Revista ÁRVORE
ISSN 1806 - 9088

Scientific Article

QUANTIFICATION AND FTIR-BASED CHEMICAL CHARACTERIZATION OF CONDENSED TANNINS EXTRACTED FROM THE BARK OF TROPICAL TREE SPECIES

Luan Cavalcanti da Silva[2*], Paula Evanyn Pessoa do Nascimento[3], Kayo Lucas Batista de Paiva[3], Denys Santos de Souza[4], Alexandre Santos Pimenta[3], João Gilberto Meza Ucella-Filho[5] and Tatiane Kelly Barbosa de Azevêdo[3]

1 Received on 24.10.2024 accepted for publication on 21.05.2025. Editors: Iara Fontes Demuner and Rodolfo Soares de Almeida.
2 Universidade Federal do Rio Grande do Norte, Mestrado em Ciências Florestais, Macaíba, Rio Grande do Norte, Brasil. E-mail: <luancavalcanti097@gmail.com>.
3 Universidade Federal do Rio Grande do Norte, Programa de Pós-Graduação em Ciências Florestais, Macaíba, Rio Grande do Norte, Brasil. E-mail: <paulaevanyn@hotmail.com>, <kayopk@hotmail.com>, <alexandre.pimenta@ufrn.br> and <tatianekellyengenheira@hotmail.com>.
4 Universidade Federal do Rio Grande do Norte, Graduado em Engenharia Florestal, Macaíba, Rio Grande do Norte, Brasil. E-mail: <denys.santos123@outlook.com.br>.
5 Universidade Federal de Viçosa, Departamento de Engenharia Florestal, Viçosa, Minas Gerais, Brasil. E-mail: <joao.meza@ufv.br>.
*Corresponding author.

ABSTRACT

The sustainable exploitation of forest species contributes to conserving biodiversity while generating income, with tannins being among the valuable products obtained. These biodegradable phenolic compounds have multiple industrial applications, including leather tanning, wastewater treatment, adhesive production, and use in pharmaceutical and cosmetic products. The quantification and chemical characterization of condensed tannins are essential to identify species with commercial potential and determine their possible applications. This study aimed to quantify and chemically characterize the condensed tannins extracted from the bark of four tropical tree species. Bark samples from *Acacia mangium*, *Copaifera arenicola*, *Hancornia speciosa*, and *Terminalia catappa* were collected, dried, and ground to reduce particle size. The ground material was subjected to extraction with boiling distilled water. Subsequently, the total solids content (TSC), Stiasny index (SI), and condensed tannin content (CTC) were determined. The extracted tannins were dried to solid form and analyzed by Fourier-transform infrared (FTIR) spectroscopy to identify the functional groups present. The SI of the analyzed species ranged from 95.34% to 55.09%, with *A. mangium* showing the highest SI value and *H. speciosa* the lowest. However, despite the higher SI of *A. mangium*, it exhibited the lowest CTC (6.30%), while *C. arenicola* showed the highest CTC (14.86%). The hydroxyl (OH) group was identified in all samples by FTIR, confirming the presence of phenolic compounds such as tannins. The studied species demonstrated potential for tannin production and extraction from bark, with possible applications in various sectors. Furthermore, since bark is often regarded as waste, further research is needed for its valorization by optimizing extraction processes and promoting the sustainable use of these natural resources, with significant ecological and economic implications.

Keywords: Phenolic compounds; Functional groups; Bark valorization; Biorefining

How to cite:
Silva, L. C. da, Nascimento, P. E. P. do, Paiva, K. L. B. de, Souza, D. S. de, Pimenta, A. S., Ucella-Filho, J. G. M., & Azevedo, T. K. B. de. (2025). Quantification and FTIR-based chemical characterization of condensed tannins extracted from the bark of tropical tree species. *Revista Árvore, 49*(1). https://doi.org/10.53661/1806-9088202549263864

Revista ÁRVORE
ISSN 1806 – 9088

QUANTIFICAÇÃO E CARACTERIZAÇÃO QUÍMICA BASEADA EM FTIR DE TANINOS CONDENSADOS EXTRAÍDOS DA CASCA DE ESPÉCIES DE ÁRVORES TROPICAIS

RESUMO A exploração sustentável de espécies florestais permite conservar a biodiversidade e gerar renda, sendo os taninos um dos produtos obtidos. Esses compostos fenólicos biodegradáveis têm múltiplas aplicações industriais, incluindo curtimento de peles, tratamento de efluentes, fabricação de adesivos e uso em produtos farmacêuticos e cosméticos. A quantificação e caracterização química dos taninos condensados são importantes para identificar espécies com potencial comercial e definir suas aplicações. Assim, este estudo teve como objetivo quantificar e caracterizar quimicamente os taninos condensados extraídos das cascas de quatro espécies arbóreas tropicais. Para isso, cascas de *Acacia mangium*, *Copaifera arenicola*, *Hancornia speciosa* e *Terminalia catappa* foram coletadas, secas e moídas para redução da granulometria. O material moído foi submetido à extração por fervura utilizando água destilada. Em seguida, foram determinados o teor de sólidos totais (TST), o índice de Stiasny (IS) e o teor de taninos condensados (TTC). Os taninos obtidos foram secos até a forma sólida e, posteriormente, analisados por espectroscopia FTIR para identificação dos grupos funcionais presentes. O IS das espécies analisadas variou entre 95,34% e 55,09%, sendo *A. mangium* a espécie com maior IS e *H. speciosa* com o menor. No entanto, embora *A. mangium* tenha apresentado o maior IS, foi a espécie com o menor TTC, com 6,30%, enquanto *C. arenicola* apresentou o maior TTC, com 14,86%. O grupo hidroxila (OH) foi identificado em todas as amostras analisadas por FTIR, indicando a presença de compostos fenólicos, como os taninos. As espécies estudadas demonstram potencial para a produção e extração de taninos a partir da casca, com possibilidades de aplicação em diferentes setores. Além disso, considerando que a casca é frequentemente tratada como resíduo, suas possíveis aplicações destacam a relevância de pesquisas voltadas à otimização da extração e ao uso sustentável desses recursos naturais, com implicações ecológicas e econômicas importantes.

Palavras-Chave: Compostos fenólicos; Grupos funcionais; Valorização da casca; Biorrefinaria

1. INTRODUCTION

The search for sustainable products has increased in recent years. Among these products are tannins, which are very versatile substances that can serve as raw materials for various processes in addition to being renewable. Tannins are biodegradable phenolic molecules that can form complexes of proteins and other minerals (Skoronski et al., 2014). They are found in various parts of plants, mainly in the bark of the trunk and branches of woody species (Ucella-Filho, et al., 2022a). Tannin extraction can be applied to develop more sustainable products, since bark collection can occur without harming the tree. The characteristics of tannins are different among species, and even within the same species. In this regard, species with high tannin levels are already exploited commercially (Chaves et al., 2021). Therefore, quantifying condensed tannins from different species is vital to identify species with the potential for commercial exploitation.

Currently, the primary use of tannins is to tan animal skins and transform them into leather. For leather production, tannins are used to precipitate proteins, replacing the use of heavy metals (Chaves et al., 2021). Tannins are also used in the petroleum and ceramics industries, as they reduce the viscosity of mixtures between water and clay and protect molds from deterioration (Das et al., 2020). They are also widely used as coagulants for the treatment of wastewater, to protect objects from corrosion, to produce natural wood adhesives, and in pharmaceuticals, cosmetics, and food products, due to their antimicrobial, antioxidant and anticancer properties (Kusmierek and Chrzescijanska, 2015; Cai et al., 2017; Maisetta et al., 2019; Cherubim et al., 2020; With this range of uses, quantifying and characterizing tannins is increasingly important to identify the properties and determine the best final uses of tannins.

In Northeast Brazil, 'angico vermelho' (*Anadenanthera colubrina* (Vell.)) is the primary species used for tannin extraction (IBGE, 2022). However, the species suffers from overharvesting, posing risks to its survival. Thus, the search for different species with potential for commercial tannin extraction is increasing steadily. This makes it necessary to investigate the tanning potential of other forest species, aiming to identify the potential use of these species for tannin extraction and avoid overharvesting of species already used commercially.

We analyzed four tree species with wide distribution in Brazil, both those already cultivated in the country and native species with potential for insertion in monoculture and mixed plantations. This effort is economically important to optimize the harnessing of these species' resources. *Acacia mangium* Willd. is a species already included in monocultures and mixed plantations and can improve soil fertility (Koutika and Richardson, 2019). According to Souza et al. (2020), this species has wood with good quality, even though it is still widely used as firewood. *Copaifera arenicola* (Ducke) J. Costa & L. P. Queiroz is an endemic species in Brazil, currently focused mainly on production of oils and resins, besides use as firewood for energy generation. Therefore, *C. arenicola* has potential to diversify the range of forestry products (Gama and Júnior, 2019; Costa, 2024). In turn, *Hancornia speciosa* Gomes, popularly called 'mangaba', is already known for its appealing fruit (Almeida et al., 2016), while other parts of the plant are also used in folk medicine. Hence, more comprehensive investigations into its biological activities are warranted (Panontin et al., 2021). Finally, *Terminalia catappa* L. is an exotic species that was introduced and is cultivated in Brazil, mainly for ornamental purposes. Howeever, it also produces edible nuts and has medicinal activities (Anand et al., 2015; Ribeiro et al., 2024).

In light of these aspects, it is evident that the bark of these four species is underexplored, with lack of well-defined uses. Indeed, the bark of these species is still often classified as forest residue. In this context, investigating potential applications of this byproduct is essential, particularly as a source of valuable compounds such as condensed tannins.

Therefore, we aimed to quantify and chemically characterize, through FTIR spectroscopy, the tannins extracted from the bark of *Acacia mangium*, *Copaifera arenicola*, *Hancornia speciosa*, and *Terminalia catappa*. To this end, we addressed the following research questions: (i) Which species presents the highest concentration of condensed tannins? (ii) What is the purity level of the extracts, as determined by the Stiasny index? and (iii) What are the characteristic functional groups of the tannins obtained from each species? The results obtained can contribute to the sustainable utilization of these residues and foster new industrial and commercial applications for the extracted tannins.

2. MATERIAL AND METHODS

2.1 Location and collection

Five healthy *A. mangium* trees were selected and harvested from a planted forest in the Ceará Mirim farm in the state of Rio Grande do Norte (RN). Five trees each of *C. arenicola* and *H. speciosa* were sampled from a native forest, along with five trees of *T. catappa*, a species employed for afforestation in the municipality of Macaíba, RN. From each species, we collected bark samples at the base, in the middle, and slightly above the middle of the trunk, aiming to represent the whole tree. The bark samples were weighed to determine their initial moisture. Soon afterward, they were air-dried and ground in a forage mill to quantify their condensed tannins.

2.2 Extraction and quantification

The tannins were quantified in each sample, and the portions that passed through the 1.00 mm sieve and were retained in the 0.25 mm sieve were used. Subsequently, the material was homogenized, and the dry

Revista ÁRVORE
ISSN 1806 – 9088

moisture content was determined for subsequent calculations of the tannin content of each sample. Distilled water was used to extract the tannic substances contained in the materials, and three new 25 g samples were taken from each dry material samples. Each sample was transferred to a 500 mL flat-bottomed flask, to which 250 mL of distilled water was added, and the mixture was boiled for two hours.

This procedure was repeated for each sample to remove the maximum amount of extractives. At the end of each extraction, the material was passed through a 0.105 mm sieve to remove sawdust particles. The obtained extract was filtered in a glass crucible and concentrated to a final volume of 500 mL. Three 50 mL fractions were taken from this concentration, two to determine the condensed tannin content (CTC) and one for evaporation in an oven at 103 ± 2 °C for 48 hours to determine the percentage of total solids content (TSC) according to the method of Anjos et al. (2022) and Ucella-Filho et al. (2022b), with adaptations.

To determine the CTC, the method adapted from Guangcheng et al. (1991) was used. In which 4 mL of formaldehyde and 1 mL of concentrated HCl were added to 50 mL of raw extract and then boiled for 30 minutes. After this process, the tannins were separated by simple filtration with a funnel and paper filter. The material retained by the filter was dried in an oven at 103 °C ± 2 °C for 24 hours to obtain and calculate the Stiasny index. The tannins in each sample are obtained by multiplying the Stiasny index by the total solids content.

2.3. Chemical characterization

The extracts were chemically characterized using Fourier-transform infrared (FTIR) spectroscopy. The characterization was carried out using an IRPrestige-21 FTIR-8400S device, which has a scanning range of 400 to 4,000 cm^{-1}. The transmittance of the condensed tannin samples was then measured.

2.4 Statistical analysis

The experiment was entirely randomized, with *A. mangium, C. arenicola, H. speciosa,* and *T. catappa*. Three replications (4 x 3) were carried out for each extraction, totaling 12. The data were subjected to analysis of variance using the Tukey test at 5% probability, applying the Jamovi software for statistical evaluation.

3. RESULTS

The species contained condensed tannins in the bark in different concentrations. *C. arenicola* presented the highest concentration of condensed tannins, and the exotic species *A. mangium* (inserted in planted forests) obtained a lower value compared to the other species (Table 1).

Although the tannin extract from the bark of *A. mangium* did not have a high content of condensed tannins, it had a Stiasny index of 95.34%. Likewise, *C. arenicola* also had a high Stiasny index, reaching 91.85%. These results indicated that more than 90% of the extracts obtained from the bark of these species consist of condensed tannins.

In the chemical characterization of tannins from the peels of the species, stretching vibrations of the OH groups were

Table 1. Quantification of the condensed tannin content of the studied forest species

Tabela 1. Quantificação do teor de tanino condensado das espécies florestais estudadas

Species	TSC (%)	SI (%)	CTC (%)	NTC (%)
Acacia mangium	7.20 a ± 0.71	95.34 a ± 3.96	6.30 a ± 0.52	0.90 a ± 0.35
Terminalia catappa	14.72 b ± 3.11	59.31 b ± 9.14	8.54 b ± 0.36	6.17 b ± 2.75
Copaifera arenicola	16.18 bc ± 0.36	91.85 a ± 1.00	14.86 c ± 0.17	1.32 a ± 0.19
Hancornia speciosa	20.35 c ± 0.40	55.09 b ± 2.19	11.20 d ± 0.28	9.15 b ± 0.60

Legend: TSC, Total solids content; SI, Stiasny index; CTC, condensed tannin content; and NTC, non-tannin content; Means followed by the same letter within the same column do not differ statistically at the 5% probability level using the Tukey test.

Legenda: TSC, Teor de sólidos totais; SI, Índice de Stiasny; CTC, Teor de tanino condensado; e NTC, Teor de não tanino. As médias seguidas da mesma letra dentro da mesma coluna não diferem estatisticamente ao nível de 5% de probabilidade pelo teste de Tukey.

identified at values of 3.313, 3.037, 3.315, and 3.373 cm^{-1} for *A. mangium, T. catappa, C arenicola,* and *H. speciosa*, respectively (Table 2). The tannin spectra peaks were 1,612, 1,606, 1,612, and 1,558 cm^{-1} for the species *A. mangium, T. catappa, Copaifera arenicola*, and *H. speciosa*, respectively (Figure 1).

Other peaks found were at 1,516 cm^{-1} and 1,436 cm^{-1} for *T. catappa*, 1,516 cm^{-1} and 1,446 cm^{-1} for *C. arenicola*, and 1,444 cm^{-1} for *H. speciosa* (Table 2).

Table 2. FTIS characterization of tannins from the bark of the studied forest species
Tabela 2. Caracterização por FTIS dos taninos da casca das espécies florestais estudadas

Peaks (cm^{-1})				Events
Am	Tm	Ca	Hs	
3,313	3,037	3,315	3,373	OH stretching hydrogen bond vibrations
-	-	-	2,922	CH asymmetric stretching vibrations of aromatic methoxy, methyl, and methylene side-chain groups
2,380	-	2,330	-	Stretching N=C=O
-	-	-	1,724	Region C=O
1,612	1,606	1,612	1,558	C = C Aromatic bond stretching vibrations
-	1,516	1,516	-	Vibrational motion of C=C bonds in aromatic rings, aromatic CH bending, CO stretching, and C–OH deformation
-	1,435	1,446	1,444	Vibrational motion of C=C bonds in aromatic rings, aromatic CH bending, CO stretching, and C–OH deformation
1,311	1,371	-	-	CH bond deformation region
-	1,263	1,265	1,263	CO extension in the pyran ring of tannins
1,168	-	1,180	-	CO extension in the pyran ring of tannins and C–OH stretching vibrations
1,096	1,091	1,101	1,056	C–O bonds
-	-	-	798	Deformation of CH due to out-of-plane vibrations of aromatic rings

Legend: Am, *A. mangium*; Tm, *T. catappa*; Ca, *C. arenicola*; and Hs, *H. speciosa*; according to the literature (Sócrates, 2004; Ricci et al., 2015; Tondi & Petutschnigg, 2015; Faris et al., 2016; Konai et al., 2017; Marques et al., 2021; Zidanes et al., 2021).
Legenda: Am, *A. mangium*; Tm, *T. catappa*; Ca, *C. arenicola*; e Hs, *H. speciosa*; de acordo com a literatura (Sócrates, 2004; Ricci et al., 2015; Tondi & Petutschnigg, 2015; Faris et al., 2016; Konai et al., 2017; Marques et al., 2021; Zidanes et al., 2021).

4. DISCUSSION

4.1 Quantification of tannins

The CTC values obtained from *A. mangium* bark are considered low in comparison with the results described by Marques et al. (2021), who obtained a condensed tannin value of 12.41% for the same species. According to Azevêdo et al. (2017), this can occur since TSC and CTC values can be influenced by factors such as plant age, temperature, soil, and collection period. For the TTC value, Trugilho et al. (1997), working with the bark of *Copaifera langsdorffii*, found a value of 5.60%, lower than that of *C. arenicola* in the present study. These differences in TSC may be mainly related to genetic and soil-climatic factors (Marques et al., 2021). Some species in this study are potential large-scale sources of condensed tannins and can diversify the tannin production chain in Brazil, reducing pressure on the few species already harvested for tannin extraction. According to Paes et al. (2010) and Haroun et al. (2013), the CTC percentage must be higher than 10% for the species to be considered as having economic potential for leather tanning. The values obtained in this work for the CTC of *Hancornia speciosa* and *C. arenicola* were higher than 10%. Therefore, harvesting these species to extract condensed tannins from the bark is quantitatively viable for leather tanning. When treating animal skins, tannins can precipitate the proteins in the skins,

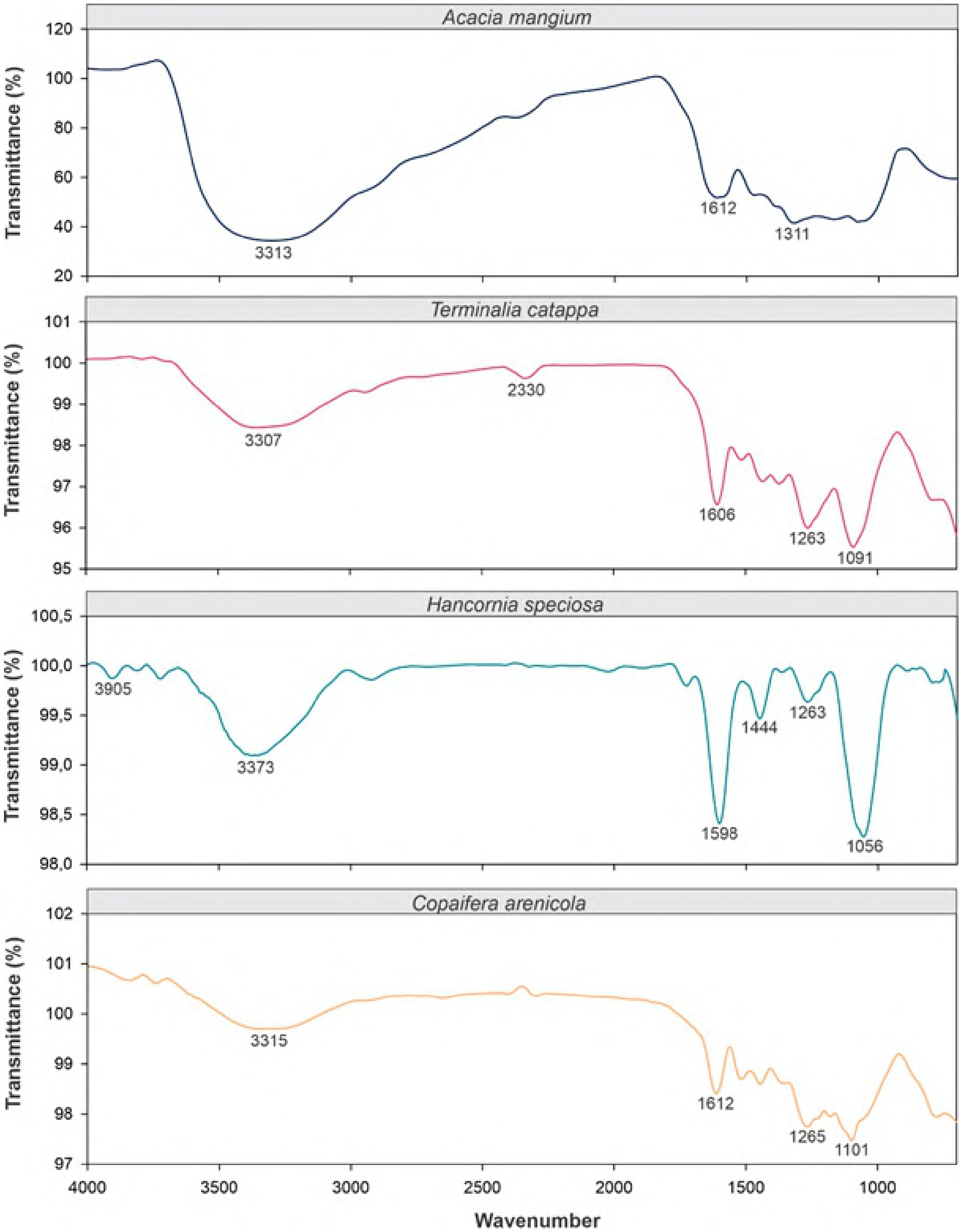

Figure 1. FTIR spectra of tannins from *A. mangium*, *T. catappa*, *C. arenicola* and *H. speciosa*
Figura 1. Espectros de FTIR dos taninos de *A. mangium*, *T. catappa*, *C. arenicola* e *H. speciosa*

transforming them into leather (Lopes et al., 2015). Therefore, the higher the amount of tannin extracted from a species, the better it will be for use by the leather industry. *H. speciosa* presented CTC above 10%, but a Stiasny index below 56%. The other substances contained in the extract can hinder the effect of tannins during application. This makes it relevant to investigate the efficiency of tannins from this species for application in animal skin tanning. However, even though certain species do not exhibit condensed tannin content suitable for large-scale leather production, the extracted material may still have chemical characteristics of interest for alternative applications. These include the treatment of wastewater, the development of wood adhesives, and potential uses in pharmaceutical or cosmetic formulations (Cosme et al., 2025; Ucella-Filho et al., 2022b; Pizzi, 2019). Therefore, the extraction and characterization of condensed tannins remain important, as the data can support the identification of viable uses for bark-derived products beyond traditional tanning processes.

Regarding the Stiasny index (SI), the species that stood out were *A. mangium* and *C. arenicola*. The Stiasny index refers to flavanol-type tannins precipitated by condensation with formaldehyde in an acidic medium, whicht are difficult to dissolve due to their high molecular weight (Medeiros et al., 2019). The highest Stiasny index obtained in this study was more significant when compared to the findings of Anjos et al. (2022), who obtained a value of 59.5% for the bark of the species *Anacardium occidentale*. According to Anjos et al. (2022), high Stiasny values indicate purity for tannic extracts of this species. Species with a low CTC content but a high Stiasny index are recommended for purposes that require tannins with a higher degree of purity, such as the wood adhesive or pharmaceutical industry (Marques et al., 2021). Based on work involving extraction of tannins from tree species present in the same biome, we can state that *A. mangium* and *C. arenicola* stand out in terms of tannin purity, surpassing results obtained for *Mimosa caesalpiniifolia*, which was the species with highest Stiasny index recorded so far, with SI of 91.27% (Azevêdo et al., 2017b). The purity of the tannin is also an indication of use, as a high Stiasny index indicates a large amount of tannin in the tannic extract. According to Chaves et al. (2021), the percentage of non-tannins should be as low as possible, as they correspond to sugars and other non-phenolic extractives, which can negatively influence the tannic extract. Extraction at high temperature promotes hydrolysis and extraction of undesirable compounds such as hemicelluloses, pectins, and gums. These non-tannic compounds increase the viscosity of the extract, which generates products with a low tannic/non-tannic ratio (Lopes et al., 2015). Species with a high degree of purity contain more tannins to interact with other substances, and are thus more effective in their respective uses.

Currently, there is no minimum value for the extraction of condensed tannins to be economically viable for water treatment or manufacturing tannin-based adhesives. Therefore, quantifying condensed tannins from forest species and testing their activities based on the condensed tannin content and the Stiasny index is essential to verify possible uses, making commercial extraction more attractive.

4.2. Chemical characterization

Condensed tannins have a degree of polymerization with a wide range of 3,700 to 3,000 cm^{-1} in the spectrum (Marques et al., 2021). The shape of the OH stretching band provides information about the occurrence of a polymerization process (Kassim et al., 2011). The OH group gives tannins a reactive character, favoring antioxidant actions (Tuyen et al., 2017). These functional groups are associated with chemopreventive and chemosensitizing effects, as well as with the inhibition of cancer cell proliferation (Cai et al., 2017; Ucella-Filho et al., 2024). Additionally, tannins exhibit mechanisms capable of suppressing cell invasion, inhibiting angiogenesis and metastasis (Cai et al., 2017). These compounds also have the ability to protect cellular DNA from oxidative damage caused by free radicals, reinforcing their therapeutic potential (Zielińska-Przyjemska et al., 2015).

According to Bulut and Ozacar (2009), this wide spectral range is a consequence of the confluence of the OH bands of the substituent in different positions in the molecules, with varying degrees of polymerization, as well as multiple interactions of the tannin molecules with a specific substrate. The stretching of the C-H

Revista ÁRVORE
ISSN 1806 – 9088

bond is located in the 3,100 to 3,000 cm^{-1} region and can extend to nearby values (Marques et al., 2021). A peak of 2,920 cm^{-1} was found for the species *H. speciosa*. According to Marques et al. (2021), smaller peaks indicate the occurrence of interactions and degrees of polymerization that are not significantly effective at the vibrational frequencies of the molecular structures. We found that the position of intense bands did not cause high modification. Smaller peaks were also found by Marques et al. (2021). In FTIR spectra of condensed tannins, stretching related to aliphatic groups serve as diagnostics that provide information about methylation in the chemical structure of these compounds (Ricci et al., 2015).

According to Ntenga et al. (2017), the combination of high SI values with intense C=C stretching bands is indicative of the high purity of tannin-rich extracts obtained through hot water extraction. Marques et al. (2021) also reported this positive correlation between the SI and C=C signal intensity in *Mimosa caesalpiniifolia* bark extracts. However, in the species analyzed in the present study, this relationship was inverse, since the extracts with higher SI values did not necessarily exhibit the most intense C=C bands. This divergence may be related to the specific chemical composition of the tannins present in the studied species, the presence of interfering compounds in the extracts, or variations in FTIR sensitivity to different aromatic structures.

The C=C stretching bands are frequently accompanied by diagnostic absorptions corresponding to C–H aromatic out-of-plane bending, C–O stretching, and C–OH deformation, which collectively support the presence of phenolic structures characteristic of condensed tannins (Konai et al., 2017). Furthermore, Baddi et al. (2004) and Easton et al. (2009) reported that the concomitant observation of distinct aliphatic C–H stretching bands in the 2,970–2,870 cm^{-1} range, along with deformation vibrations between 1,460 and 1,330 cm^{-1}, commonly referred to as "umbrella deformation", provides compelling spectral evidence of methyl-substituted aromatic rings, a structural feature commonly associated with methylated condensed tannins.

Ping et al. (2012) attributed peaks at 1,311 and 1,371 cm^{-1} to plane vibration in bending. According to Tondi and Petutschnigg (2015), the range between 1,350 and 1,100 cm^{-1} is related to stretching vibrations of the C-O bond, with 1,300 to 1,200 cm^{-1} being vibrations of the tannin B ring, while 1,200 to 1,100 cm^{-1}1 are vibrations of the tannin B ring. Therefore, the peaks found at 1,263 cm^{-1} for *T. catappa* and *H. speciosa* and the peak at 1,265 cm^{-1} of *Copaifera arenicola* (Table 2) represent C=O stretching of the carboxyl groups, which indicates the presence of residues of gallic acid (Konai et al., 2017), with vibrations of the tannin B ring. These peak values obtained for these species also indicate the presence of catechin and proanthocyanidins, as reported by Sócrates (2004) and Konai et al. (2017). The peaks in the range of 900 to 740 cm^{-1} are attributed to the out-of-plane curvature of aromatic CH and OH movements of aromatic alcohols (Sócrates, 2004). In this work, only the species *H. speciosa* was found to have a peak in this range, with a value of 798 cm^{-1}.

The FTIR analyses confirmed the presence of condensed tannins and revealed structural variations among the studied species, associated with differences in the degree of polymerization, aromatic substitution patterns, and methylation of the phenolic structures. The identified vibrational modes, particularly those related to C–O, C=C, and C–H bonds, as well as the detection of gallic acid residues and proanthocyanidins, indicate the chemical complexity and potential bioactivity of the extracts.

5. CONCLUSION

The findings presented here confirm the significant presence of condensed tannins in the bark of the four analyzed species, with particularly high concentrations observed in *C. arenicola*. The quantification and chemical characterization of these tannins demonstrate the potential application of these species in various industrial sectors. Notably, the high Stiasny index values obtained for *A. mangium* and *C. arenicola* indicate high tannin purity, suggesting suitability for applications requiring greater reactivity, such as the production of adhesives or coagulants.

Although this study focused on the quantification and chemical profiling of tannins, potential applications can be proposed in a broad sense for all four species. These suggestions aim to guide future research toward validating their actual performance in specific industrial contexts. Further investigations should include application-oriented tests to determine the efficacy of these tannins in pharmaceutical formulations, natural adhesives, coagulants, and cosmetics or food products. Additionally, the valorization of bark, frequently regarded as a processing residue, offers ecological and economic benefits, reinforcing the importance of sustainable extraction and utilization strategies for these natural compounds.

6. ACKNOWLEDGEMENTS

Funding for this study was provided by the Study Group on Non-Timber Forest Products (GEPFLONM), the Postgraduate Program in Forest Sciences (PPGCFL) of Federal University of Rio Grande do Norte (UFRN), the Jundiai Agricultural School (EAJ), and the Office to Coordinate Improvement of Higher Education Personnel (CAPES).

AUTHOR CONTRIBUTIONS

SILVA L. C.: Conception of the article; Bibliographic review, Application of methodology; Data curation; Data analysis; Data discussion; Writing - review and editing; NASCIMENTO P. E. P.: Application of methodology - extraction of tannins from species; PAIVA K. L. B.: Application of methodology - extraction of tannins from species and Cationization; SOUZA D. S.: Application of methodology - extraction of tannins from species; PIMENTA A. S.: Writing - Translation and review; UCELLA-FILHO J. G. M.: Supervision; Data analysis; Data discussion; Writing - review, graphs, figures, editing and corrections; AZEVÊDO T. K. B.: Supervision; Concept of the article; Methodology; Data analysis; Writing - review, discussion, editing and corrections.

DATA AVAILABILITY

The entire dataset supporting the findings of this study has been published within the article.

7. REFERENCES

Almeida, A. B. S., Ferreira, M. A. C., Barbosa, T. A., Siqueira, A. P. S., & Souza, E. R. B. (2016). Elaboração e avaliação sensorial de sorvete diet e sem lactose de mangaba endêmica do Cerrado. *Revista de Agricultura Neotropical, 3*(3), 38–41. https://doi.org/10.32404/rean.v3i3.1206

Anand, A., Divya, N., & Kotti, P. (2015). An updated review of *Terminalia catappa*. *Pharmacognosy Reviews, 9*(18), 93. https://doi.org/10.4103/0973-7847.162103

Anjos, B. F., Azevêdo, T. K. B., Silva, B. R. F., Braga, R. M., Pimenta, A. S., & Andrade, F. A. F. (2022). Tannins from cashew tree (*Anacardium occidentale*) bark as a flocculant for water clarification. *Revista Ambiente & Água, 17*(3). https://doi.org/10.4136/ambi-agua.2815

Azevêdo, T. K. B. D., Paes, J. B., Calegari, L., & Santana, G. M. (2017a). Teor de taninos condensados presente na casca de jurema-preta (*Mimosa tenuiflora*) em função das fenofases. *Floresta e Ambiente, 24*. https://doi.org/10.1590/2179-8087.026613

Azevêdo, T. K. B., Almeida, C. M. G., Campos, D. B. P., Souza, D. G., Nunes, L. J., Gomes, J. P. S., Carnaval, A. A. A., & Silva, G. G. C. (2017b). Substâncias tânicas presentes em partes da árvore sabiá (*Mimosa caesalpiniifolia* Benth.) em plantio comercial de 5 anos. *Revista Agroecossistemas, 9*(2), 263–274. https://www.periodicos.ufpa.br/index.php/agroecossistemas/article/viewFile/5033/4649

Baddi, G. A., Albuquerque, J. A., González, J., Cegarra, J., & Hafidi, M. (2004). Chemical and spectroscopic analyses of organic matter transformations during composting of olive mill wastes. *International Biodeterioration & Biodegradation, 54*(1), 39–44. https://doi.org/10.1016/j.ibiod.2003.12.004

Bulut, E., & Ozacar, M. (2009). Rapid, facile synthesis of silver nanostructure using hydrolyzable tannins. *Industrial & Engineering Chemistry Research, 48*(12), 5686–5690. https://doi.org/10.1021/ie801779f

Cai, Y., Zhang, J., Chen, N. G., Shi, Z., Qiu, J., He, C., & Chen, M. (2017). Recent advances in anticancer activities and drug delivery systems of tannins. *Medicinal Research Reviews, 37*(4), 665–701. https://doi.org/10.1002/med.21422

Chaves, I. L. S., Gonçalves, F. G., Brito, A. S., Paes, J. B., Lelis, R. C. C., Lopez, Y. M., Jesus, F. Q., Dambroz, G. B. V., & Fantuzzi, N. H. (2021). Taninos vegetais: Qualidade e rendimento são influenciados pelo ambiente? *Sistemas Integrados de Produção: Pesquisa e Desenvolvimento de Tecnologias, 1*(1), 33–52. https://doi.org/10.37885/210605031

Cherubim, D. J. L., Martins, C. V. B., Fariña, L. O., & Lucca, R. A. S. (2020). Polyphenols as natural antioxidants in cosmetics applications. *Journal of Cosmetic Dermatology, 19*(1), 33–37. https://doi.org/10.1111/jocd.13093

Cosme, F., Aires, A., Pinto, T., Oliveira, I., Vilela, A., & Gonçalves, B. (2025). A comprehensive review of bioactive tannins in foods and beverages: Functional properties, health benefits, and sensory qualities. *Molecules, 30*(4), 800. https://doi.org/10.3390/molecules30040800

Costa, J. A. S. (n.d.). Copaifera. In Flora e Funga do Brasil. Jardim Botânico do Rio de Janeiro. https://floradobrasil.jbrj.gov.br/FB116609

Das, A. K., Islam, M. N., Faruk, M. O., Ashaduzzaman, M., & Dungani, R. (2020). Review on tannins: Extraction processes, applications and possibilities. *South African Journal of Botany, 135*, 58–70. https://doi.org/10.1016/j.sajb.2020.08.008

Easton, C. D., Jacob, M. V., Shanks, R. A., & Bowden, B. F. (2009). Surface and chemical characterization of PolyLA thin films fabricated using plasma polymerization. *Chemical Vapor Deposition, 15*(7–9), 179–185. https://doi.org/10.1002/cvde.200806719

Faris, A. H., Ibrahim, M. N. M., & Rahim, A. A. (2016). Preparation and characterization of green adhesives using modified tannin and hyperbranched poly (amine ester). *International Journal of Adhesion and Adhesives, 71*, 39–47. https://doi.org/10.1016/j.ijadhadh.2016.08.009

Gama, D. C., & Júnior, J. M. N. (2019). *Copaifera arenicola* [(Ducke) J. Costa e L. P. Queiroz] Fabaceae-Caesalpinioideae em regiões do Nordeste da Bahia. *Agroforestalis News, 4*(1), i–viii. https://periodicos.ufs.br/AGRO/article/view/10867

Guangcheng, Z., Yunlu, L., & Yazaki, Y. (1991). Extractives yields, Stiasny values and polyflavanoid contents in barks from six Acacia species in Australia. *Australian Forestry, 54*(3), 154–156. https://doi.org/10.1080/00049158.1991.10674572

Haroun, M., Khirstova, P., & Covington, T. (2013). Evaluation of vegetable tannin contents and polyphenols of some indigenous and exotic woody plant species in Sudan. *Journal of Forest Products and Industries, 2*(4), 48–54. https://www.academia.edu/7204714/Evaluation_of_VegetableTannin_Contents_and_Polyphenols_of_some_Indigenous_and_Exotic_woody_Plants_Species_in_Sudan

IBGE – Instituto Brasileiro de Geografia e Estatística. (2022). Produção da extração vegetal e da silvicultura (n. 31, p. 55). https://sidra.ibge.gov.br/tabela/289

Kassim, M. J., Hussin, M. H., Achmad, A., Dahon, N. H., Suan, T. K., & Hamdan, H. S. (2011). Determination of total phenol, condensed tannin and flavonoid contents and antioxidant activity of *Uncaria gambir* extracts. *Indonesian Journal of Pharmacy, 22*(1), 50–59. https://www.researchgate.net/publication/235930372_Determination_of_total_phenol_condensed_tannin_and_flavonoid_contents_and_antioxidant_activity_of_Uncaria_gambir_extracts

Konai, N., Raidandi, D., Pizzi, A., & Meva'a, L. (2017). Characterization of *Ficus sycomorus* tannin using ATR-FT MIR, MALDI-TOF MS and 13C NMR methods. *European Journal of Wood Products, 75*, 807–815. https://doi.org/10.1007/s00107-017-1177-8

Koutika, L. S., & Richardson, D. M. (2019). *Acacia mangium* Willd: Benefits and threats associated with its increasing use around the world. *Forest Ecosystems, 6*(1), 1–13. https://link.springer.com/article/10.1186/s40663-019-0159-1

Kusmierek, E., & Chrzescijanska, E. (2015). Tannic acid as corrosion inhibitor for metals and alloys. *Materials and Corrosion, 66*(2), 169–174. https://doi.org/10.1002/maco.201307277

Lopes, P. J. G., Calegari, L., Calegari, C. C. A., Oliveira, E., Stangerlin, D. M., & Gatto, D. A. (2015). Produtividade em casca e taninos condensados de jurema-preta. *Nativa, 3*(2), 95–101. https://doi.org/10.31413/nativa.v3i2.2015

Maisetta, G., Batoni, G., Caboni, P., Esin, S., Rinaldi, A. C., & Zucca, P. (2019). Tannin profile, antioxidant properties, and antimicrobial activity of extracts from two Mediterranean species of parasitic plant Cytinus. *BMC Complementary and Alternative Medicine, 19*, 1–11. https://doi.org/10.1186/s12906-019-2487-7

Marques, S. R. R., Azevêdo, T. K. B., Castilho, A. R. F. D., Braga, R. M., & Pimenta, A. S. (2021). Extraction, quantification, and FTIR characterization of bark tannins of four forest species grown in Northeast Brazil. *Revista Árvore, 45*, e4541. https://doi.org/10.1590/1806-908820210000041

Medeiros, J. X., Calegari, L., Silva, G. H., Tanajura, J. A., & Braz, R. L. (2019). Bark and fruit extracts *Anadenanthera colubrina* (Vell.), *Mimosa tenuiflora* (Willd.) and *Acacia mearnsii* (Wild.) species. *Journal of Experimental Agriculture, 30*(1), 1–7. https://doi.org/10.9734/JEAI/2019/46500

Ntenga, R., Pagore, F. D., Pizzi, A., Mfoumou, E., & Ohandja, L. M. A. (2017). Characterization of tannin-based resins from the barks of *Ficus platyphylla* and *Vitellaria paradoxa*: Composites' performances and applications. *Materials Sciences and Applications, 8*(12), 899. https://doi.org/10.4236/msa.2017.812066

Paes, J. B., Santana, G. M., Azevedo, T. K. B., Morais, R. M., & Calixto Junior, J. T. (2010). Substâncias tânicas presentes em várias partes da árvore angico-vermelho (*Anadenanthera colubrina* (Vell.) Brenan var. *cebil* (Gris.) Alts.). *Scientia Forestalis, 38*(87), 441–447. http://www.bibliotecaflorestal.ufv.br/handle/123456789/16466

Panontin, J. F., Neres, R. P., Fernandes, R. D. M. N., Scapin, E., & Seibert, C. S. (2021). Chemical characterization and toxicological analyses of hydroalcoholic extracts from the stem and leaves of mangabeira (*Hancornia speciosa* Gomes) as a guide for the development of green cosmetics. *Journal of Medicinal Plants Research, 15*(8), 366–379. https://doi.org/10.5897/JMPR2021.7099

Ping, L., Pizzi, A., Guo, Z. D., & Brosse, N. (2012). Condensed tannins from grape pomace: Characterization by FTIR and MALDI TOF and production of environment-friendly wood adhesive. *Industrial Crops and Products, 40,* 13–20. https://doi.org/10.1016/j.indcrop.2012.02.039

Pizzi, A. (2019). Tannins: Prospectives and actual industrial applications. *Biomolecules, 9*(8), 344. https://doi.org/10.3390/biom9080344

Ribeiro, R. T. M., Marquet, N., & Loiola, M. I. B. (2024). Combretaceae in Flora e Funga do Brasil. Jardim Botânico do Rio de Janeiro. https://floradobrasil.jbrj.gov.br/FB22511

Ricci, A., Olejar, K. J., Parpinello, G. P., Kilmartin, P. A., & Versari, A. (2015). Application of Fourier Transform Infrared (FTIR) spectroscopy in the characterization of tannins. *Applied Spectroscopy Reviews, 50*(5), 407–442. https://doi.org/10.1080/05704928.2014.100046

Skoronski, E., Niero, B., Fernandes, M., Alves, M. V., & Trevisan, V. (2014). Estudo da aplicação de tanino no tratamento de água para abastecimento captada no rio Tubarão, na cidade de Tubarão, SC. *Revista Ambiente & Água, 9*, 679–687. https://doi.org/10.4136/ambi-agua.1303

Socrates, G. (2004). *Infrared and Raman characteristic group frequencies: Tables and charts*. John Wiley & Sons. https://doi.org/10.1007/s00396-004-1164-6

Souza, J. B., Azevêdo, T. K. B., Sousa, T. B., Silva, G. G. C., Júnior, J. B. G., & Pimenta, A. S. (2020). Plywood bonding with an adhesive based on tannins from *Acacia mangium* Wild. bark from trees grown in Northeastern Brazil. *Revista Brasileira de Ciências Agrárias, 15*(4), 1–7. https://doi.org/10.5039/agraria.v15i4a8659

Tondi, G., & Petutschnigg, A. (2015). Middle infrared (ATR FT-MIR) characterization of industrial tannin extracts. *Industrial Crops and Products, 65*, 422–428. https://doi.org/10.1016/j.indcrop.2014.11.005

Trugilho, P. F., Caixeta, R. P., Lima, J. T., & Mendes, L. M. (1997). Avaliação do conteúdo em taninos condensados de algumas espécies típicas do cerrado mineiro. *Cerne, 3*(1), 1–13. https://www.researchgate.net/publication/242409903_AVALIACAO_DO_CONTEUDO_EM_TANINOS_CONDENSADOS_DE_ALGUMAS_ESPECIES_TIPICAS_DO_CERRADO_MINEIRO

Tuyen, P., Xuan, T., Khang, D., Ahmad, A., Quan, N., Tu Anh, T., Hoang Anh, L., & Minh, T. N. (2017). Phenolic compositions and antioxidant properties in bark, flower, inner skin, kernel and leaf extracts of *Castanea crenata* Sieb. et Zucc. *Antioxidants, 6*(2), 31. https://doi.org/10.3390/antiox6020031

Ucella-Filho, J. G. M., Freire, A. D. S. M., Carréra, J. C., Lucas, F. M. F., Zucolotto, S. M., Júnior, A. F. D., & Mori, F. A. (2022a). Tannin-rich bark extract of plants as a source of antimicrobial bioactive compounds: A bibliometric analysis. *South African Journal of Botany, 150*, 1038–1050. https://doi.org/10.1016/j.sajb.2022.09.018

Ucella-Filho, J. G. M., Lorenço, M. S., Souza, E. C., Costa, G. M., Piccoli, R. H., Dias Júnior, A. F., & Mori, F. A. (2022b). Tannin-rich tree bark extracts inhibit the development of bacteria associated with bovine mastitis. *Bioresources, 17*(4), 6578–6587. https://doi.org/10.15376/biores.17.4.6578-6587

Ucella-Filho, J. G. M., Lorenço, M. S., Silva, B. R. F., Ferreira, V. R. F., Monteiro, J. R. B., Ferreira, N. S., Cardoso, M. G., Kitagawa, R. R., Resende, J. A., Júnior, A. F. D., Piccoli, R. H., & Mori, F. A. (2024). Exploring the potential of tannin-rich tree bark extracts in combating foodborne diseases and gastric cancer. *Food Bioscience, 57*, 103559. https://doi.org/10.1016/j.fbio.2023.103559

Zidanes, U. L., Dias, M. C., Lorenço, M. S., Araujo, E. S., Silva, M. J. F., Sousa, T. B., Ferreira, S. R., Ugucioni, J. C., Tonoli, G. H. D., Bianchi, M. L., & Mori, F. A. (2021). Preparation and characterization of tannin-based adhesives reinforced with cellulose nanofibrils for wood bonding. *Holzforschung, 75*(2), 159–167. https://doi.org/10.1515/hf-2020-0033/html

Zielińska-Przyjemska, M., Ignatowicz, E., Krajka-Kuźniak, V., & Baer-Dubowska, W. (2015). Effect of tannic acid, resveratrol and its derivatives, on oxidative damage and apoptosis in human neutrophils. *Food and Chemical Toxicology, 84*, 37–46. https://doi.org/10.1016/j.fct.2015.07.013