Vol. 23, No. 2(2024) Alim24220
Revista Mexicana de Ingeniería Química

Influence of geographical location and type of thermal treatment on the nutritional and physicochemical properties of pacaya inflorescences

Influencia de la localidad de crecimiento y tipo de tratamiento térmico aplicado en las propiedades nutricionales y fisicoquímicas de inflorescencias de pacaya

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Received: November 30, 2023; Accepted: January 30, 2024

Abstract

In this study, the effects of thermal treatment and geographical location on the nutritional profile, techno-functional properties, and chemical-structural changes of *Chamaedorea tepejilote* were investigated. The results showed that both parameters caused changes in lipid and crude fiber content. The techno-functional properties (water absorption capacity, oil absorption capacity, swelling capacity, and solubility in water) showed significant differences ($p < 0.05$) due to thermal treatment, with cooking in the microwave and thermal treatment yielding the lowest values. Geographical location caused differences ($p < 0.05$) especially in water solubility, which was associated with changes in crude fiber composition. The FTIR spectrum showed changes in the profiles, especially in the bands associated with cellulose, pectin, hemicellulose, and protein signals. This is due to the high temperature, steam pressure, and microwave during the thermal treatment, but also to the geographical location; perhaps both parameters triggered the hydrolysis of the bonds of these biomolecules. According to the results of this work, geographical location and thermal treatment are parameters that influence the physical, chemical, and techno-functional properties of pacaya inflorescences.

Keywords: *Chamaedorea tepejilote*, techno-functional, properties, FTIR, thermal treatments, geographic location.

Resumen

En este estudio se evaluaron los efectos del tratamiento térmico y la ubicación geográfica sobre el perfil nutricional, las propiedades tecno-funcionales y los cambios químico-estructurales de *Chamaedorea tepejilote*. Los resultados mostraron que ambos parámetros indujeron cambios en el contenido de lípidos y fibra cruda. Las propiedades tecno-funcionales (capacidad de absorción de agua, capacidad de absorción de aceite, capacidad de hinchamiento y solubilidad en agua) mostraron diferencias significativas ($p < 0.05$) debido al tratamiento térmico, siendo la cocción con microondas y el tratamiento térmico los que arrojaron los valores de propiedades más bajos. Por otro lado, la ubicación geográfica provocó diferencias ($p < 0.05$) principalmente en la solubilidad en agua asociada con cambios en la composición de la fibra cruda. El espectro FT-IR mostró cambios en los perfiles, especialmente en las bandas asociadas a señales de celulosa, pectina, hemicelulosas y proteínas. Esto se debe a la alta temperatura, la presión del vapor y el microondas durante el tratamiento térmico, pero también la ubicación geográfica; quizás ambos parámetros desencadenaron la hidrólisis de los enlaces de estas biomoléculas. Según los resultados de este trabajo, la ubicación geográfica y el tratamiento térmico son parámetros que influyen en las propiedades físicas, químicas y tecno-funcionales de las inflorescencias de pacaya.

Palabras clave: *Chamaedorea tepejilote*, tecno-funcionales, propiedades, FTIR, tratamientos térmico, ubicación geográfica.

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https://doi.org/10.24275/rmiq/Alim24220
ISSN:1665-2738, *issn-e*: 2395-8472

1 Introduction

Most vegetables are usually consumed after they have been treated with traditional (boiled, roasted, or fried) or innovative (microwave, steam with increased pressure, electric pulses, etc.) thermal processes. However, regardless of the type of treatment, water or oil is almost always used as the heat transfer medium (Pérez-Burillo *et al*., 2019). In this context, there is controversy about the advantages and disadvantages of heat treatments in the processing of vegetables. Some authors have made five important points about the benefits of heat treatments: (1) inactivation of pathogens in foods, (2) inactivation of toxins and degradative enzymes, (3) high nutritional value due to improved digestibility and bioavailability of nutrients, (4) important sensory quality due to improvement of flavor, texture and aroma, and finally (5) health benefits due to the biological activity of their components (*e.g*. prebiotic, anticancer, antioxidant, etc.) (van Boekel *et al*., 2010). In contrast, other authors point out that thermal processing can negatively affect the nutritional, organoleptic, physical, and chemical properties, which has an impact on food quality and consumer acceptance (Ma *et al*., 2011; Liu *et al*., 2020).

However, regardless of the positive effect of heat treatment on vegetables, it has been shown that parameters such as the type of plant, the type of heat treatment, the temperature, the time of processing, the pH value, the heat transfer, the physicochemical properties of the vegetables and the place of growth cause changes in the nutritional, chemical and sensory properties of the final product (Toydemir *et al*., 2020; Morales-Tapia *et al*., 2022). Of all these parameters, the growing site is considered the most important, as some biotic and abiotic conditions are unique to each area, such as climatic conditions, temperature, soil properties, irrigation, fertilization and light intensity. These factors can influence the growth, physicochemical, and nutraceutical properties of vegetables, as some authors have already reported for chia (*Salvia hispanica* L.) (Wang *et al*., 2023), apples (*Malus domestica*) (McGhie *et al*., 2005) and leafy vegetables of Amaranthus, cowpea and moringa (Sivakumar *et al*., 2018).

The pacaya or tepejilote palm (*Chamaedorea tepejilote* Liebm) is a species that grows in southern Mexico, Central America and north-eastern Colombia. It is mainly used as an ornamental plant and a traditional food (Castillo-Mont *et al*., 1994). The inflorescence of the pacaya is consumed by Mexican indigenous communities in Veracruz, Oaxaca, and Chiapas after traditional thermal treatment (*e.g.*, roasted, fried or boiled) or mixed with other ingredients (*e.g.*, eggs and tomato sauce) (Castillo-Mont *et al*., 1994). Some authors have reported that pacaya powder is present in commonly consumed Mexican foods such as tostadas, chorizo, and breakfast cereals (Montejos Ramos and Márquez Montes, 2012; Palacios Pola *et al*., 2014). From a nutritional point of view, according to Centurión-Hidalgo *et al*. (2009), Montejos Ramos and Márquez Montes (2012), and Palacios Pola *et al*. (2014), male pacaya inflorescences are an excellent source of proteins (1.14-24.19 %), lipids (1.61-5.95 %), crude fiber (6.14-12.16 %) and carbohydrates (36.47-62.43 %). In addition, some authors have described the nutraceutical properties of pacaya as having hypoglycemic (Riquett Robles and Solórzano Carranza, 2013; Carola Cruz and Andrade-Cetto, 2015), antitussive, and antimicrobial activity (Pérez *et al*., 2008) in extracts from the inflorescences without thermal treatment. For this reason, it is important to analyze the effects of traditional and innovative thermal treatments on the physicochemical, nutritional, and techno-functional properties of traditionally consumed vegetables, as in the case of tepejilote.

2 Materials and methods

2.1 *Conditioning of plant material*

Male inflorescences of *Chamaedorea tepejilote* Liebm palms were harvested in February 2020. This study compared two geographical locations in Chiapas, Mexico (Tapachula and Comitán). The yellow inflorescences, which showed no mechanical or microbiological damage, were cut into cubes of about 1 cm and stored in batches of 300 g under vacuum in PVC bags. The bags were refrigerated at 4 °C for no longer than 24 hours before thermal processing (LG model GR-452SH refrigerator, LG electronics, Monterrey, N.L., Mexico).

2.2 *Thermal treatments*

The thermal treatments were carried out under conditions previously described by Hernández-Castillo *et al*. (2020). Briefly, the hydrothermal treatment was performed in a water bath at 90° C for 15 minutes; for microwave cooking, the samples were placed in a microwave oven (model Goldstar MS-157XC, LG Corp., Seoul, Korea) at 1500 watts with an operating frequency of 2450 MHz for 15 minutes at 90ºC. For steaming under elevated pressure, the samples were placed on a tray in a pressure cooker and steamed for 15 minutes at 125 °C and a pressure of 124,106 Pa. All samples with and without thermal treatment were freeze-dried using a laboratory freeze-dryer (Scientz-10N, Ningbo, China). Samples were labeled as hydrothermal treatment (HT), steaming at

elevated pressure (SEP), microwave cooking (MC), and without thermal treatment (WTT).

2.3 Proximal chemical characterization

The chemical proximate analysis was determined according to the official methods of the Association of Official Agricultural Chemists (AOAC, 1995): Moisture content was determined by method No. 925.09, crude protein by the micro-Kjeldahl method (No. 955.04, using a conversion factor of N × 6.25), crude lipid by method No. 920.39, and crude fiber by method No. 923.03. Carbohydrates were calculated by difference as indicated in equation 1.

$$Carbohydrates(\%) = 100 - (\%CP + \%L + \%CF + \%A) \quad (1)$$

Where CP is crude protein content (%), L is lipids content (%), CF is crude fiber content (%), and A is ash content (%).

2.4 Techno-functional properties

2.4.1 Water absorption capacity (WAC)

This property was determined according to the method described by Bashir *et al*. (2017) with some modifications, 3 g of inflorescence of pacaya powder was dispersed in 25 mL of distilled water. Then the tube was shaken at room temperature for 30 minutes and centrifuged at 3000 rpm for 15 minutes (Centrificient IV, CRM globe, USA). The supernatant was decanted, and the centrifuge tube was reweighed. The WAC was expressed as grams of water absorbed per gram of pacaya powder, as shown in Equation 2.

$$WAC(g/g) = \frac{(m_3 - m_2) - m_1}{m_1} \quad (2)$$

Where m_1 is the weight of the pacaya powder of the inflorescences (g), m_2 is the weight of the centrifuge tube (g), and m_3 is the weight of the centrifuge tube + residue (g).

2.4.2 Oil absorption capacity (OAC)

OAC was measured according to the method described by Bashir *et al*. (2017). In a previously weighed centrifuge tube, 0.5 g of the pacaya powder of the inflorescences was dispersed in 6 mL of corn oil. The mixture was shaken for 1 minute for a perfect distribution of the sample in the oil. After 30 minutes, the sample was centrifuged at 3000 rpm for 15 minutes. The oil layer was completely removed with a pipette. The OAC was calculated using Equation 3.

$$OAC(g/g) = \frac{(m_3 - m_2) - m_1}{m_1} \quad (3)$$

Where m_1 is the weight of the pacaya powder of the inflorescences (g), m_2 is the weight of the centrifuge tube (g), and m_3 is the weight of the centrifuge tube + residue (g).

2.4.3 Swelling capacity (SC)

SC was determined according to the method described by Chen *et al*. (2015). 200 mg of the pacaya powder from the inflorescences was placed in a graduated cylinder containing 10 mL of distilled water, the mixture was allowed to settle at room temperature, and the final volume was measured after 18 h. The SC was calculated using Equation 4.

$$SC(mL/g) = \frac{V_1}{m_1} \quad (4)$$

s Where V_1 is the volume (mL) occupied by the sample, and m1 is the weight (g) of the sample.

2.4.4 Solubility in water (SW)

SW was evaluated according to the method described by Dong *et al*. (2020). 500 mg of the pacaya powder of the inflorescences was mixed vigorously with 5 mL of distilled water in a centrifuge tube. The mixture was incubated (90 °C for 30 minutes) and centrifuged at 4000 rpm for 15 minutes. The supernatant was collected, dried at 105 °C and weighed. The SW was calculated using Equation 5.

$$SW(\%) = \frac{m_2}{m_1} \times 100 \quad (5)$$

Where m_1 is the weight of pacaya powder (g) and m_2 is the weight of dried supernatant (g).

2.5 Fourier transform-infrared spectroscopy (FTIR) characterization

The FTIR spectral data of the pacaya powder of the inflorescences were recorded using a Perkin Elmer FTIR spectrophotometer (Perkin Elmer Inc., MA, USA). The discs were prepared with potassium bromide (KBr). The spectra (16 scans) were recorded in transmission mode with a 4000 to 400 cm^{-1} resolution. Origin Pro software, version 2021 (OriginLab Corporation, Northampton, MA, USA), was used for peak signal analysis.

2.6 Experimental design and statistical analysis

The experiments were carried out in a completely randomized two-factor factorial design. The factor of geographical location was assessed at two levels: Tapachula and Comitán. The thermal treatment factor was evaluated at four levels: hydrothermal treatment (HT), steaming at elevated pressure (SEP), microwave cooking (MC), and without thermal treatment (WTT).

A two-way analysis of variance (ANOVA) was performed, followed by a *post hoc* Tukey-Kramer test (multiple comparisons of means) to determine differences between the means. The data of the variable water solubility (SW), expressed as a percentage, were transformed with the arcsine function before the ANOVA was performed. The Pearson correlation test was used to determine the relationship between the nutritional and techno-functional variables. The statistical analyses were performed with a p-value < 0.05. The Origin Pro statistical package, version 2021 (OriginLab Corporation, Northampton, MA, USA), was used for the bivariate statistical analysis. The statistical package XLSTAT version 2023 (Lumivero, 2023) was used for multivariate analysis (Pearson's correlation test).

3 Results and discussion

The data of the nutritional characteristics of the pacaya inflorescences from Tapachula Chiapas were presented at the 3rd International Electronic Conference on Foods: Food, Microbiome, and Health-A Celebration of the 10th Anniversary of Foods' Impact on Our Wellbeing (Mancera-Castro *et al*., 2022).

3.1 Nutritional characterization

Table 1 shows that the geographical location has an influence on the nutritional properties of pacaya inflorescences before thermal treatment. The pacaya inflorescences from Chiapas (Tapachula and Comitán) have between 7.3 and 30.35% higher protein content, 11.45-15.79% more lipids and 18.7-24.72% more crude fiber compared to the pacaya from Acapetahua and La Independencia, Chiapas, and Teapa, Tabasco. According to Padayachee *et al*, 2017 and Churkova (2013), these results could be related to climatic conditions, as they indicate that the concentration of crude fiber increases when the temperature and rainfall are higher, which is due to the fact that the fiber is the support of the plants and regulates the permeability of the cell wall, in this sense, the Mexican National Meteorological Service reported that between April and June of the year 2020, the total rainfall (mm) was 44.8 to 216.6 and 79.8 to 368.6 for Comitán and Tapachula, respectively; and the average temperature (°C) was 20.4 to 21.0 and 26.7 to 28.2 in the same regions. For this reason, the pacaya from Comitán appear to have a lower crude fiber content than the pacaya from Tapachula.

The values of the chemical proximate analysis of inflorescences from Tapachula were higher than those of inflorescences from Acapetahua, Chiapas (~2.26 %) (Palacios Pola *et al*., 2014), Teapa, Tabasco (~12.63 %) (Centurión-Hidalgo *et al*., 2009), and La Independencia, Chiapas (~4.53 %) (Montejos Ramos and Márquez Montes, 2012), while the values of the chemical proximate analysis of the inflorescences from Comitán were higher than inflorescences from Acapetahua, Chiapas (~4.43 %) (Palacios Pola *et al*., 2014), Teapa, Tabasco (~14.56 %) (Centurión-Hidalgo *et al*., 2009), and La Independencia, Chiapas (~6.64 %) (Montejos Ramos & Márquez Montes, 2012). According to Kasale *et al*. (2019) and Adebayo *et al*. (2020), these variations are related to differences in variety, genotype, phenotype, soil type, irrigation, climatic conditions, fertilization, and light intensity. This behavior was also observed in some other vegetables and seeds, such as pepper (*Capsicum* spp.) (Lee *et al*., 2005) and flax (*Linum usitatissimum* L.) (Jarošová *et al*., 2024). In contrast, crude protein and ash showed no significant differences ($p > 0.05$) (Table 2).

The results (Table 2) show that the geographical location and the type of thermal treatment (HT, SEP, and MC) influenced some nutritional components of pacaya inflorescences. MC was the only thermal treatment that showed a significant decrease ($p < 0.001$) in the lipid content of the sample, while the protein, ash, and crude fiber content of the samples did not change ($p > 0.05$).

Table 1. Proximal composition of inflorescences of pacaya from differents locations.

Geographic location	Proteins	Lipids	Crude fiber	Carbohydrates	Reference
Acapetahua, Chiapas	13.06	4.14	6.14	59.92	Palacios-Pola *et al*. (2014)
Teapa, Tabasco	24.19	1.61	12.16	36.47	Centurión-Hidalgo *et al*. (2009)
La Independencia, Chiapas	1.14	5.95	11.81	62.43	Montejos Ramos & Márquez Montes (2012)
Tapachula, Chiapas	31.49	10.80	30.86	12.04	Experimental
Comitán, Chiapas	31.24	17.40	13.84	24.64	Experimental

Data are expressed on a dry weight basis (g/100 g).

Table 2. Proximate composition of pacaya inflorescences from two geographical locations in Chiapas, Mexico, and with different thermal treatments (g/100g dry sample).

Geographical location	Treatment	Crude protein	Lipids	Crude fiber	Ash	Carbohydrates
		g/100g dry sample				
Tapachula	WTT	31.49±0.59^{a}	10.80±0.46^{b}	30.86±0.24^{a}	14.81±0.46^{a}	12.04±0.08^{d}
	HT	31.39±0.92^{a}	11.51±0.44^{b}	31.76±0.51^{a}	12.40±0.16^{b}	12.94±0.37^{d}
	SEP	31.81±1.27^{a}	10.82±0.36^{b}	28.88±1.99^{a}	13.00±1.91^{ab}	14.50±2.47^{d}
	MC	30.53±0.80^{a}	6.77±1.12^{c}	31.39±0.89^{a}	12.98±1.03^{ab}	18.33±1.02^{c}
Comitán	WTT	31.24±0.92^{a}	17.40±0.73^{a}	13.84±0.17^{b}	12.87±0.13^{ab}	24.64±1.02^{b}
	HT	32.59±0.61^{a}	17.80±0.96^{a}	13.21±0.54^{b}	13.60±0.07^{ab}	22.80±1.09^{b}
	SEP	32.02±0.82^{a}	16.66±0.39^{a}	13.89±0.14^{b}	13.00±0.27^{ab}	24.43±1.30^{b}
	MC	31.18±0.96^{a}	12.50±0.16^{b}	14.46±0.18^{b}	13.44±0.08^{ab}	28.43±0.84^{a}
* Two-way ANOVA (p-value < 0.05)						
A: Geographical location		> 0.05	< 0.001	< 0.001	> 0.05	< 0.001
B: Treatment		> 0.05	< 0.001	> 0.05	> 0.05	< 0.001
Interaction: $A \times B$		> 0.05	> 0.05	> 0.05	< 0.05	> 0.05

Without thermal treatment (WTT), hydrothermal treatment (HT), steam cooking at elevated pressure (SEP), microwave cooking (MC) and carbohydrates (CH). The results are the mean ± standard deviation (n = 3). The superscript letters within each column indicate significant differences at $p < 0.05$. *In two-way ANOVA, the p-values in bold represent a significant statistical effect at $p < 0.05$.

In addition, the results showed that the geographical location of development had a statistically significant effect ($p < 0.05$) on the lipid, crude fiber and carbohydrate content, with the crude fiber content in the inflorescences from Tapachula being about twice as high (~30.86 %) as into the inflorescences from Comitán (~13.84 %). However, the inflorescences from Comitán had a higher lipid and carbohydrate content than the inflorescences from Tapachula (about 0.5-fold and one-fold, respectively).

According to Zhang *et al*. (2014), Waseem *et al*. (2022), and Amor *et al*. (2023) the decrease ($p < 0.001$) in lipid content in the MC samples could be due to lipid oxidation caused by the high temperature, high pressure, or microwave power used in this work. The stability of protein and ash content could be due to the fact that the pacaya inflorescences were vacuum-packed in PVC bags before each thermal treatment, which reduces leaching by the cooking water, as reported by Lutz *et al*. (2011), Ahmed and Ali (2013), Badwaik *et al*. (2015), Doniec *et al*. (2022) and Waseem *et al*. (2022). The crude fiber content does not change because the temperature and duration of the thermal treatment were not high enough to hydrolyze the fibers or change their solubility, as reported by Ahmed and Ali (2013) and Tejada-Ortigoza *et al*. (2016).

Several authors have reported about the chemical composition of pacaya inflorescences without thermal treatment from different geographical areas in Mexico. Regarding ash content, the values were ~4.85 % lower than in inflorescences from Tabasco reported by Centurión-Hidalgo *et al*. (2009) and similar to inflorescences from Acapetahua, Chiapas (Palacios Pola *et al*. 2014). In this sense, the protein content in the inflorescences in this work was higher than the values reported by Palacios Pola *et al*. (2014) (~18.43 %) and Montejos-Ramos and Márquez Montes (2012) (~30.25 %) for inflorescences from Tabasco and Chiapas, respectively. In this work, geographic location influenced crude fiber content, as values from Tapachula were higher than those from Comitán. Other studies have reported that the chemical composition of fruits and vegetables such as carrots (Kasale *et al*., 2019), tomatoes (Adebayo *et al*., 2020) and peppers (Kim *et al*., 2019) was also influenced by geographical location.

3.2 Techno-functional properties

The results (Table 3) show that the geographical location has no significant statistical influence ($p > 0.05$) on the WAC values. However, the type of thermal treatment showed significant statistical differences ($p < 0.001$), with a significant decrease, especially in the microwave treatment.

Table 3 shows that the geographical location had a statistical influence on the OAC values ($p < 0.001$) as the powders from pacaya inflorescences from Tapachula had higher values ($p < 0.001$) than the powders from pacaya inflorescences from Comitán. Likewise, it was observed that thermal treatments caused a significant statistical decrease ($p < 0.001$) due to the effect of high temperatures; according to Twarogowska *et al*. (2020) the temperature and pressure can alter the structure, which is associated with changes in the porous matrix responsible for absorption capacity (Tejada-Ortigoza *et al*., 2018).

Table 3. Techno-functional properties of pacaya inflorescences from two geographical locations in Chiapas, Mexico.

Geographic location	Treatment	WAC g/g	OAC g/g	SC mL/g	SW %
Tapachula	WTT	5.27 ± 0.08^{c}	2.22 ± 0.02^{b}	9.95 ± 0.50^{bc}	43.12 ± 0.92^{a}
	HT	6.10 ± 0.02^{b}	1.95 ± 0.04^{c}	8.61 ± 0.80^{cd}	43.24 ± 0.88^{a}
	SEP	7.18 ± 0.26^{a}	2.65 ± 0.04^{a}	12.68 ± 0.75^{a}	45.93 ± 1.63^{a}
	MC	3.47 ± 0.08^{d}	1.31 ± 0.08^{e}	5.43 ± 0.43^{e}	29.61 ± 1.78^{bc}
Comitán	WTT	6.82 ± 0.05^{a}	1.58 ± 0.04^{d}	10.47 ± 0.01^{b}	13.93 ± 0.66^{e}
	HT	5.61 ± 0.27^{bc}	1.15 ± 0.01^{f}	7.98 ± 0.01^{d}	26.81 ± 0.30^{c}
	SEP	5.79 ± 0.25^{bc}	0.98 ± 0.06^{g}	7.95 ± 0.35^{d}	30.13 ± 0.59^{b}
	MC	3.66 ± 0.29^{d}	1.21 ± 0.05^{ef}	5.15 ± 0.28^{e}	20.50 ± 1.03^{d}
Two-way ANOVA (p-value) *					
A: Geographic location		> 0.05	< 0.001	< 0.001	< 0.001
B: Treatment		< 0.001	< 0.001	< 0.001	< 0.001
Interaction: $A \times B$		< 0.001	< 0.001	< 0.001	< 0.001

Without thermal treatment (WTT), hydrothermal treatment (HT), steaming at elevated pressure (SEP), cooking in the microwave (MC), water absorption capacity (WAC), oil absorption capacity (OAC), swelling capacity (SC) and solubility in water (SW). The results are the mean ± standard deviation (n = 3). The superscript letters in each column indicate statistically significant differences at $p < 0.05$. *In the two-way ANOVA, the p-values in bold represent a significant statistical effect at $p < 0.05$.

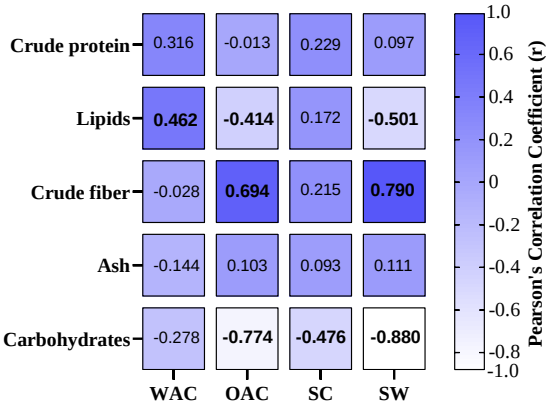

Figure 1. Pearson's correlation coefficients (r) of the chemical proximal and techno-functional properties of pacaya inflorescences. Water absorption capacity (WAC), oil absorption capacity (OAC), swelling capacity (SC) and solubility in water (SW). The Pearson correlation coefficients in bold indicate a significant correlation ($p < 0.05$) between the measured variables.

The Pearson correlation coefficients (Figure 1) show that crude protein and ash content have no significant statistical relationship between the techno-functional variables measured. However, crude fiber and carbohydrate content show a high statistical positive and negative correlation, respectively. On the other hand, lipids have a positive influence on WAC and a negative influence on OAC and SW. According to Zidani and Boudraa (2020), the negative effects on the WAC could be due to the structural damage and loss of hydrophilic regions caused by high temperatures and microwave power. In addition, it has been reported that the proteins have a strong influence on the WAC due to the hydrophilic and hydrophobic regions due to their amino acids (Chandra *et al.*, 2015), which according to Hernández-Castillo *et al.* (2020) could be modified by the type of heat treatment. While OAC values showed a positive correlation with crude fiber ($r = 0.694$, $p < 0.001$); these results could be a cause of the thermal treatment. According to Twarogowska *et al.* (2020), the temperature of the process could cause changes in some parameters such as surface properties, hydrophobic areas, porosity, and charge density, which favors OAC.

Carbohydrates and lipids showed a negative correlation with OAC ($r = -0.774$, $p < 0.001$ and $r = -0.414$, $p < 0.05$, respectively), this behavior for soluble carbohydrates or soluble dietary fiber could be due to the fact that their density charge is hydrophilic in nature; as previously reported by López *et al.* (1996) who found the lowest value of OAC in soluble dietary fiber (mainly consisting of fructooligosaccharides and pectins) of artichoke compared to the highest value in insoluble dietary fiber (mainly composed of cellulose, insoluble hemicelluloses, and lignin). While, a high lipid concentration could have a negative effect on OAC. However, proteins are the most important chemical component that could affect OAC as these biomolecules consist of both hydrophilic and hydrophobic regions and non-polar amino acid side chains that can form hydrophobic interactions with the hydrocarbon chains of lipids; similar results were observed by Chandra *et al.* (2015) and Jitngarmkusol *et al.* (2008).

Regarding SC, geographical location and thermal

treatments have influence on SC values ($p < 0.001$). However, a very significant decrease in values is observed in the microwave treatment (0.83-fold and 1.03-fold) at both geographical locations, although all other thermal treatments also show a decrease in SC. Moreover, carbohydrate content was the only parameter that showed a negative correlation ($r = -0.476$, $p < 0.005$) with SC values. Previously, Benítez *et al*. (2011) and Tejada-Ortigoza *et al*. (2018) reported that thermal treatment can alter swelling capacity as temperature can change the structure of polysaccharides and dietary fiber due to the loss of hydrophilic groups.

The results showed that the geographical location and the type of thermal treatment applied had significant statistical effects ($p < 0.05$) on the values of SW. In addition, it was found that the powders of pacaya inflorescences from Tapachula had higher values for SW than those from Comitán. Likewise, crude fiber content ($r = 0.790$, $p < 0.001$) is positively correlated with the values of SW, and according to Benítez *et al*. (2019) and Twarogowska *et al*. (2020), insoluble fibers mainly influence this techno-functional property. However, physicochemical factors, such as the changes in chemical structure, the association between molecules, the effects of solvents and temperature, the porosity, and the size of the particles, can influence the relationship between the content of insoluble fibers and their structure and SW values (Resende *et al*., 2019; Twarogowska *et al*., 2020).

In addition, lipid and carbohydrate content are negatively correlated with SW ($r = -0.501$, $p < 0.05$ and $r = -0.880$, $p < 0.001$, respectively); this behavior could be due to the high lipid content of pacaya inflorescence powders from Comitán, and since lipids are hydrophobic, SW was negatively affected, as found by Qamar *et al*. (2020). In addition, it has been reported that temperature and ionic strength can affect the structure of polysaccharides or soluble dietary fiber, altering their solubility (Elleuch *et al*., 2011). Likewise, it has been demonstrated that proteins can negatively affect SW depending on the matrix in which they are immersed (Timilsena *et al*. 2016).

Several authors have concluded that the chemical composition of foods can be positively or negatively correlated with their techno-functional properties as a result of thermal treatments, due to changes or damage in the hydrophilic and lipophilic regions, porosity, and chemical structure or redistribution of nutrients, especially in crude protein, lipids, and crude fiber (Ochoa Rivas *et al*., 2017; Wang *et al*., 2021).

3.3 FT-IR spectroscopy characterization

The results show that the pacaya inflorescences from the different geographical locations with thermal treatment have similar FT-IR absorption spectral profiles to those of the sample without thermal treatment (WTT); however, the intensity of the absorption in the signal shows differences (Figure 2, Table 4), in particular, microwave cooking was the thermal treatment that showed the greatest loss of intensity in the absorption bands associated with proteins, cellulose and hemicellulose, as reported by previous authors (Latorre *et al*., 2013; Pankyamma *et al*., 2019).

Table 4. FT-IR absorption spectral profiles of pacaya inflorescences from two geographical locations in Chiapas, Mexico.

Tapachula				Comitán				Related molecule	Assignment	Reference
WTT	HT	SEP	MC	WTT	HT	SEP	MC			
3425	3425	3425	3425	3288	3279	3276	3273	(GA) (C) (P)	O-H stretching	Hernández-Castillo *et al*. (2020); Hong *et al*. (2021)
2924	2924	2924	2927	2922	2924	2924	2924	(C)	C-H_3 stretching	Kallel *et al*. (2016)
2852	2850	2850	2848	2856	2858	2858	2853	(C)	C-H_2 stretching	Kallel *et al*. (2016)
1747	1747	1747	1747	1736	1736	1734	1732	(GA) (H)	C=O stretching of esterified carboxylic groups; C=O stretching (ester bond from hemicelluloses)	Fajardo *et al*. (2012); Ma *et al*. (2012)

1640	1631	1635	1632	1629	1619	1618	1618	(GA) (P)	C=O stretching of Amide I region and free carboxylic groups associated with GA	Barth (2007); Fajardo *et al*. (2012)
1603	1604	1600	1605	1599	1602	1604	1604	(CP)	Stretching of C=OO- and aromatic C=C	Lucarini *et al*. (2020)
1526	1554	1554	1526	1540	1525	1525	1532	(P) (L) (CP)	N-H bending, C-N stretching (Amide II), C=C stretching of the aromatic ring	Barth (2007); Chen *et al*. (2011); Lucarini *et al*. (2020)
1463	1464	1464	1466	1464	1466	1464	1465	(H)	C-H bending, O-H bending, C-H_2 bending	Ma *et al*. (2012)
1454	1456	1450	1457	1454	1455	1454	1453	(CP)	Aromatic C-C stretching	Lucarini *et al*. (2020)
1410	1412	1412	1413	1408	1410	1405	1410	(C)	C-H_2 symmetric bending	Ciolacu *et al*. (2011)
1368	1371	1371	1369	1368	1368	1369	1370	(H)	C-H bending, O-H bending, C-H_2 bending	Ma *et al*. (2012)
1316	1317	1318	1316	1315	1316	1318	1318	(C)	C-H_2 symmetric bending; C-C and C-O skeletal vibration	Chen *et al*. (2011); Szymanska-Chargot & Zdunek (2013)
1162	1162	1162	1162	1161	1163	1161	1162	(H)	C-O stretching, C-O-C stretching, O-H bending (Arabinoxylans)	Ma *et al*. (2012)
1149	1147	1149	1149	1138	1143	1136	1140	(CP)	Aromatic C-H stretching	Lucarini *et al*. (2020)
1038	1038	1039	1036	1041	1037	1037	1029	(C)	C-O stretching, C-C stretching	Szymanska-Chargot & Zdunek (2013)
894	895	896	895	895	896	896	900	(C)	C1-H bending	Szymanska-Chargot & Zdunek (2013)
833	833	836	833	844	842	845	844	(P)	Ring vibration	Szymanska-Chargot & Zdunek (2013)
782	783	782	782	785	792	795	793	(PC)	Rocking of CH_2	Lucarini *et al*. (2020)

Data corresponded as Wavenumber (cm^{-1}). Without thermal treatment (WTT), hydrothermal treatment (HT), steaming at elevated pressure (SEP), microwave cooking (MC), lipids (L), cellulose (C), pectin-related polygalacturonic acid (GA), hemicelluloses (H), proteins (P), and phenolic compounds (PC).

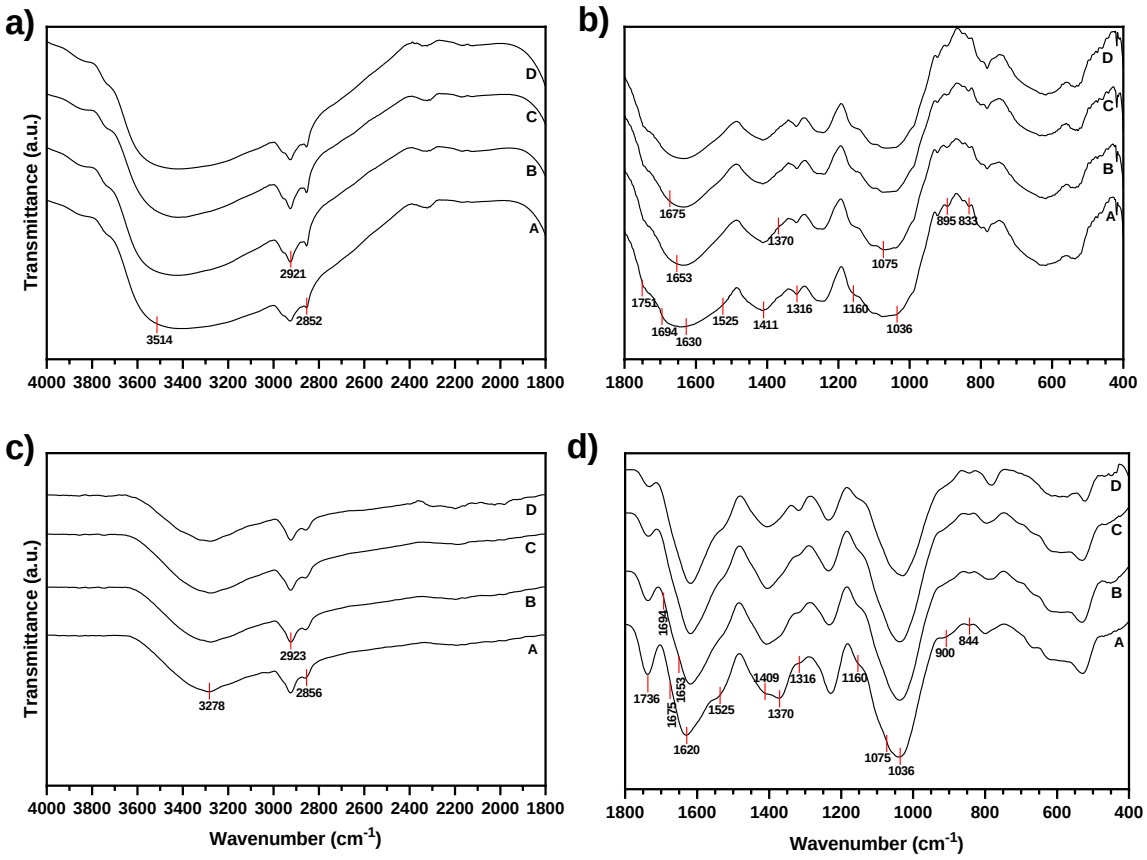

Figure 2. FT-IR patterns of pacaya inflorescences from two different geographical locations. FT-IR spectrum of inflorescences from Tapachula at a) 4000-1800 cm^{-1} and b) 1800-400 cm^{-1} (fingerprint region); and FT-IR spectrum of inflorescences from Comitán at c) 4000-1800 cm^{-1} and d) 1800-400 cm^{-1} (fingerprint region). Without thermal treatment (A), hydrothermal treatment (B), steaming at elevated pressure (C), and microwave cooking (D).

The observed changes could be due to the fact that thermal treatments can break non-covalent bonds, especially hydrogen bonds, ionic and hydrophobic bonds, and cause structural changes related to functional groups of biological macromolecules, such as cellulose, pectins, lipids, enzymes, and proteins (Liu *et al*., 2020). These changes can lead to denaturation, weakening of the cell wall, and loss, enhancement or alteration of biological activity (Liu *et al*., 2020).

The FT-IR spectrum of all samples shows an intense and broad band between 3600-3000 cm^{-1} (Figure 2a and Figure 2c), corresponding to the stretching vibration of O-H, which is abundant in polysaccharides such as pectin, cellulose (Kallel *et al*., 2016; Hong *et al*., 2021), proteins (Hernández-Castillo *et al*., 2020), phenolic structures (Jiang *et al*., 2020), and other macromolecules. Defined bands at ~2926 cm^{-1} and ~2859 cm^{-1} were observed, assigned to C-H_3 stretching vibrations and C-H_2 stretching vibrations, respectively, indicating the aliphatic moiety of cellulose present in the sample (Kallel *et al*., 2016).

Some studies have shown that the FT-IR region at 1800-800 cm^{-1} (Figure 2b and Figure 2d) is commonly referred to as the "fingerprint region" and is characterized by absorption bands at specific wavenumbers that can be assigned to chemical structures (functional groups) of pectin, hemicelluloses, cellulose, lignin, lipids, proteins, and phenolic structures (Kačuráková *et al*., 2000; Szymanska-Chargot and Zdunek, 2013; Canteri *et al*., 2019; Liu *et al*., 2021).

In all samples analyzed in this work, different bands were observed (Figure 2b and Figure 2d), which according to Zainudin *et al*. (2018), are characteristic of pectins and are located between 1400 cm^{-1} and 1000 cm^{-1}, where C-H bending (pyranoid ring), C-O-C stretching (glycosidic bond), C-O stretching, and C-H_3 bending ($COOCH_3$). Differences were observed in the spectra of the samples after the thermal treatments, mainly in the bands associated with the polygalacturonic acids and related to pectin, *e.g.* a decrease in the band intensity assigned to the C=O stretching of the esterified carboxyl groups at ~1751 cm^{-1} and an increase in the band at ~1627 cm^{-1} assigned to the C=O stretching of the free carboxyl

groups. These changes suggest that thermal treatment may have caused the breakage of the ester bond of the galacturonic acid molecules (Fajardo *et al*., 2012; Kyomugasho *et al*., 2015; La Cava *et al*., 2018).

According to Ma *et al*. (2012), most absorption bands of hemicellulose are located at ~1464 cm^{-1} and ~1366 cm^{-1} and are associated with C-H, OH, or C-H_2 bending vibrations. In this work, the thermally treated samples showed a decrease in the absorption band at ~1736 cm^{-1} associated with C=OO- of hemicelluloses; this effect could possibly be due to the complete cleavage of ester bonds by temperature, pressure, and microwave (Ma *et al*., 2012). In addition, a loss of intensity of the absorption bands associated with xylose-containing hemicelluloses at ~1035 cm^{-1} (Hong *et al*., 2021), mannose-containing hemicelluloses at ~1065 cm^{-1} and ~807 cm^{-1} (Hong *et al*., 2021), and arabinose-xylose-containing hemicelluloses at ~1157 cm^{-1} was observed (Ma *et al*., 2012). The same bands were detected by Liu *et al*. (2021), working with vegetables and fruits, and Ma *et al*. (2012), working with legumes. These results could be because to the possible degradation of hemicelluloses due to the cleavage of bonds by the temperature effect, as reported by Cheng *et al*. (2013) and Özgenç *et al*. (2017).

In Figure 2b and Figure 2d, bands corresponding to aromatic skeletal vibrations along with C=C stretching vibrations at ~1603 cm^{-1} were observed next to aromatic skeletal vibrations at ~1509 cm^{-1} associated with the lignin structure (Cheng *et al*., 2016). Furthermore, a decrease in the bands associated with the guaiacyl unit was observed, characterized by the C-O stretching at ~1268 cm^{-1} and associated with the syringyl ring vibration along with the C-O stretching at ~1215 cm^{-1}; these results could be due to the cleavage of the ether bond from the lignin structure during heat treatment as reported by Cheng *et al*. (2016).

According to several reports (Barth, 2007; Kong and Yu, 2007; Han *et al*., 2018; Wang *et al*., 2022; Calix-Rivera *et al*., 2023), in the range of 1700-1600 cm^{-1}, it is possible to analyze the secondary structure of proteins: α-helix (~1653 cm^{-1}), β-sheet (~1675 cm^{-1} and ~1630 cm^{-1}), β-turn (~1694 cm^{-1}, ~1689 cm^{-1}, ~1683 cm^{-1}, ~1671 cm^{-1}, and ~1663 cm^{-1}), and random coil structures. In this work, it was observed that all thermal treatments caused changes in band intensity related to the secondary structure of the proteins; however, this effect was mainly observed in the microwave cooking (MC) treatment (Figure 2b and Figure 2d). These changes could be since non-covalent bonds in the protein molecules (disulfide bonds and hydrogen bonds) can be broken by the effect of temperature, microwave power, water activity, and treatment time, as reported by Han *et al*. (2018) and Flores-Silva *et al*. (2022). In addition, it has been reported by other authors that thermal treatment can cause protein aggregation due to the changes in the Amida I and Amida II regions related to the loss of the α-helix structure (Hernández-Castillo *et al*., 2020). This aggregation could be due to the formation of new bonds mainly disulfide bridges, hydrophobic and electrostatic bonds, which alter biological activity and techno-functionality (Hernández-Castillo *et al*., 2020; González-Cruz *et al*., 2020; Nasrabadi *et al*., 2021).

Finally, some authors (Abbas *et al*., 2017; Lucarini *et al*., 2020) reported that the FT-IR analysis of phenolic compounds is very complex due to the diversity of structures and functional groups associated with them; however, the same authors identified some narrow absorption bands that could be associated with phenolic compounds, *e.g.* the C=COO- stretching and the C=C groups at ~1600 cm^{-1}, the C-C stretching at ~1520 cm^{-1} and ~1443 cm^{-1}, the C-H stretching at ~1143 cm^{-1} and the rocking of CH_2 at ~782 cm^{-1}, all of which are present in the aromatic compounds. In this work, it was observed that the intensity of the absorption bands increased, which could be due to the effect of thermal treatment (Figure 2b and Figure 2d, Table 4). This is consistent with the previous study by Mancera-Castro *et al*. (2022), who observed by colorimetric methods that chlorophyll a and chlorophyll b in the pacaya inflorescences were degraded by thermal treatment; on the other hand, the carotenoids and total phenolic compounds increased as a result of the thermal treatment which could be caused by the weakening of the cell walls, which increases the extractability of these compounds (González-Cruz *et al*., 2018; Mancera-Castro *et al*., 2022).

Conclusions

The geographical location and the type of thermal treatment affected the nutritional value of pacaya inflorescences and their techno-functional properties such as OAC, SW and SC, with microwave treatment causing the most changes, while traditional treatment by boiling and steam pressure maintained most of the nutritional properties. WAC was not altered by either parameter, but decreased by microwave cooking. A positive correlation was observed between OAC, SW and crude fiber content, while a negative correlation was observed between OAC and carbohydrates and lipids. For the bands between 1751 cm^{-1} and 1627 cm^{-1} associated with pectin, changes were observed due to temperature causing the breakup of galacturonic acid molecules, C=O stretching of esterified carboxyl groups and C=O stretching of free carboxyl groups. The same effect was observed for the band at 1736 cm^{-1} associated with C=OO- of hemicelluloses, which are cleaved by temperature, pressure and

microwave effects. Microwave treatment was the treatment that caused a significant loss in the intensity of the secondary structure of the proteins, and thermal treatment led to an increase in the intensity of the bands associated with the aromatic groups of the phenolic compounds.

Acknowledgements

Pedro Mancera-Castro is supported by a doctoral fellowship (grant number 958449) from the CONAHCYT-México.

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