biometric parameters, oil content and oil fatty acid composition to evaluate industrial potential

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Abstract Due to increased global demand for vegetable oils, diversification of the supply chain with sustainable sources is necessary. *Acrocomia aculeata* has recently gained attention as a multi-purpose, sustainable crop for oil production. However, the information necessary for effective selection of promising varieties for agricultural production is lacking. The aim of this study was to assess variability in fruit morphology and oil composition of individual *Acrocomia aculeata* plants growing wild in different climatic regions of Costa Rica. Fruits at the same ripening stage were collected at three locations, and biometric features, oil content, fatty acid composition of oils from kernels and pulp, as well as fiber composition of husks were determined. Biometric parameters showed high variability among the regions assessed. Moreover, oil content and relative proportions of unsaturated fatty acids were higher at the most tropical location, whereas lauric acid content was lowest under these conditions, indicating a potential environmental effect on oil composition. Pulp oil content correlated positively with annual precipitation and relative humidity, but no clear relation to

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temperature was observed. The oil chemical composition was similar to that reported for *Elaeis guineensis*, suggesting that *Acrocomia aculeata* from Costa Rica may be a suitable alternative for industrial applications currently based on African palm oil. Analysis of husks as a coproduct revealed the possibility of obtaining materials with high lignin and low water and ash contents that could be used as a solid bioenergy source. In conclusion, *Acrocomia aculeata* oil is a promising alternative for industrial applications currently based on African palm oil and byproducts of its oil production could find additional use as a renewable energy source.

Keywords Coyol palm · Macauba palm · Multipurpose crop · Fruit biometric parameters · Vegetable oil · Fatty acid composition

Introduction

Vegetable oil is an important raw material for food production, but also for the manufacture of bio-based products, such as detergents, cosmetics, and biofuels (Montoya et al. 2016). For this reason, both vegetable oil demand and production have increased during the last decade and are expected to continue to rise in future (Colombo et al. 2018). Due to their high yield potential and low production costs, oleaginous palms are considered the most promising species for vegetable oil production (Poetsh et al. 2012; Del Río et al. 2016; Colombo et al. 2018). Among oleaginous palms, *Acrocomia aculeata* may be a profitable and sustainable alternative for oil production (Colombo et al. 2018). Previous studies suggest the cultivation of this species in rural areas of Central and South America has high industrial potential with socio-economic and environmental advantages (Lopes et al. 2013; Plath et al. 2016).

Acrocomia aculeata is a perennial, fruit-bearing palm belonging to the Arecaceae family. It extends throughout the Neotropical region, from Mexico to Argentina (Crocomo and Melo 1996; Plath et al. 2016), mainly in open pasture areas, in disturbed forests and in association with crops (Barbosa-Evaristo et al. 2018). *A. aculeata* grows optimally in tropical and subtropical regions with high precipitation and solar irradiation (César et al. 2015). However, it is robust and adapts well to other environments, including subtropical and semiarid conditions (Del Río et al. 2016).

The *Acrocomia* palm has additional characteristics relevant for its future cultivation as an oil crop, such as tolerance of long drought periods and nutrient-deficient soils. Moreover, it promotes recovery of marginal soils (César et al. 2015) and, to date, there are no reports of relevant diseases affecting wild *Acrocomia* populations (Plath et al. 2016; Colombo et al. 2018). In addition, it has been shown that cultivation of *Acrocomia* in agroforestry systems increases the productivity and yield of the co-cultivated crops (Moreira et al. 2018).

Acrocomia has not yet been domesticated and biometry, oil yield, and composition have only been studied in wild genotypes in Brazil (Cardoso et al. 2017; Coelho et al. 2019), where large phenotypic variability has been associated with environmental conditions and genetic diversity (Abreu et al. 2012). The breeding of genetically improved plants with optimized height, increased productivity and drought tolerance is one of the major directions in present *Acrocomia* research (Cardoso et al. 2017; Colombo et al. 2018). In studies from Brazil, it was found that productivity—in terms of oil yield—is determined by fruit size and oil content, which are in turn related to environmental parameters (e.g. soil conditions, water availability), as well as genetic variability (Ciconini et al. 2013; Castro et al. 2017; Coelho et al. 2019). In these studies, the best performance—in terms of productivity, fruit characteristics and oil content—were found in regions with higher precipitation and mild temperatures, both typical features of the Atlantic Rainforest (Castro et al. 2017).

Despite the economic potential of *Acrocomia* in Costa Rica, native populations have not been sufficiently characterized (Schex et al. 2018). Neither has the potential effect of climatic/edaphic conditions on biometric parameters and their relation to oil content and fatty acid composition—as observed in other oleaginous plants (Rached et al. 2017; Tous and Romero 2017)—been investigated. However, the commercialization of *Acrocomia* production in Costa Rica requires the selection and breeding of the most suitable genotypes for the specific location, which must be guided by knowledge of genotype and environment interactions. The aim of this study was to contribute to this knowledge by investigating the influence of fruit biometric parameters of the native palm *A. aculeata* on oil content and composition under different climatic conditions in Costa Rica.

Materials and methods

Plant material

Fruits were collected at the end of the harvest season between July and August 2018 from wild *A. aculeata* palms located at three sites in Costa Rica: El Coyol, Alajuela, Alajuela (N10°00′10.0″, W84°15′14.5″ and N10°00′19.5″, W84°14′57.4″, altitude 849 and 860 m.a.s.l., average annual temperature of 25 °C, annual precipitation of 1750 mm), La Garita, Alajuela, Alajuela (N10°00′11.7″, W84°16′13.7″, altitude 840 m.a.s.l., average annual temperature of 22 °C, annual precipitation of 1940 mm) and La Palma, Palmar, Puntarenas (N8°38′41.6″, W83°27′33.7″, altitude 16 m.a.s.l., average annual temperature of 28 °C, annual precipitation of 3500 mm) (Fig. 1, Table 1). Climatic data of each site are reported as long-term historic average values and were obtained from monitoring systems at Universidad de Costa Rica and National Meteorology Institute (Instituto Meteorológico Nacional, San José, Costa Rica). One palm from the regions La Palma and La Garita and two palms from El Coyol were randomly chosen for fruit collection. As is common practice for *Acrocomia* harvesting, completely ripe fresh fruits (20–70 according to availability) were collected from each palm from the ground shortly after falling from the fruit bunch. The fruit ripening stage was defined according to previous reports (Schex et al. 2018). Fully ripe fruits detach naturally from the bunch (Crocomo and Melo 1996; Montoya et al. 2016) and display a brown exocarp and a yellow mesocarp (Schex et al. 2018; Lieb et al. 2019). Soil samples were taken at each location and analyzed for texture and chemical properties (Appendix 1).

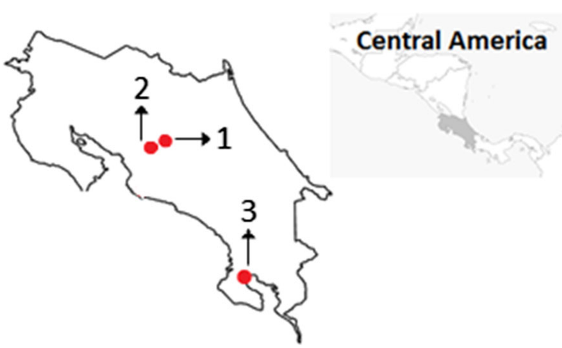

Fig. 1 Location of the three harvesting sites in Costa Rica. 1: El Coyol (Alajuela), 2: La Garita (Alajuela) and 3: La Palma (Puntarenas)

Biometric analysis

A randomized sample (n = 5), chosen blind from a bucket, was taken from each location to assess transversal and longitudinal diameter, and fresh and dry weight of the different fruit structures (husk, pulp, shell and kernel; Fig. 2). For moisture determination, fresh fruits were separated into the structures mentioned above. They were dried separately in a forced-air oven at 60 °C for 72 h and moisture content was determined gravimetrically.

Sample pretreatment

For lipid quantification and fatty acid profiling, eight fresh fruits from each location were randomly chosen, manually peeled, and pulp and kernel were immediately frozen in liquid nitrogen to avoid degradation. Samples were freeze-dried for 72 h under light protection in a laboratory freeze-dryer (Alpha 1–2 LD Christ, Osterode, Germany) at − 50 °C and transported to Germany in vacuum-sealed polyethylene bags covered with aluminum foil.

Processing for ash and fiber content determination was based on the methodology described by Kiesel et al. (2017). The husk of approximately 50 randomly chosen fruits from each location was separated manually, weighed, dried with a forced-air oven at 60 °C for 72 h and transported to Germany in vacuum-sealed polyethylene bags.

Chemical analysis

Quantification of total lipid content

Samples from each location were individually ground using a commercial coffee grinder and aliquots of 1.5 g were extracted in triplicate using 20 mL *n*-hexane (HPLC grade) for 30 min under continuous agitation at room temperature (20–25 °C). The hexane fraction containing the lipid extract was vacuum-

Table 1 Climatic data and characteristics of fruit collection sites of *Acrocomia aculeata* in Costa Rica. Source: Instituto Meteorológico Nacional, San José, Costa Rica

Location	Altitude (m.a.s.l.)	Annual average temperature (°C)	Average Precipitation (mm/year)	Average relative humidity (%)
El Coyol	860	25	1750	72
	849			
La Garita	840	22	1940	72
La Palma	16	28	3500	89

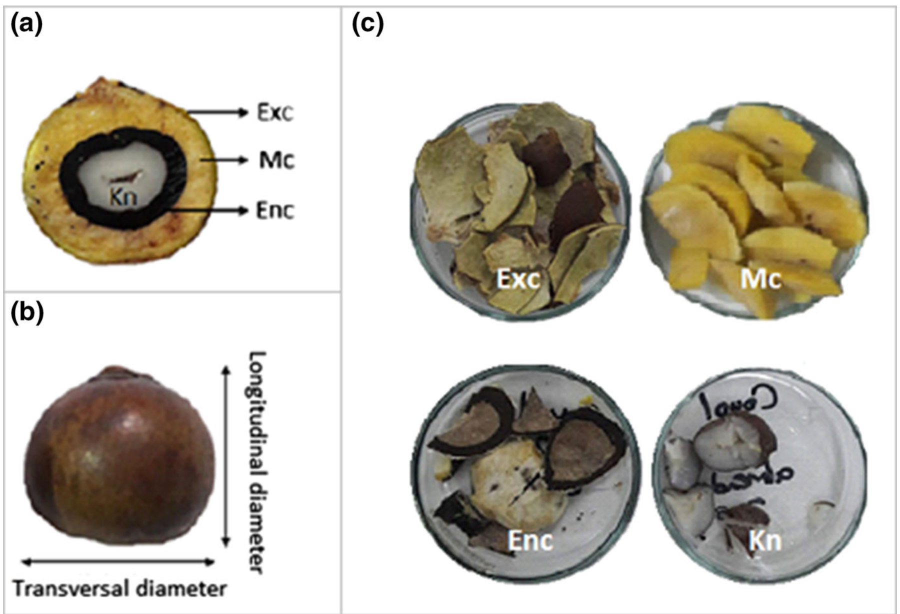

Fig. 2 Biometrical features of *Acrocomia aculeata* fruit. **a** Transversal view of a sectioned fruit; *Exc* exocarp (husk), *Mc* mesocarp (pulp), *Enc* endocarp (shell) and *Kn* kernel (seed). **b** Transversal and longitudinal diameters. **c** Fruit fresh biomass after the separation of structures

filtered through a 0.2 µm polyether sulfone membrane filter (Sigma Aldrich, Germany) and recovered in a distillation flask. The solvent was removed by rotary evaporation at 30 °C and 250 mbar until dryness. Lipid content was determined gravimetrically. Lipid extracts from the same location were pooled and stored protected from light and humidity at − 80 °C.

Preparation of fatty acid methyl esters (FAMEs)

Transesterification was performed according to Wendlinger et al. (2014). An aliquot of the lipid extract was placed into a reaction tube and the solvent evaporated under a gentle stream of nitrogen. Then, 1 mL of 1% sulfuric acid in methanol (v/v) was added and the tube incubated at 80 °C for 1 h with occasional shaking. After cooling down the sample on ice, 0.5 mL demineralized water, 0.5 mL saturated NaCl solution and 2 mL *n*-hexane were added, mixed by vortex and centrifuged at 1000 rpm for 3 min. Subsequently, 1 mL of the *n*-hexane supernatant was transferred into a 1.5 mL vial for instrumental analysis.

FAMEs were identified by gas chromatography with mass spectrometry (GC/MS) using a 5890 series II Plus/5972 system in combination with a 7673 autosampler (Hewlett-Packard/Agilent, Waldbronn, Germany) operated in full-scan mode. An Rtx 2330 capillary column (60 m × 0.25 mm coated with

0.1 μm 10% cyanopropylphenyl, 90% bis-cyanopropyl polysiloxane; Restek, Bellefonte, PA, USA) was used in combination with the following oven program. After 1 min at 60 °C, the temperature was raised by 6 °C/min to 150 °C, then by 4 °C/min to 190 °C, and finally by 7 °C/min to 250 °C, which was held for 7 min (Wendlinger et al. 2014). Helium (purity 5.0) was used as carrier gas at a flow rate of 1.2 mL/min. Peak identification was based on retention times and mass spectra in comparison with commercial standards (Sigma Aldrich, Taufkirchen, Germany).

Fatty acid profiles were determined as FAMEs by gas chromatography with flame ionization detection (GC/FID) using a 5890 series II system in combination with a 7673A autosampler (Hewlett-Packard/Agilent, Waldbronn, Germany). Oven program and column were identical to those described above for GC/MS.

Determination of ash and fiber content of husks

Analyses were conducted following the methodology applied by Kiesel et al. (2017). Dried husks from each location were processed by a SM-200 cutting mill equipped with a 1-mm sieve. For ash determination, the husk samples were incinerated in a muffle kiln at 550 °C for 4 h according to VDLUFA book III method 8.1 and ash content was determined gravimetrically. The contents of neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL) were estimated for husk fractions by near infrared spectroscopy (NIRS), using a ANKOM2000 Fiber Analyzer coupled to a Daisy II Incubator, according to VDLUFA book III method 6.5.1 (NDF), 6.5.2 (ADF), and 6.5.3 (ADL) (Naumann et al. 1976). The ADL value was considered lignin content; ADF minus ADL was considered cellulose content and NDF minus ADF was considered hemicellulose content. The ash and NDF/ADF/ADL analysis was carried out twice for each sample.

Statistical analyses

Statistical analyses were performed using the software Minitab® 18. Normality of data was checked by Anderson–Darling test (Appendix 2) and homogeneity of variances was assessed by Levene's test (Appendix 3). Analysis of variance (ANOVA) was used to assess significant differences in morphological and chemical characteristics of fruits between locations. The means of significantly different data were compared by Tukey test (HSD). Spearman's Rho test was performed to assess correlations between oil yield and environmental and soil parameters. A significance value (α) of 0.05 was used for all statistical tests.

Results

Biometric analyses

Biometric data of the fruits obtained from Costa Rican *A. aculeata* are shown in Table 2. The size and weight of the fruits varied between the different locations. The largest fruits, in terms of transverse and longitudinal diameter, were found at the location "*El Coyol*", and these were also significantly heavier than those collected in *"La Garita"* and *"La Palma"*.

There were significant differences in relative proportions of the various structures between fruits from *"La Palma"* and the other two locations. *"La Palma"* fruits had the highest proportion of husk (32.4 ± 2.1%) and lowest relative proportion of shell (17.5 ± 1.2%). The pulp mass of fruits from all three was between 44 and 49% of total fruit weight with significant differences being observed between locations (Table 2). The kernel fractions differed significantly with a share of 9.07 ± 0.96% in *"La Garita*", 7.82 ± 0.95% in *"El Coyol"* and 5.92 ± 0.48% in *"La Palma"*.

Quantification of total lipid content

Moisture and lipid contents of the different structures are shown in Table 3. As expected, the moisture content was much higher in the pulp than the kernels, while a higher oil content was observed in the kernels. Kernel moisture did not differ between locations. Pulp moisture content was highest in the "*La Palma*" samples, followed by "*La Garita*" and then by "*El Coyol*". The analysis of variance suggested that the geographical origin also had an impact on the oil content of ripe *A. aculeata* fruit pulp. The location with the highest oil content was *"La Palma"*, with a mean value of 39.6 ± 2.1 g oil/100 g in the dried pulp. The lipid content in Costa Rican *A. aculeata* kernels showed no significant differences between the studied locations. The overall average oil content sampled was around 54% of the total kernel mass on a

Table 2 Biometric characteristics of Costa Rican *Acrocomia aculeata* fruits collected from three different locations (mean values within columns not sharing a common superscript letter are significantly different at $P < 0.05$)

Location	Fresh weight of fruit (g)	Structure weight of fresh material (g)				Diameter (cm)	
		Husk	Pulp	Shell	Kernel	Transverse	Longitudinal
El Coyol	45.0 ± 3.0^{a}	10.6 ± 1.9^{a}	21.0 ± 3.9^{a}	9.9 ± 1.3^{a}	3.5 ± 0.5^{a}	4.5 ± 0.1^{a}	4.4 ± 0.1^{a}
La Garita	33.0 ± 3.7^{c}	6.9 ± 0.8^{b}	16.2 ± 2.0^{b}	7.3 ± 1.2^{b}	3.0 ± 0.5^{a}	4.1 ± 0.2^{b}	4.0 ± 0.1^{c}
La Palma	39.6 ± 3.0^{b}	12.9 ± 2.8^{a}	17.5 ± 1.1^{ab}	6.9 ± 0.3^{b}	2.3 ± 0.2^{b}	4.2 ± 0.1^{b}	4.2 ± 0.1^{b}

Table 3 Moisture and lipid content in main structures of Costa Rican *Acrocomia aculeata* fruits collected from three different locations (mean values within columns not sharing a common superscript letter are significantly different at $P < 0.05$)

Location	Moisture (g/100 g fresh material)		Lipid content (g/100 g dry matter)	
	Kernel	Pulp	Kernel	Pulp
El Coyol	14.9 ± 4.7^{a}	47.2 ± 5.7^{c}	48.7 ± 4.9^{b}	26.6 ± 2.2^{c}
La Garita	17.7 ± 3.1^{a}	57.5 ± 3.7^{b}	58.4 ± 2.1^{a}	33.5 ± 2.0^{b}
La Palma	19.2 ± 0.7^{a}	66.4 ± 3.2^{a}	53.7 ± 0.7^{ab}	39.6 ± 2.1^{a}

dry basis (lowest value: 48.7 ± 4.9%, highest value: 58.4 ± 2.1%).

Fatty acid profiles

Fatty acid profiles for both kernel and pulp are shown in Fig. 3.

The fatty acid profile of the lipid fraction obtained from kernels revealed that, in all locations, lauric acid (12:0) was the most abundant (40.9%), followed by oleic acid (18:1*n-9*) and myristic (14:0) acid (20.2% and 12.0%, respectively). The remaining percentage is represented in descending order by caprylic (8:0), palmitic (16:0), capric (10:0), linoleic (18:2*n-6*) and stearic acid (18:0).

A lower proportion of the saturated lauric acid was found in samples from *"La Palma"* (36.0 ± 1.1%) than in the other locations (44.5 ± 1.6% and 41.9 ± 2.2%). The *"La Palma"* location also had a significantly higher content of 18:1*n-9*, accounting for 26.4 ± 0.2% of total fatty acids, while an average of 17.2% was determined for *"El Coyol"* and *"La Garita"*. Capric and caprylic acids also showed significant differences between locations, the lowest being found in *"La Palma"*. The opposite tendency was observed for stearic, linoleic and palmitic acids, which were higher at this location.

Analysis of the lipid fraction obtained from the pulp identified six fatty acids, predominantly oleic acid (18:1*n-9*, and possibly its isomer vaccenic acid), followed by the saturated palmitic acid (16:0) and smaller amounts of stearic (18:0), palmitoleic (16:1*n-7*), linoleic (18:2*n-6*) and α-linoleic acid (18:3*n-3*). In contrast to kernel oils, no fatty acids with a chain length shorter than 16 carbons were detected in pulp oil. The 18:1 isomer concentration was significantly higher in pulp oil from *"La Palma"* (76.4 ± 0.2%) than in the other two locations (47.6 ± 7.0% and 45.1 ± 1.8%). By contrast, the second most abundant fatty acid (palmitic acid) had a significantly lower proportion in *"La Palma"* (14.0 ± 0.0%) than in the other two locations (24.5 ± 2.4% and 25.7 ± 0.4%).

In general, the fatty acid composition of oils obtained from *"La Garita"* and *"El Coyol"* had a very similar composition in both kernel and pulp. Those obtained from *"La Palma"* differed significantly, with a higher content of unsaturated fatty acids mainly in the form of 18:1.

Ash, lignin and fiber content of husk

Lignin was the most abundant organic compound in husks at two of the three locations, followed by cellulose, with hemicellulose being the least abundant

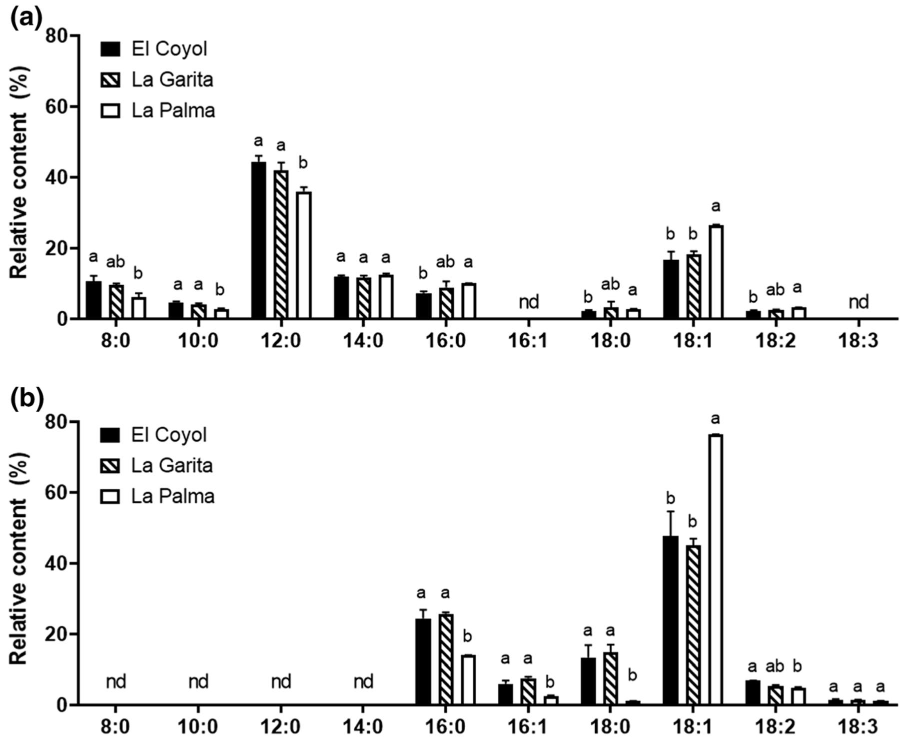

Fig. 3 Fatty acids as methyl esters in kernel (**a**) and pulp (**b**) of Costa Rican *Acrocomia aculeata* from three locations obtained by conventional hexane extraction [values represent arithmetic means ± standard deviation (n = 3)]. For each fatty acid, bars not sharing a common superscript letter are significantly different at $P < 0.05$; *nd* = not detected in the sample

Table 4 Moisture, lignin, fiber and ash content in the husk of Costa Rican *Acrocomia aculeata* fruits collected from three different locations (mean values within columns not sharing a common superscript letter are significantly different at $P < 0.05$)

Location	Moisture (g/100 g fresh material)	Lignin (g/100 g dry material)	Cellulose (g/100 g dry material)	Hemicellulose (g/100 g dry material)	Ash (g/100 g dry material)
El Coyol	42.4 ± 4.2^{b}	35.0 ± 4.8^{a}	25.9 ± 1.5^{a}	11.3 ± 3.5^{a}	3.5 ± 0.5^{a}
La Garita	44.0 ± 5.7^{b}	33.6 ± 3.1^{ab}	28.0 ± 0.5^{a}	5.1 ± 3.1^{a}	4.0 ± 0.1^{a}
La Palma	61.2 ± 4.6^{a}	23.2 ± 0.1^{b}	27.2 ± 0.9^{a}	10.0 ± 0.4^{a}	3.8 ± 0.5^{a}

(Table 4). Lignin concentrations (identified as acid detergent lignin) were significantly higher in fruits from “*El Coyol*” (35.0 ± 4.8 g / 100 g DM) than in those from *“La Palma”* (23.2 ± 0.1 g / 100 g DM). Samples from “*La Garita*” had an intermediate value that did not differ significantly to the other two locations. Cellulose contents varied from 28.0 ± 0.5 g / 100 g DM at “*La Garita*” to 25.9 ± 1.5 g / 100 g DM at “*El Coyol”*. Ash content was virtually the same for all locations with an average inorganic residue of 3.8 ± 0.5 g / 100 g DM.

Correlation Analysis

Significant positive correlations were found between the pulp oil content and precipitation as well as relative humidity. Also, positive correlations were found between pulp oil content and both sand and silt contents of the soils (Table 5). No significant correlations were observed between pulp oil content and annual average temperature.

Discussion

This study revealed large variations in biometric parameters and composition between *A. aculeata* fruits from different accessions in Costa Rica, as has been observed in previous studies performed both in Costa Rica (Schex et al. 2018) and other Latin American regions (Ciconini et al. 2013; Lescano et al. 2015; Castro et al. 2017; Coelho et al. 2019).

The fruits collected in Costa Rica were smaller than to those of Brazilian palms documented in several previous reports (Ciconini et al. 2013; Castro et al. 2017; Vianna et al. 2017). However, even smaller sizes have been reported for *A. aculeata* fruits at a similar maturity stage collected in Costa Rica (Schex et al. 2018) and for some Brazilian accessions (Manfio et al. 2011; Ciconini et al. 2013), indicating strong variability among populations. Large biometric variability is therefore characteristic of wild *Acrocomia* populations and has been associated with genetic variability and environmental influences – in particular soil chemical properties and soil water availability—on plant functioning (Manfio et al. 2011; Coelho et al. 2019).

Our data suggest that geographical location has a strong influence on the oil content of the pulp of ripe *A. aculeata* fruits from Costa Rica. The highest oil content was observed in "*La Palma*", with a mean value of 39.6 ± 2.1% pulp oil on a dry basis, followed by *"La Garita"* at 33.5 ± 2.0%, and "*El Coyol"* at 26.6 ± 2.2% (Table 3). Correlation data revealed that the fruits from the location with the highest annual rainfall and relative humidity (La Palma, Puntarenas) had the highest oil content in pulp (0.895 and 0.709; $p < 0.001$), indicating that precipitation may be an important determinant of oil content. These results are in agreement with other studies from Brazil where *A. aculeata* palms perform better and have higher oil contents in regions with higher precipitation (Castro et al. 2017).

This finding on the strong influence of precipitation is also supported by the even lower oil content previously reported in pulp from fruits collected in "*Bagaces*" (Guanacaste, Costa Rica), a dry region on the northwest Pacific coast (Schex et al. 2018; Lieb et al. 2019). Additionally, the lowest pulp and kernel oil contents measured in the present study were found in the largest fruits, harvested at the site "*El Coyol*", suggesting that biometric parameters may also influence oil content. In line with our results, Ciconini et al. (2013) found that smaller *A. aculeata* fruits growing in Mato Grosso do Sul, Brazil, had higher kernel oil content. Fruit size determination in plants is multifactorial, involving genetic, environmental and other factors such as nutrient availability and pollination efficiency (Guo and Simmons 2011). Other oleaginous crops, such as olive (*Olea europaea* L.), also reveal an inverse relation between fruit size and oil concentration, which is steered by the source-sink ratio (Trentacoste et al. 2010). However, further observations are required to be able to draw ultimate conclusions for the selection of *A. aculeata* accessions with the optimal fruit size for high oil contents.

The pulp oil concentration varied significantly between accessions, even between the fruits from the relatively close locations of "*La Garita*" and "*El Coyol"*. It can be assumed that closer populations share more genetic similarities, have developed under similar environmental conditions and thus display comparable phenotypic fruit characteristics. However, samples from "*La Garita"* were obtained from a genotype originating from Brazil whereas those from

Table 5 Spearman Rho correlation test between pulp oil content (g/100 g dry material) and environmental and soil parameters from three different locations in Costa Rica

Variable	Correlation coefficient	*P* value
Precipitation (mm/year)	0.895	≤ 0.001
Annual temperature (°C)	0.243	0.223
Average relative humidity (%)	0.709	≤ 0.001
Sand (%)	0.756	≤ 0.001
Slit (%)	0.861	≤ 0.001
Clay (%)	− 0.756	≤ 0.001

other origins are assumed to come from more indigenous genotypes. Further analysis of the genetic background of Costa Rican populations is necessary to assess whether they provide suitable material for variety development and how they compare to genotypes of Brazilian origin.

Nevertheless, pulp oil contents of the Costa Rican fruits in this study were higher than those reported for populations in the Brazilian regions of Cerrados, Pantanal (25.1%) (Ciconini et al. 2013) and Mato Grosso do Sul (23.6 ± 1.1%) (de Oliveira et al. 2017). This may be explained by the lower precipitation in these Brazilian regions and confirms the positive correlation observed in this study between pulp oil content and precipitation level. By contrast, similar levels of pulp oil content to those found in the Costa Rican fruits have been reported for fruits from the Brazilian state of Minas Gerais, although precipitation at that location was relatively low (1200 mm) (Montoya et al. 2016). This could be related to the large genetic diversity observed in this species (Abreu et al. 2012; Oliveira et al. 2012; Araújo et al. 2017) and the fact that the highest kernel oil content in our Costa Rican study was found for the *Acrocomia* genotype that originates from Brazil, growing at the location "*La Garita*".

There were significant differences in kernel oil content between the three locations assessed in this study, with wide variation in values. The mean oil content of 54% of the total kernel mass (by dry weight; lowest value: 48.7 ± 4.9% and highest: 58.4 ± 2.1%) was similar to the 53 and 56% reported for Costa Rican samples from the *"Bagaces"* region (Schex et al. 2018; Lieb et al. 2019). It is also comparable to those reported for Brazilian samples (Belén-Camacho et al. 2005; Lescano et al. 2015), with the exception of one publication that cited higher values of 63.5–68.9% (Ciconini et al. 2013).

These results suggest that the oil content in pulp may be more influenced by environmental or genetic variation than that of kernels. However, although the kernels have a higher oil content than the pulp, the total oil yield from *Acrocomia* is mainly determined by the oil content of the pulp, as this accounts for a higher mass proportion of the fruit.

The lipids extracted from the pulp and kernel fractions exhibit completely different characteristics, and this has implications for their application in potential final products (Del Río et al. 2016; Souza et al. 2016). The oil extracted from the pulp of *A. aculeata* fruits from Costa Rica was mainly composed of unsaturated fatty acids, while the lipid fraction obtained from the kernels was rich in short-chain saturated fatty acids, predominantly lauric acid. This confirms findings by Coimbra and Jorge (2012) for differences in pulp and kernel oil from Brazilian *Acrocomia* fruits.

Chemical similarity to oil obtained from the African oil palm (*Elaeis guineensis* Jacq.) may indicate potential applications for *Acrocomia* oil. *E. guineensis* is one of the most important oil crops, accounting for approximately 40% of global vegetable oil production. Its fatty acid profile and low costs are considered two key factors that make pulp oil from *E. guineensis* particularly suitable for industrial applications (Choudhary and Grover 2019). By comparison, *A. aculeata* fruits from Costa Rica had lower proportions of saturated palmitic acid and higher proportions of the monounsaturated oleic acid (Lieb et al. 2017).

Unsaturated fatty acids are considered "healthy" fats because of their beneficial cardiovascular effects (Lunn and Theobald 2006). However, they are more susceptible to oxidation and the generation of undesired compounds, while oils with higher content of saturated fatty acids have a higher oxidative stability and are thus more suitable for a number of industrial applications (Souza et al. 2016). Nonetheless, it has been suggested that despite its unsaturated nature, high concentrations of oleic acid may increase oil oxidative stability and thermal operability at low temperatures and these could be useful characteristics for the food industry and biodiesel production (Nunes et al. 2015; Del Río et al. 2016; Lieb et al. 2017).

The fatty acid composition of pulps from *"La Garita"* and *"El Coyol"* (Alajuela) were the closest to those reported for *E. guineensis.* For these two neighboring locations, pulp oleic acid content averaged 46.4% and palmitic acid 25.1%. The composition of the oil extracted from fruit pulps in *"La Palma"* exhibited completely different characteristics, with higher content of oleic acid (76.4%) and lower content of palmitic acid (14%). In general, the fatty acid profiles of the samples taken from Costa Rican *A. aculeata* were similar to those reported for Brazilian accessions, where oleic acid was also the main component (between 55 and 60%), followed by palmitic acid (between 19 and 23%) and linoleic acid (between 4 and 10%) (Coimbra and Jorge 2012; Nunes et al. 2015; Del Río et al. 2016; Prates-Valério et al. 2019). For *E. guineensis* accessions, oleic acid contributed 36% and palmitic acid 39% to the total pulp fatty acids (Prates-Valério et al. 2019).

The lipid fraction obtained from *E. guineensis* kernels is considered a valuable product with applications in the cosmetic, pharmaceutical (Kalustian 1985) and food (Ali and Dimick 1994; Keng et al. 2009) industries. Palm kernel oil and other lauric acid-containing oils are extensively used in a wide range of cosmetic and pharmaceutical formulations as direct additives or as a source of modified chemical compounds (Kalustian 1985). The fatty acid composition of kernel oil obtained from *A. aculeata* fruits from Costa Rica showed a similar composition to that of *E. guineensis* (Kalustian 1985; Keng et al. 2009; Lieb et al. 2017), suggesting that this new source could be used for similar purposes (Belén-Camacho et al. 2005; Coimbra and Jorge 2012; César et al. 2015; Del Río et al. 2016).

E. guineensis kernel oil is rich in lauric acid (between 48 and 55%) and oleic acid (up to 15%) (Kalustian 1985; Keng et al. 2009; Lieb et al. 2017). As observed for pulp oil, kernel oil from fruits collected in *"El Coyol"* and *"La Garita"* was closer in composition to that of *E. guineensis,* with 43.4% lauric acid and 17.2% oleic acid. However, the fatty acid profile of kernels collected in "La Palma" was considerably lower in lauric acid (36%) and higher in oleic acid (26.4%). Kernel oil from *"Bagaces"* (Guanacaste, Costa Rica) has characteristics similar to those from *"El Coyol"* and *"La Garita"*, which means that lauric acid was also the predominant fatty acid (41.6–42.9%), followed by oleic acid (around 20%) (Lieb et al. 2019). In contrast, the kernel oil extracted from fruits in Minas Gerais (Brazil) displayed a similar chemical composition to the ones from "*La Palma*", with lower lauric acid (32%) and higher oleic acid concentrations (28%) (Coimbra and Jorge 2012; Del Río et al. 2016).

As summarized by Efendy Goon et al. (2019), fatty acid composition of kernel and pulp oils obtained from *E. guineensis* can be significantly modified by fractioning, bleaching and other industrial operations. The refining of *Acrocomia* oil may provide oil fractions with different fatty acid compositions for particular industrial applications (Nunes et al. 2015), a field that has not yet been explored for Costa Rican fruits. The development of *Acrocomia*'s potential as a source of enriched lipid fractions may promote an increased valorization of this resource.

Industrial extraction of oil from *A. aculeata* fruits will result in the production of byproducts mainly from the husk fraction (Colombo et al. 2018; Prates-Valério et al. 2019). To extend the efficiency of the energy generation process and increase profits, it is advisable to exploit potential byproducts that can provide an added value, for example through use in the production of combustion-derived energy, carbon and activated charcoal (Evaristo et al. 2016).

For combustion, materials with low ash and moisture contents and high lignin content are preferred, since these factors influence the calorific value and thus the energy yield (Kiesel et al. 2017). From a compositional perspective, the husks of the fruits collected from "*El Coyol*" (with the highest lignin and lowest ash content) were the most suitable for energy generation. However, these fruits did not have the highest husk proportion of the accessions. The largest husk and smallest shell fractions were obtained in the "*La Palma*" location but these had lower lignin contents than at the other two locations and, consequently, a lower heating value.

After oil extraction, the cakes obtained from both pulp and kernel are mainly composed of fiber and protein (Evaristo et al. 2016) and could potentially be used as animal feed (Traese et al. 2015; Del Río et al. 2016). The chemical composition, in particular with regard to any anti-nutritional compounds and thus the economic potential of this material, needs to be further assessed. However, as these did not form part of this study, they are not addressed here.

Acrocomia is a crop unfamiliar to farmers in Costa Rica. For this reason, its successful adoption requires farmers to be informed of its potential and provided with productive genotypes and effective production technology. The harvest practices applied in this study are those commonly used in the commercial utilization of *Acrocomia*. However, much of the reported variation in composition of *Acrocomia* fruits has been attributed to a lack of reproducibility of the harvesting method. Traditional harvesting of *Acrocomia* fruits involves collecting self-detached fruits lying on the ground. As it is known that the ripening stage has an effect on fruit composition (Montoya et al. 2016; Kiesel et al. 2017), future research should focus on the standardization of harvesting methods. Commercial cultivation of *Acrocomia* may require the development of standardized harvesting protocols, similar to those available for *E. guineensis* (Nunes et al. 2015).

However, it is to be expected that *Acrocomia* will be produced in systems different from the plantation management practiced for *E. guineensis. Acrocomia* adapts more easily to environments with lower competition for light and nutrients than to dense forests (Coelho et al. 2019). Therefore, it is probably more suitable for agroforestry systems than for plantation management. Moreover, in Brazil, *Acrocomia* has a broader geographical distribution than *E. guineensis*, including dry areas (Cardoso et al. 2017). Thus, *Acrocomia* could also be grown for oil production in regions or under conditions not suitable for *E. guineensis.* As *Acrocomia*—unlike *E. guineensis*—occurs naturally mostly in areas outside of tropical rainforests (Plath et al. 2016), the production of vegetable oil from *Acrocomia* would not compete with rainforest regions and could reduce the pressure on its deforestation. Instead, Cardoso et al. (2017) recommend the production of *Acrocomia* in integrated systems. In this way, the benefits of agroforestry systems can be taken advantage of. These include, for example, the improved environmental performance and yields of concomitant crops, as have been reported for intercropping of *Acrocomia* with coffee (Moreira et al. 2018). At the same time, *Acrocomia* production allows for the diversification of goods for local producers, as it delivers a high-value agricultural product—i.e. vegetable oil—and multiple by-products, such as press cake and shells suitable for food, feed or energetic uses. However, this is only true if a market for these novel goods exists. For this reason, before farmers are motivated to plant *Acrocomia* palms, consumer studies need to be performed on the demand for and acceptance of such products. With the observed trend towards high levels of acceptance for (more) sustainably produced goods (see e.g., Koh and Lee 2012), *Acrocomia* products may have a good chance of adoption by the consumer if appropriate information is provided together with the product.

Conclusions

Costa Rican *Acrocomia aculeata* pulp oil is rich in unsaturated fatty acids, especially oleic acid, and kernel oil is rich in short-chain saturated fatty acids, mainly lauric acid. *A. aculeata* oils have similar compositions to those of the African oil palm *E. guineensis* and may be a more sustainable alternative for applications in the cosmetic, pharmaceutical, chemical and food industries, as well as for the production of biodiesel.

As smaller-sized fruits were found to have higher oil contents, the selection of genotypes with small fruits may be a suitable approach for the breeding of commercial varieties in Costa Rica. However, as the overall fruit yield per palm tree was not assessed in this study, further investigations along these lines are necessary before selection criteria for the most promising genotypes can ultimately be recommended.

For the selection of high oil yielding genotypes for Costa Rican locations, *Acrocomia* from Brazil should be tested along with native genotypes. Also, selection should rather focus on genotypes with high pulp oil than high kernel oil content because the pulp accounts for a higher mass proportion of the fruit.

Further investigations into genetic diversity, harvesting methodologies and the effect of oil processing on its chemical composition are required to implement agricultural production and industrial applications of vegetable oils from *A. aculeata*.

Its properties make *Acrocomia* most suitable for integration into agricultural production systems that benefit from an increased yield of concomitant crops and an improved environmental performance. As shown by this study, the farmer can benefit from producing vegetable oils for high-value products, including food, cosmetics and pharmaceuticals, together with by-products that are usable for food, feed, chemicals and energy production.

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Appendix 1

See Table 6.

Table 6 Physical and chemical characteristics of the soil samples collected at each location

Variable analysed	El Coyol	La Garita	La Palma
Sand (%)	30	42	35
Silt (%)	8	18	18
Clay (%)	62	40	47
pH	6.5	6.6	6.4
Acidity (cmol/L)	0.11	0.11	0.17
Ca (cmol/L)	13.51	12.53	23.29
Mg (cmol/L)	4.07	4.29	9.39
K (cmol/L)	1.12	1.00	0.27
CEC (cmol/L)	18.81	17.93	33.12
SA (%)	0.6	0.6	0.5
P (mg/L)	2	5	4
Zn (mg/L)	6.5	2.4	1.8
Cu (mg/L)	19	13	9
Fe (mg/L)	72	63	51
Mn (mg/L)	18	3	14
EC (mS/cm)	0.3	0.2	0.1

CEC cation exchange capacity = acidity + Ca + Mg + K

SA acidity saturation percentage = acidity/CEC*100

EC electric conductivity

Appendix 2

See Table 7.

Table 7 Verification of data normality by the test of Anderson-Darling with a significance level of 0.05

Variable	P value	N	Mean
Longitudinal diameter (cm)	0.841	19	4.262
Transversal diameter (cm)	0.416	19	4.304
Fresh weight of the fruit (g)	0.569	19	40.42
Dry weight of the fruit (g)	0.038	15	21.8
Fresh weight of the husk (g)	0.666	19	10.13
Dry weight of the husk (g)	0.808	19	5.126
Fresh weight of the pulp (g)	0.034	19	18.79
Dry weight of the pulp (g)	0.135	17	8.323
Fresh weight of the shell (g)	0.504	19	8.425
Dry weight of the shell (g)	0.082	18	6.828
Fresh weight of the kernel (g)	0.616	19	3.072
Dry weight of the kernel (g)	0.436	16	2.537

Appendix 3

See Table 8.

Table 8 Verification of homogeneity between variances by the test of Levene with a significance level of 0.05

Variable	P value
Longitudinal diameter vs. Location	0.389
Transversal diameter vs. Location	0.114
Fresh weight of the fruit vs. Location	0.928
Fresh weight of the husk vs. Location	0.287
Fresh weight of the pulp vs. Location	0.247
Fresh weight of the shell vs. Location	0.297
Fresh weight of the kernel vs. Location	0.118
Water content of the husk (%) vs. Location	0.914
Oil content in the kernel (%) vs. Location	0.645
Oil content in the pulp (%) vs. Location	0.702
Capric acid in kernel (%) vs. Location	0.484
Lauric acid in kernel (%) vs. Location	0.669
Oleic acid in kernel (%) vs. Location	0.534
Caprylic acid in kernel (%) vs. Location	0.305
Myristic acid in kernel (%) vs. Location	0.250
Oleic acid in pulp (%) vs. Location	0.234
Palmitic acid in pulp (%) vs. Location	0.367
Stearic acid in pulp (%) vs. Location	0.169
Linoleic acid in pulp (%) vs. Location	0.435

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