UNIVERSIDADE FEDERAL DE PERNAMBUCO
CENTRO DE BIOCIÊNCIAS
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MARCELA MARIA ALBUQUERQUE SILVA

COMPOSIÇÃO FENÓLICA EM PLANTAS MEDICINAIS LENHOSAS DA CAATINGA EM RELAÇÃO À VERSATILIDADE DAS ESPÉCIES E SOB EFEITO DA PRECIPITAÇÃO

RECIFE - PE
2025

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Tese apresentada ao Programa de Pós-Graduação em Biologia Vegetal da Universidade Federal de Pernambuco, como requisito parcial para obtenção do título de doutor(a) em Biologia Vegetal.

Área de concentração: Ecologia e Conservação.

Orientador: Prof. Dr. Ulysses Paulino de Albuquerque

Coorientador: Prof. Dr. Marciel Teixeira de Oliveira

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Aprovada em 13/05/2025.

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as minhas filhas, Maria Eduarda e Maria Elisa.

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RESUMO

As plantas são comumente utilizadas como recursos medicinais e sua atividade biológica está ligada a compostos de metabolismo secundário, como os compostos fenólicos. Embora não sejam essenciais para o crescimento e sobrevivência das plantas, esses compostos são cruciais no desenvolvimento, adaptação ao ambiente, resistência ao estresse e atuam na defesa da planta contra herbívoros e patógenos. A importância dos compostos fenólicos é bem estabelecida devido às amplas atividades farmacológicas comprovadas, tais como antioxidante, antimicrobiana e anti-inflamatória. Na Caatinga, floresta sazonalmente seca do Brasil, a eficácia terapêutica de espécies medicinais é associada à presença de compostos fenólicos, como fenóis, taninos e flavonoides. Considerando que as espécies medicinais mais versáteis apresentam maior número de usos em sistemas médicos locais, questiona-se se essa versatilidade está relacionada à quantidade desses compostos. Paralelamente, diante da previsão de redução da precipitação no cenário de mudanças climáticas, torna-se essencial compreender como essa diminuição pode afetar a síntese de compostos fenólicos em plantas medicinais amplamente utilizadas pela população local. Para investigar a relação entre compostos fenólicos e versatilidade medicinal, amostras de cascas do fuste de vinte espécies foram coletadas no Parque Nacional do Catimbau, Pernambuco, e categorizadas quanto à versatilidade com base no índice de importância relativa (IR) em alta (IR>1) e baixa (IR<1) versatilidade, a partir de dados prévios. As análises dos extratos metanólicos envolveram o uso do reagente Folin-Ciocalteu para fenóis totais, caseína para taninos e cloreto de alumínio para flavonoides. Embora se esperasse maior concentração desses compostos nas espécies mais versáteis, não foram observadas diferenças significativas entre os grupos. As espécies *Astronium urundeuva* (IR = 1,94) e *Anadenanthera colubrina* (IR = 1,69), ambas espécies altamente versáteis, apresentaram maiores níveis de fenois totais (232,846 mg e 254,244 mg TAE/100 g MS respectivamente). No entanto, espécies menos versáteis, como *Mimosa tenuiflora* (IR = 0,74) e *Schinopsis brasiliensis* (IR = 0,62), também apresentaram níveis mais elevados de fenois (244,857 mg e 219,847 mg TAE/100 g MS respectivamente). Taninos seguiram a mesma tendência dos fenóis, enquanto os flavonoides não variaram entre os grupos. Também foi analisado o efeito da precipitação sobre a síntese de compostos fenólicos, através da coleta de cascas das espécies em áreas de baixa e alta pluviosidade. Embora se esperasse maior teor em áreas mais secas, fenóis totais e taninos foram mais elevados nas áreas com maior precipitação. Flavonoides, em geral, não apresentaram variação, embora 40% das espécies de áreas secas tenham mostrado concentrações mais altas. Dentre as dez espécies analisadas, *Cenostigma microphyllum* e *Senegalia piauhiensis*, não apresentaram variação no conteúdo total de fenólicos e taninos entre as áreas. Os teores de flavonoides de *C. microphyllum*, *Jatropha mutabilis* e *Pityrocarpa moniliformis* também não variaram entre as áreas com diferentes precipitações. Assim, a versatilidade das espécies não se relaciona com a concentração de compostos fenólicos, embora esses compostos estejam associados à atividade terapêutica de espécies relevantes. Já a redução da pluviosidade afeta negativamente a produção de fenóis e taninos totais em plantas medicinais da Caatinga.

Palavras-chave: Ecologia química; Etnobotânica; Fenólicos; Plantas versáteis; Pluviosidade; Semiárido brasileiro.

ABSTRACT

Plants are commonly used as medicinal resources, and their biological activity is linked to secondary metabolites, such as phenolic compounds. Although not essential for plant growth and survival, these compounds are crucial for plant development, environmental adaptation, stress resistance, and defense against herbivores and pathogens. The importance of phenolic compounds is well established due to their broad proven pharmacological activities, such as antioxidant, antimicrobial, and anti-inflammatory. In the Caatinga, Brazil's seasonally dry forest, the therapeutic efficacy of medicinal species is associated with the presence of phenolic compounds, such as phenols, tannins, and flavonoids. Considering that the most versatile medicinal species have a greater number of uses in local medical systems, the question arises whether this versatility is related to the quantity of these compounds. Furthermore, given the predicted reduction in precipitation under climate change, it is essential to understand how this decrease may affect the synthesis of phenolic compounds in medicinal plants widely used by the local population. To investigate the relationship between phenolic compounds and medicinal versatility, bark samples from twenty species were collected in Catimbau National Park, Pernambuco, and categorized according to versatility based on the relative importance index (RI) as high (RI>1) or low (RI<1) versatility, based on previous data. Analyses of methanolic extracts involved the use of the Folin-Ciocalteu reagent for total phenols, casein for tannins, and aluminum chloride for flavonoids. Although higher concentrations of these compounds were expected in the more versatile species, no significant differences were observed between the groups. The species *Astronium urundeuva* (RI = 1.94) and *Anadenanthera colubrina* (RI = 1.69), both highly versatile species, presented higher levels of total phenols (232.846 mg and 254.244 mg TAE/100 g DM, respectively). However, less versatile species, such as *Mimosa tenuiflora* (RI = 0.74) and *Schinopsis brasiliensis* (RI = 0.62), also presented higher phenol levels (244.857 mg and 219.847 mg TAE/100 g DM, respectively). Tannins followed the same trend as phenols, while flavonoids did not vary between groups. The effect of precipitation on the synthesis of phenolic compounds was also analyzed by collecting bark from species in areas of low and high rainfall. Although higher contents were expected in drier areas, total phenols and tannins were higher in areas with higher rainfall. Flavonoids, in general, did not show variation, although 40% of the species from drier areas showed higher concentrations. Among the ten species analyzed, *Cenostigma microphyllum* and *Senegalia piauhiensis* showed no variation in total phenolic and tannin content between areas. The flavonoid contents of *C. microphyllum*, *Jatropha mutabilis*, and

Pityrocarpa moniliformis also did not vary between areas with different rainfall. Thus, the versatility of species is not related to the concentration of phenolic compounds, although these compounds are associated with the therapeutic activity of relevant species. Reduced rainfall, however, negatively affects the production of total phenols and tannins in medicinal plants from the Caatinga.

Keywords: Chemical ecology; Ethnobotany; Phenolics; Versatile plants; Rainfall; Brazilian semiarid region.

LISTA DE FIGURAS

FUNDAMENTAÇÃO TEÓRICA

ARTIGO 1 - IS THERE A RELATIONSHIP BETWEEN THE CONCENTRATION OF PHENOLIC COMPOUNDS AND THE VERSATILITY OF MEDICINAL PLANTS IN THE CAATINGA BIOME?

ARTIGO 2 - PRECIPITATION DYNAMICS AND PHENOLIC COMPOUND ACCUMULATION IN WOODY MEDICINAL PLANTS OF THE CAATINGA

LISTA DE TABELAS

FUNDAMENTAÇÃO TEÓRICA

ARTIGO 1 - IS THERE A RELATIONSHIP BETWEEN THE CONCENTRATION OF PHENOLIC COMPOUNDS AND THE VERSATILITY OF MEDICINAL PLANTS IN THE CAATINGA BIOME?

ARTIGO 2 - PRECIPITATION DYNAMICS AND PHENOLIC COMPOUND ACCUMULATION IN WOODY MEDICINAL PLANTS OF THE CAATINGA

SUMÁRIO

1 INTRODUÇÃO

As plantas medicinais são amplamente utilizadas por populações humanas desde contextos históricos até atualmente. O seu uso é justificado pela presença de bioativos, que são sintetizados a partir do metabolismo secundário vegetal, incluindo os compostos fenólicos. Esses compostos estão, muitas vezes, relacionados às indicações terapêuticas atribuídas às plantas medicinais através do conhecimento tradicional das pessoas. Os compostos fenólicos possuem múltiplas atividades farmacológicas comprovadas, incluindo atividades antioxidantes, anti-inflamatórias, antimicrobianas e cicatrizantes (SUN et al., 2023).

O grupo dos fenólicos compreende uma ampla e diversificada classe de compostos, tais como os ácidos fenólicos, flavonoides, taninos e lignanas. Embora não sejam essenciais aos processos vitais das plantas, os fenólicos estão envolvidos em inúmeras funções adaptativas (LI et al., 2020). São considerados compostos cruciais para a resiliência das plantas, uma vez que a sua síntese favorece a resiliência das plantas em condições de estresse abióticos e bióticos, atuando como antioxidantes, fortificantes estruturais e moléculas sinalizadoras (SHARMA et al., 2019; SAINI et al., 2024). Os fatores ambientais exercem uma influência significativa e complexa na composição fenólica das plantas, envolvendo variáveis importantes como clima, nutrientes do solo, altitude, disponibilidade de água, temperatura e luz, refletindo diretamente na quantidade nos tipos de compostos fenólicos produzidos, o que permite às plantas a se adaptarem às condições e aos estressores locais (ALBERGARIA et al., 2020; ZAGOSKINA et al., 2023; KUMAR et al., 2023).

A ampla funcionalidade desses compostos nas plantas está relacionada a sua variabilidade estrutural, permitindo que os fenólicos exerçam múltiplos papéis essenciais ao desenvolvimento, defesa e adaptação. O tipo de estrutura determina sua capacidade de atuar como antimicrobianos, repelentes de herbívoros, protetores contra radiação UV e agentes antioxidantes. Por exemplo, flavonoides específicos protegem contra a radiação UV, enquanto as ligninas reforçam a parede celular (KUMAR et al., 2020; SAINI et al., 2024).

Compostos fenólicos são importantes agentes envolvidos na regulação do crescimento e nos processos de sinalização, tais como a diferenciação celular e a comunicação planta-microrganismo, com diferentes estruturas sendo reconhecidas por diferentes parceiros simbióticos ou patógenos (KUMAR et al., 2020).

Na região da Caatinga, Floresta Sazonalmente Seca de ocorrência no Brasil, a presença de compostos fenólicos foi identificada na maioria das plantas utilizadas pela população como recurso medicinal, sendo a relação de subsistência das pessoas com os recursos desta região bem documentada (ALBUQUERQUE et al., 2017). A pesquisa sobre compostos fenólicos na Caatinga tem se concentrado em famílias botânicas importantes, tais como Fabaceae, Euphorbiaceae, Myrtaceae, Rhamnaceae e Lamiaceae. Essas famílias são reconhecidas por sua abundância, importância ecológica e pelo alto teor fenólico de suas espécies (ALBUQUERQUE et al., 2007; ALBUQUERQUE; OLIVEIRA, 2007; MAGALHÃES et al., 2019). Espécies como *Astronium urundeuva*, *Amburana cearensis*, *Anadenanthera colubrina*, *Sideroxylon obtusifolium*, *Ziziphus joazeiro*, *Anacardium occidentale* e *Schinopsis brasiliensis* são amplamente valorizadas na região, sendo utilizadas no tratamento de doenças respiratórias e digestivas, afecções de pele e outros sintomas em geral (SILVA; ALBUQUERQUE, 2005; ALBUQUERQUE et al., 2007; MAGALHÃES et al., 2019).

A Caatinga é característica por sua sazonalidade climática devido a precipitação irregular, influenciando tanto no metabolismo das espécies, quanto no comportamento das pessoas em relação aos recursos da região (ARAÚJO et al., 2007; 2011). Diante da previsão da diminuição nos níveis de pluviosidade em regiões áridas e semiáridas como a Caatinga (IPCC, 2019), é preciso compreender qual o impacto na composição fenólica nas espécies, refletindo na dinâmica das comunidades vegetais, na disponibilidade e qualidade do recurso medicinal utilizado pelas pessoas, uma vez que estão associados às variáveis ambientais.

Portanto, esta tese se estrutura em dois capítulos que se complementam ao investigar a composição fenólica em plantas medicinais da Caatinga, tendo como objetivo: investigar as variações nos teores de compostos fenólicos (fenois, taninos e flavonoides) em plantas medicinais lenhosas da caatinga, em relação à versatilidade medicinal e sob efeito de níveis de precipitação. Como objetivos específicos, tem-se:

1º. Selecionar e categorizar as espécies medicinais lenhosas da Caatinga, considerando o seu valor de Importância Relativa (IR) obtido na literatura.

2º. Quantificar os teores de fenólicos totais, taninos e flavonoides dos extratos metanólicos da casca das espécies medicinais.

3º. Avaliar os teores de compostos fenólicos entre as espécies lenhosas mais e menos versáteis no uso medicinal na Caatinga.

4º. Avaliar como variações na precipitação influenciam nos teores de compostos fenólicos em espécies lenhosas de uso medicinal na Caatinga.

Portanto, ambos os capítulos convergem na tentativa de compreender como a produção de compostos fenólicos se relaciona a fatores ecológicos e etnobotânicos, contribuindo para o entendimento integrado da química ecológica e do uso tradicional de plantas na Caatinga.

2 FUNDAMENTAÇÃO TEÓRICA

2.1 Compostos fenólicos em plantas: aspectos funcionais, farmacológicos e ecológicos

Os compostos fenólicos correspondem ao grupo de metabólitos secundários com maior distribuição entre as plantas. A principal característica desses compostos é a presença de ao menos um anel aromático ligado a um ou mais grupos hidroxila (Figura 1). Modificações químicas e o grau de polimerização resultam em uma ampla diversidade de compostos com diferentes propriedades e funções biológicas, como ácidos fenólicos, flavonoides e taninos (ZAGOSKINA et al., 2023)

Essas ligações são encontradas desde a sua forma mais simples, como também em cadeias mais complexas, conferindo aos fenólicos propriedades químicas e biológicas distintas, bem como a classificação desse grupo em diversas categorias (LA ROSA et al., 2019).

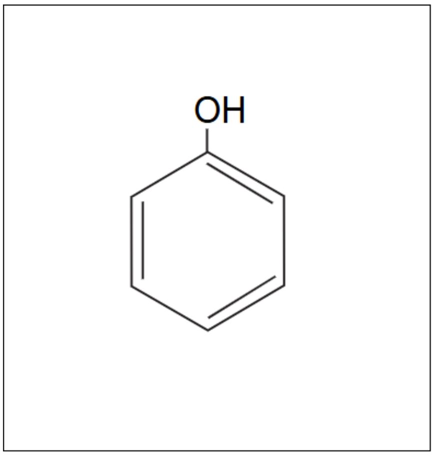

Figura 1. Estrutura do fenol. Fonte: Elaboração própria.

Ao estudar e descrever os fenólicos, os pesquisadores costumam classificá-los em “flavonoides e não flavonoides”, uma vez que os flavonoides correspondem a cerca de 50% dos compostos fenólicos; ou ainda serem classificados em “fenois simples e polifenois”, embora, ambas as classificações incluam as subclasses: ácidos fenólicos, cumarias, flavonoides, taninos, lignanas e estilbenos, que também são classificados dependendo de sua estrutura química e grau de polimerização (COSME et al., 2020; SUN; SHAHRAJABIAN, 2023).

Nas plantas, fenólicos compõem os compostos formados a partir do metabolismo secundário vegetal, assim como os alcaloides, terpenoides e esteroides. A diferença fundamental deste para o metabolismo primário, é que este último envolve a produção de compostos que atuam nos processos vitais, tais como respiração e fotossíntese, enquanto que os metabólitos secundários estão envolvidos em múltiplas funções, especialmente na adaptação e interação das plantas com o meio (YANG et al., 2018).

A biossíntese dos compostos fenólicos pode ocorrer através de três vias: a via do ácido chiquímico, a via do malonato-acetato e a via isoprenoide. A principal delas, a via do ácido chiquímico, também chamada de via fenilpropanoide, produz três aminoácidos aromáticos: fenilalanina (Phe), tirosina (Try) e triptofano (Trp) (Figura 2). Basicamente, a fenilalanina é modificada progressivamente até a formação dos ácidos cinâmicos, que por sua vez originam os fenólicos complexos como ácido hidroxicinâmicos, flavonoides e cumarinas (SANTOS-SÁNCHEZ et al., 2019; RESHI et al., 2023).

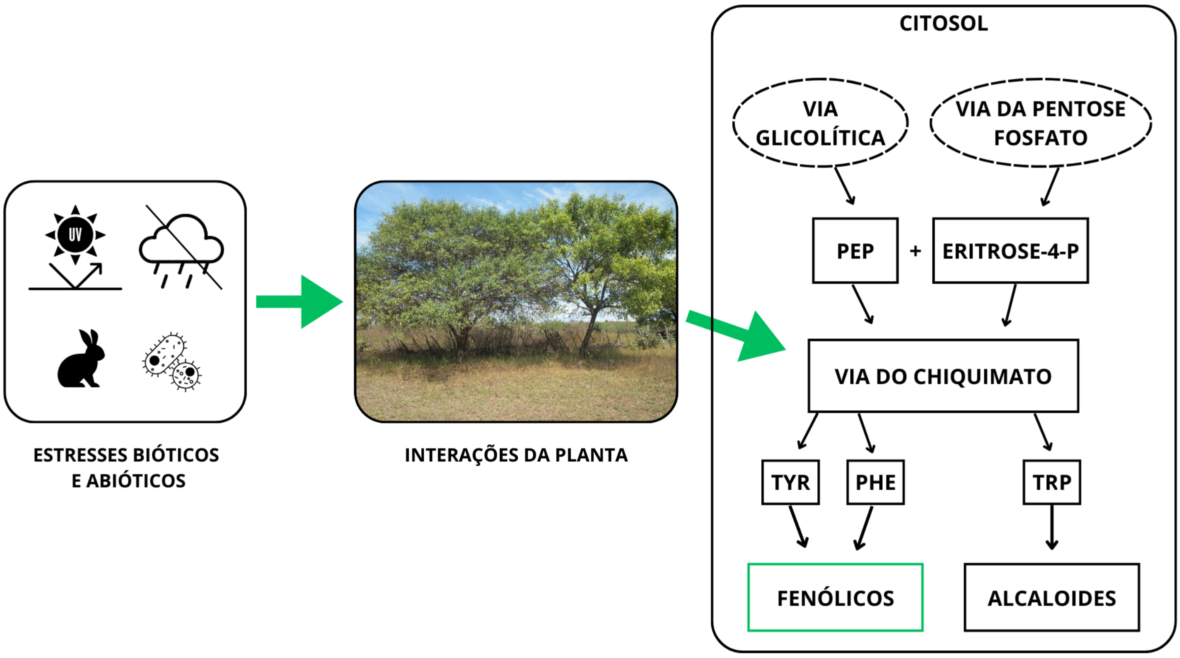

Figura 2. Representação esquemática da influência de estresses bióticos e abióticos na planta e sua relação com a via do chiquimato e a síntese de compostos fenólicos. Fonte: Elaboração própria, com base em Santos-Sánchez et al., (2019) e Reshi et al., (2023).

PEP: fosfoenolpiruvato; ERITROSE-4-P: eritrose-4-fosfato; TYR: tirosina; PHE: fenilalanina; TRP: triptofano.

Conforme mostrado na Fig. 2., a via fenilpropanoide é regulada a partir dos estímulos ambientais. Fatores como radiação UV, condições de seca, salinidade, ataque de herbívoros e patógenos ativam genes atrelados a esta e a outras vias de produção dos fenólicos como resposta adaptativa. Além disso, a produção de fenólicos também está relacionada a influências endógenas, como ação de hormônios ou estágio de desenvolvimento da planta (RESHI et al., 2023). Os fenólicos também agem como antioxidantes a nível celular, removendo espécies reativas de oxigênio produzidas sob condições de estresse, além de estarem envolvidos com a lignificação da parede celular vegetal e na interação entre plantas e animais, especialmente os flavonoides e antocianinas, que são responsáveis pela pigmentação de flores e frutos atraindo polinizadores e dispersores de sementes (SHARMA et al., 2019).

Os compostos fenólicos são defensores versáteis, com ações multifuncionais, tornando-os essenciais para a resiliência das plantas em ambientes em constante mudança. Na defesa antioxidante, os fenólicos neutralizam as espécies reativas de oxigênio (EROs) nocivas geradas durante o estresse, prevenindo danos celulares e mantendo o equilíbrio metabólico (RAO et al., 2025). Fenólicos como lignina e suberina atuam no reforço estrutural, fortalecendo as paredes celulares, tornando as plantas mais resistentes a lesões físicas, invasão de patógenos e perda de água (KUMAR et al., 2020; SAINI et al., 2024). Alguns fenólicos também apresentam propriedades quelantes, atuando na desintoxicação de metais pesados, reduzindo sua toxicidade e protegendo os tecidos vegetais, além da proteção UV, onde flavonoides e fenólicos relacionados absorvem a radiação UV, protegendo os tecidos vegetais dos danos induzidos pela luz (KUMAR et al., 2023; RAO et al., 2025).

Estudos também indicam que os fenólicos possuem efeitos alelopáticos através da ação de fitoalexinas fenólicas, que associados a outros compostos, inibem patógenos e pragas e também podem atuar inibindo o estabelecimento e desenvolvimento de plantas concorrentes (KUMAR et al., 2020; SAINI et al., 2024). Os fenólicos participam de vias de sinalização e regulação, onde o aumento da sua síntese ativam respostas ao estresse e coordenam mecanismos de defesa na planta (SAINI et al., 2024; RAO et al., 2025). A ampla variabilidade estrutural desses compostos permite que as plantas ajustem a produção e o tipo de fenólico sintetizado em resposta a diferentes estresses ambientais, como seca, salinidade, metais pesados e ataque de patógenos (SHARMA et al., 2019; ZAGOSKINA et al., 2023; SAINI et al., 2024).

A atividade antioxidante dos fenólicos é a principal e mais estudada ação farmacológica desse grupo. Os compostos fenólicos atuam como sequestradores de radicais livres, ativam enzimas antioxidantes (como SOD - superóxido dismutase e GPX - glutationa peroxidase) e inibem a formação de espécies reativas de oxigênio, protegendo componentes celulares essenciais contra danos oxidativos (KUMAR et al., 2019; COSME et al., 2020; LIU et al., 2023). Essa ação antioxidante também tem impactos positivos na saúde humana, estando associada à redução do risco de doenças relacionadas ao estresse oxidativo, como câncer, diabetes, doenças cardiovasculares e neurodegenerativas (KUMAR et al., 2019; COSME et al., 2020; MATSUMURA et al., 2023).

Além da atividade antioxidante, a atividade anti-inflamatória é uma importante ação farmacológica dos compostos fenólicos, que envolve a modulação de múltiplas vias e mediadores inflamatórios, o que reforça seu potencial terapêutico em diversas doenças crônicas relacionadas à inflamação (YAHFOUFI et al., 2018; RAHMAN et al., 2021). Esses compostos atuam na inibição de vias de sinalização inflamatória, inativam fatores de transcrição como NF-κB e modulam as vias MAPK, PI3K/Akt, JAK/STAT e mTORC1, reduzindo a expressão de genes pró-inflamatórios (YAHFOUFI et al., 2018; RAHMAN et al., 2021; XIE et al., 2024). Esses mecanismos refletem na prevenção e tratamento de doenças inflamatórias crônicas, como artrite, doenças intestinais, cardiovasculares, neurodegenerativas e de pele (LIU et al., 2018; RAHMAN et al., 2021; XIE et al., 2024).

Diversos estudos têm evidenciado uma ampla gama de atividades biológicas associadas aos compostos fenólicos, as quais contribuem para seus potenciais efeitos terapêuticos. A Tabela 1 apresenta um resumo dessas atividades, seus mecanismos de ação e as principais referências que as descrevem.

Tabela 1. Principais atividades biológicas atribuídas aos compostos fenólicos e seus mecanismos de ação.

Atividade	**Descrição**	**Referências**
Antimicrobiana	Inibem o crescimento de bactérias, fungos e vírus, inclusive cepas resistentes a antibióticos	Rahman et al. 2021; Liu et al. 2023
Anticancerígena	Inibem a proliferação de células tumorais, modulam vias de sinalização e induzem apoptose	Rahman et al. 2021; Liu et al. 2023
Antidiabética	Regulam o metabolismo da glicose, inibem enzimas digestivas de carboidratos e melhoram a sensibilidade à insulina	Kumar et al. 2019; Liu et al. 2023
Cardioprotetora	Reduzem pressão arterial, modulam lipídios sanguíneos e inibem a enzima conversora de angiotensina (ECA)	Kumar et al. 2019; Rahman et al. 2021; Liu et al. 2023

Neuroprotetora	Inibem enzimas como colinesterase, protegem contra estresse oxidativo e inflamação cerebral	Rahman et al. 2021; Liu et al. 2023

Logo, a síntese de compostos fenólicos pelas plantas justifica seu uso medicinal, uma vez que elas têm sido utilizadas universal e historicamente como recursos terapêuticos pela humanidade. Muitas das propriedades medicinais atribuídas às plantas estão frequentemente associadas à presença de compostos fenólicos, cuja importância farmacológica é amplamente reconhecida e tem sido explorada em diversos estudos com plantas medicinais (SUN et al., 2023).

Conforme abordado, a síntese de compostos fenólicos nas plantas é modulada por diferentes fatores ambientais, tais como a disponibilidade de recursos no meio. A hipótese ecológica da disponibilidade de recurso (HDR) fundamenta-se na relação planta-herbívoro e prevê, simplificadamente, que em ambientes com baixa disponibilidade de recursos, as plantas apresentem um maior investimento em defesas anti-herbívoro em relação ao seu crescimento (ENDARA; COLEY, 2010). Outras hipóteses ecológicas foram previstas com base na HDR, como a do balanço de carbono-nutriente (BCN) em plantas lenhosas. A hipótese BCN sugere que plantas com excesso de carbono (por exemplo, sob baixa disponibilidade de nutrientes) tendem a investir mais em compostos de defesa à base de carbono, como fenóis e taninos. Quando os nutrientes são abundantes, o investimento em crescimento é priorizado e a produção desses compostos é reduzida (LERDAU et al., 2002).

Uma meta-análise demonstrou que a regulação do metabolismo secundário em plantas lenhosas tem relação com a HDR em ambientes limitantes, especialmente produzindo compostos derivados da via fenilpropanoide (KORICHEVA et al., 1998). Em ambientes com variações sazonais, como a Caatinga, parte do bioma de Florestas Tropicais Sazonalmente Secas de ocorrência no Brasil, a HDR tem suas previsões suportadas em relação à presença de compostos fenólicos, como os taninos. Esses ambientes são caracterizados por alta incidência de luz e baixa disponibilidade hídrica, por vezes limitantes ao desenvolvimento de plantas na região (ALBUQUERQUE et al., 2012).

A síntese de compostos fenólicos ocorre praticamente em todas as partes das plantas, mas a quantidade e o tipo de fenólico varia conforme o órgão vegetal e as condições ambientais. De maneira geral, a parte aérea (folha, caules e flores) apresenta maior acúmulo de fenólicos e flavonoides (GARCÍA-PÉREZ et al., 2020). Conforme abordado, o maior acúmulo desses compostos ocorre sob condições limitantes, especialmente nas partes mais expostas como folhas (SHARMA et al., 2019; KUMAR et al., 2023; ZAGOSKINA et al., 2023). Os fenólicos também são amplamente encontrados na casca de plantas vasculares lenhosas, apresentando um grande potencial bioativo (TANASE et al., 2019).

A casca de diversas espécies contém uma ampla variedade de compostos fenólicos, incluindo ácidos fenólicos (como ácido clorogênico, ferúlico, gálico), flavonoides (catequina, epicatequina, rutina, quercetina), taninos, estilbenos e lignanas (TANASE et al., 2019; PIĄTCZAK et al., 2020). Em especial, as famílias Salicaceae (*Salix alba*), Fabaceae (*Libidibia ferrea*), Anacardiaceae (*Lannea*, *Pseudospondias*) e Myrtaceae (*Eucalyptus globulus*) aparecem com frequência em revisões e estudos de análises químicas em cascas do fuste, ritidoma ou madeira, refletindo sua importância tanto na pesquisa básica quanto nos usos tradicional e comercial (TANASE et al., 2019; PIĄTCZAK et al., 2020; MALÚ et al., 2024; SANTANA et al., 2024).

2.2 Versatilidade medicinal e a possível relação com a química de plantas da Caatinga

Compreender os motivadores da relação entre pessoas e o uso de plantas define a etnobotânica, ciência que explora essa inter-relação (ALBUQUERQUE; FERREIRA-JÚNIOR, 2023). A seleção das plantas como recurso pelas pessoas integra o funcionamento dos sistemas socioecológicos, que por sua vez são sistemas abertos e dinâmicos, o que torna complexo compreender essa seleção (ALBUQUERQUE et al., 2019). Referente às plantas medicinais, a seleção de espécies tem sido investigada explorando a sua distribuição geográfica, diversificação no uso, versatilidade medicinal, filogenia (HART et al., 2017; GAOUE et al., 2017; GAOUE et al., 2021).

Ao longo da evolução humana, os processos de seleção das plantas foi baseado na experimentação para alimentação, o que permitiu a identificação de espécies tóxicas, que eram direcionadas para o tratamento de doenças, com a informação sobre as essas plantas repassada entre gerações (ALBUQUERQUE et al., 2020). Logo, o uso de plantas medicinais integra o processo evolutivo humano e se fundamentam em fatores biológicos e culturais dos sistemas socioecológicos e que por sua vez, formam os sistemas médicos tradicionais (ALBUQUERQUE et al., 2020). Em cada sistema médico local, existe um conjunto de plantas que são utilizadas como recurso medicinal. Porém, há espécies que se tornam mais preferidas para usos do que outras. Evidências indicam que essa preferência se baseia na percepção da eficácia terapêutica sobre a espécie (FERREIRA-JÚNIOR et al., 2011), o que reflete em sua versatilidade medicinal (MACÊDO et al., 2018).

A versatilidade de uma planta medicinal consiste na sua indicação para tratamentos de diferentes alvos terapêuticos dentro de uma comunidade ou cultura. A versatilidade pode ser mensurada através do Índice de Importância Relativa (IR) proposto por Bennett e Prance (2000). A variação desse índice vai de 0 a 2, considerando o número de propriedades medicinais atribuídas a uma planta e a quantidade de sistemas corporais aos quais essas propriedades estão associadas. Quanto maior o número de propriedades medicinais e sistemas corporais indicados, maior é a versatilidade daquela espécie.

O IR é uma métrica importante aplicada em estudos com plantas medicinais. Em relação às plantas da Caatinga, um levantamento realizado apontou que maiores valores de IR estavam associados à presença de compostos fenólicos, ao correlacionar informações terapêuticas com dados disponíveis sobre a atividade fitoquímica e farmacológica das espécies listadas (ALBUQUERQUE et al., 2007). Recentemente, o IR foi utilizado no levantamento de espécies medicinais da Caatinga, para o cálculo do Índice de Prioridade de Conservação dessas espécies, evidenciando que aquelas com alta versatilidade apresentavam maiores índices para prioridade de conservação (CAMPOS; ALBUQUERQUE, 2021).

Alguns fatores são explorados como norteadores da versatilidade de uma espécie, como a sua disponibilidade local (LUCENA et al., 2007). Porém, a disponibilidade sozinha não explicou a versatilidade medicinal em uma comunidade da Caatinga, e sim conjuntamente com a eficiência percebida (CAETANO et al., 2020), que já tinha sido apontada em outros estudos (ALBUQUERQUE et al., 2007; FERREIRA-JÚNIOR et al., 2011). A eficácia percebida também explicou o consenso local no uso de plantas medicinais em detrimento a disponibilidade percebida e a frequência percebida de doenças (SOUSA et al., 2023). A facilidade na aquisição do recurso, como o descasque de cascas do caule, parte comumente extraída de espécies da Caatinga para uso medicinal, também foi investigada como motivadora da versatilidade com base em características anatômicas, o que não foi corroborado (ELIAS et al., 2024).

Através da percepção da eficácia, a presença de compostos fenólicos foi associada às indicações terapêuticas de algumas espécies medicinais da Caatinga, comumente através do uso da casca dessas espécies, que são amplamente utilizadas por comunidades locais, tanto na medicina humana quanto veterinária, devido à sua riqueza em compostos bioativos, especialmente fenólicos e taninos (ALBUQUERQUE; OLIVEIRA, 2007; LINS et al., 2019;

MAGALHÃES et al., 2019; SENES-LOPES et al., 2023). O uso tradicional é sustentado pelo conhecimento empírico que é transmitido entre gerações e que vem sendo validado por estudos científicos recentes.

Em estudo realizado na região da Caatinga, comunidade Carão, no município de Altinho, em Pernambuco, as espécies indicadas para tratamentos cicatrizantes e antiinflamatórias tinham forte associação com os taninos, sendo as espécies *Anadenanthera colubrina* (Vell.) Brenan e *Astronium urundeuva* Allemão as espécies que apresentaram os maiores níveis desse composto (ARAÚJO et al., 2008). Igualmente, na mesma comunidade, espécies indicadas pela população como antimicrobianas também apresentaram altos teores de taninos, com maiores teores quantificados na espécie *Mimosa tenuiflora* (Willd.) Poir., popularmente conhecida como jurema-preta (SIQUEIRA et al., 2012).

Ao investigar a possível relação entre a teoria da aparência e a seleção e uso de plantas medicinais na Caatinga, um levantamento etnobotânico foi combinado à análise fitoquímica em espécies popularmente usadas nas comunidades da região de Xingó (Nordeste do Brasil), em municípios localizados entre os estados de Sergipe e Alagoas. Os autores constataram que fenóis foram encontrados em 100% das espécies (n = 41) estudadas, enquanto que taninos foram identificados em 56% das espécies (ALMEIDA et al., 2005). Em estudo semelhante, a triagem fitoquímica de 61 espécies medicinais utilizadas localmente foi realizada (município de Altinho, comunidade Carão). Dentre as classes analisadas, fenóis e taninos aparecem como os compostos mais frequentes, com mais de 80% de ocorrência nas espécies, independente do hábito (árvores, arbustos ou ervas), enquanto que flavonoides aparecem em proporção intermediária (≅55%), sendo também relevantes (ALENCAR et al., 2009). Ambos estudos reforçam que compostos fenólicos, especialmente os de alto peso molecular como taninos, foram predominantemente identificados em espécies recomendadas pela população local em comunidades da Caatinga no tratamento de diversas doenças.

Conforme abordado, os compostos fenólicos têm importância farmacológica significativa, uma vez que apresentam múltiplas atividades biológicas comprovadas, desde a ação antiinflamatória até anticâncer (LIN et al., 2016; RAHMAN et al., 2021). Tais compostos são considerados versáteis devido à sua grande diversidade estrutural e múltiplos mecanismos de ação, o que lhes permite atuar em diferentes funções biológicas e aplicações, tanto em plantas quanto em humanos (KUMAR et al., 2019; KUMAR et al., 2020; MAI et al., 2023). Paralelamente, uma espécie medicinal é considerada versátil quando a mesma é utilizada no tratamento de diferentes doenças, ou seja, possui diversas aplicações terapêuticas

(BENNETT; PRANCE, 2000). Os valores de IR além de servirem como indicativo da versatilidade, também são utilizados como referência na identificação de espécies promissoras para estudos de bioprospecção na região (CARTAXO et al., 2010; RIBEIRO et al., 2014a; 2014b). Portanto, como a maior versatilidade medicinal está relacionada com a maior quantidade de indicações terapêuticas (sendo a eficiência percebida um dos seus motivadores), do ponto de vista fitoquímico, a maior concentração dos compostos fenólicos (incluindo taninos e flavonoides), pode estar relacionada com maior versatilidade das plantas medicinais da Caatinga. Porém, essa abordagem ainda não foi explorada em estudos com foco na Caatinga. A variabilidade biológica da química fenólica poderia ser um dos fatores que justificam a ampla utilização terapêutica de espécies mais versáteis em sistemas médicos locais nesta região.

2.3 Importância da Caatinga como ambiente de estudo

A região da Caatinga brasileira representa cerca de 30% do bioma global das Florestas e Bosques Tropicais Sazonalmente Secos (Seasonally Dry Tropical Forests and Woodlands - SDTFW), sendo o maior núcleo de floresta seca deste bioma. É característico por ser sazonal (cerca de 5 a 6 meses/ano com pluviosidade inferior a 100 mm), com valores de precipitação anual menores que 1800 mm/ano (QUEIROZ et al., 2017). É bem documentado que a sazonalidade da região impõe limitações ao desenvolvimento das plantas, que por sua vez, apresentam estratégias de sobrevivência, muitas vezes associadas com com a disponibilidade hídrica (período chuvoso), com maiores picos reprodutivos nesse período e consumindo o mínimo de energia no cenário inverso (ausência de chuvas), até o período chuvoso seguinte (SANTOS et al., 2014; RITO et al., 2017).

Esta sazonalidade também se caracteriza por apresentar altos níveis de radiação, que combinados a baixa disponibilidade hídrica, impõem às espécies lenhosas da região um crescimento mais lento e um maior investimento em defesas químicas como os fenólicos, principalmente os taninos (ALBUQUERQUE et al., 2012). A Hipótese da Disponibilidade de Recursos também corrobora com essa perspectiva, pois espera-se que espécies que ocorram em ambientes com recursos limitados (déficit hídrico por exemplo), invistam na produção de defesas químicas, como os fenólicos (COLEY 1985).

A limitação hídrica, comum em florestas secas tropicais como a Caatinga, tem sido explorada como um fator que pode influenciar a síntese de metabólitos secundários em plantas medicinais, embora descobertas recentes apontem que a produção desses compostos varia dependendo da espécie e do tipo de limitação ocorrente ou imposta (ALBERGARIA et al., 2020). Assim, como forma de adaptação fisiológica, as espécies desses ambientes sintetizam compostos bioativos na tentativa de regular sua sobrevivência, e esses compostos têm sido investigado em estudos etnobotânicos e etnofarmacológicos (ALBUQUERQUE et al., 2012; AMORIM et al., 2021).

Sabe-se que a regeneração da Caatinga ocorre em resposta a condições naturais de chuvas. Portanto, estima-se que estas regiões sofram de maneira mais acentuada os efeitos das mudanças climáticas, o que pode intensificar ainda mais a aridez nessa região (RITO et al., 2017). Segundo projeções do Painel Intergovernamental sobre Mudanças Climáticas (IPCC, 2019), regiões semiáridas podem se tornar ainda mais secas devido à redução dos índices pluviométricos. Além disso, a Caatinga apresenta áreas com diferentes gradientes de precipitação, ainda que dentro da mesma condição de sazonalidade climática. Um exemplo prático é o Parque Nacional do Catimbau em Pernambuco, Nordeste do Brasil (Figura 3), com área aproximada de 60.000 ha e precipitação anual variando de 510 a 1100 mm, onde são realizadas pesquisas que exploram os contrastes da região através do projeto PELD Catimbau (Programa de Estudos de Longa Duração). As pesquisas buscam entender como a região da Caatinga é afetada por fatores ambientais e antrópicos a partir das interações ecológicas, comportamento humano e dinâmica de espécies vegetais (OLIVEIRA et al., 2020; SILVA et al., 2023; SOUZA et al., 2024).

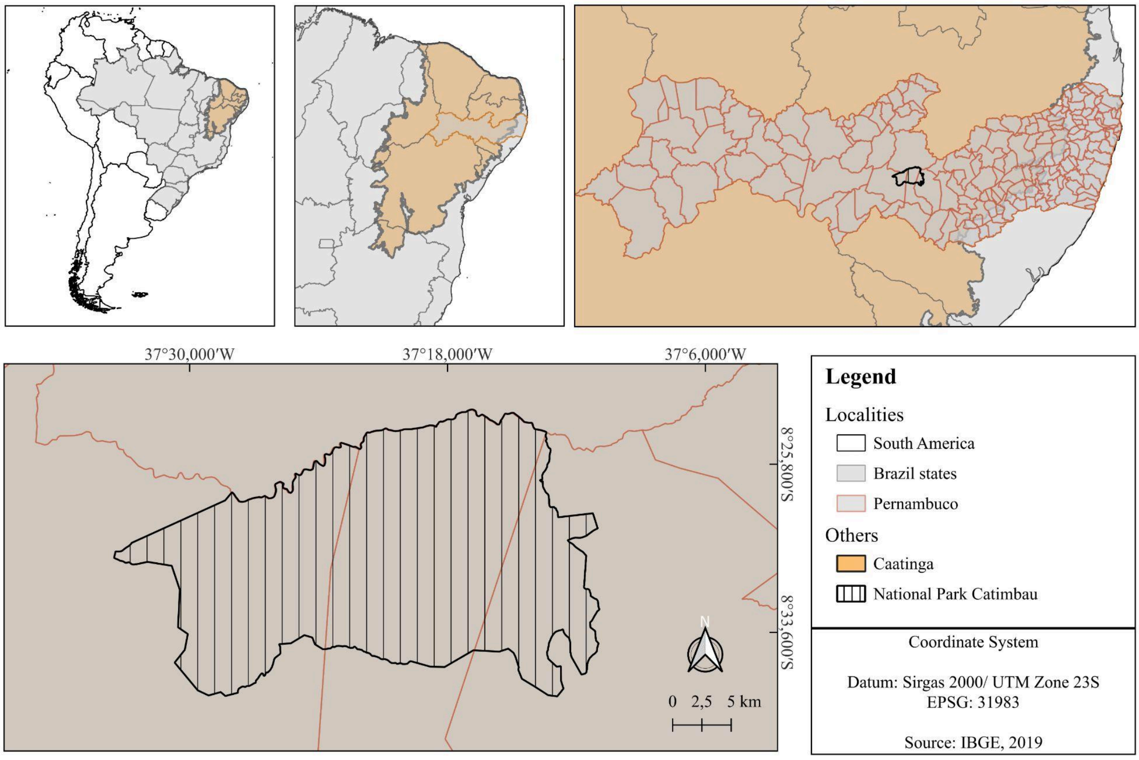

Figura 3. Localização geográfica do Parque Nacional do Catimbau (Estado de Pernambuco, Nordeste do Brasil). Fonte: Elaborado com base em dados do IBGE (2019). Sistema de referência: SIRGAS 2000 / UTM Zona 23S - EPSG: 31983. Ilustração elaborada sob encomenda pela autora.

Pesquisas apontam que a previsão da diminuição nos níveis de precipitação afetará a estrutura e o funcionamento dos ecossistemas naturalmente áridos, refletindo diretamente na prestação de serviços ecossistêmicos e estabilidade de populações humanas que habitam essas regiões (OLIVEIRA et al., 2020). Essas populações desenvolveram uma relação de subsistência com os recursos vegetais, que são necessários à manutenção de suas práticas culturais ou necessidades adicionais (ARAÚJO et al., 2007; ALBUQUERQUE et al., 2017).

Estudos também têm abordado os efeitos das variações sazonais e climáticas na síntese de compostos fenólicos em plantas medicinais em outras regiões (SRIVASTAVA et al., 2021; SUN et al., 2023). Os efeitos da diminuição dos níveis de chuvas como fator climático foram investigados foram em árvores de *Argania spinosa* (L.), como mecanismo de resistência às condições do ambiente em regiões áridas e semiáridas em sete áreas no sul de Marrocos, conforme um gradiente de aridez crescente (de semiárido a árido). O conteúdo de fenois totais e flavonoides foram maiores nas regiões mais áridas de Ait Baha e Bouizakarne, que apresentam valores de precipitação anual de 120 mm e 146 mm, respectivamente (FAHMI et al., 2020).

Condições de déficit hídrico, mensuradas pela indução ao estresse ou alterações nos níveis de pluviosidade, têm efeitos variados na quantificação de compostos fenólicos em plantas medicinais, conforme sistematizado por Albergaria et al., (2020). O estudo também concluiu que pesquisas abordando a síntese de fenólicos em espécies arbóreas sob condições climáticas naturais são escassas (ALBERGARIA et al., 2020). Efeitos da variação sazonal na síntese de taninos em duas importantes espécies medicinais da Caatinga foi investigada, mostrando que houve um aumento na produção desses compostos na casca de *Anadenanthera colubrina* (Vell.) Brenan e folhas de *Astronium urundeuva* (M.Allemão) Engl., durante o período de seca (MONTEIRO et al., 2006). Na espécie medicinal *Cenostigma microphyllum*, variações nos níveis de chuvas em diferentes áreas não influenciaram a síntese de fenois totais e taninos, enquanto que a fertilidade afetou negativamente os teores de fenois totais (ALBERGARIA et al., 2021). A influência de fatores abióticos na diversidade fitoquímica de *Anacardium occidentale* L. foi estudada em duas área da Caatinga, apontando que a variação na quantificação de compostos fenólicos apresenta alta relação com os níveis de pluviosidade anual (COSTA et al., 2022).

Diante desse contexto, é fundamental consolidar o entendimento sobre a variação nos níveis de precipitação na composição fenólica das plantas, especialmente as medicinais, tanto do ponto de vista ecológico e funcional das comunidades vegetais, quanto na disponibilidade e/ou eficácia do recurso medicinal para as populações, com implicações nos sistemas socioecológicos da Caatinga.

2.4 **Importância das espécies lenhosas da Caatinga como recurso medicinal**

A região da Caatinga é rica em diversidade de plantas medicinais. As espécies vegetais utilizadas na medicina tradicional local da região abrange cerca de 385 espécies de plantas lenhosas, que são utilizadas pelas pessoas no tratamento de inflamações, infecções, problemas respiratórios, gastrointestinais, entre outros (ALBUQUERQUE et al., 2007). Determinadas famílias e espécies botânicas se destacam como as mais estudadas e amplamente utilizadas na medicina tradicional (Tabela 2). As famílias mais frequentemente estudadas são Fabaceae, Euphorbiaceae, Myrtaceae, Rhamnaceae e Lamiaceae, enquanto que as espécies-chave incluem *Astronium urundeuva*, *Amburana cearensis*, *Anadenanthera colubrina*, *Ziziphus joazeiro* e *Lippia alba* (ALBUQUERQUE et al., 2007; ALBUQUERQUE; OLIVEIRA, 2007; MAGALHÃES et al., 2019; SANTOS-NEVES et al., 2024).

Tabela 2. Famílias botânicas frequentemente estudadas em relação ao uso medicinal na Caatinga.

Família	**Gêneros/Espécies Notáveis**	**Relevância Medicinal**	**Referências**
Fabaceae	*Astronium urundeuva*, *Amburana cearensis*, *Anadenanthera colubrina*	Mais citadas para uso medicinal; casca e raízes comumente usadas	Albuquerque et al. 2007; Albuquerque; Oliveira, 2007; Roque et al. 2010; Magalhães et al. 2019.
Euphorbiaceae	*Croton* spp., *Jatropha* spp.	Frequentemente citado em pesquisas etnobotânicas	Oliveira et al. 2010; Silva et al. 2015
Myrtaceae	*Psidium* spp., *Eugenia* spp.	Importante em usos alimentar e medicinal	Santos-Neves et al. 2024
Rhamnaceae	*Ziziphus joazeiro*	Conhecida pela versatilidade e alto consenso entre os usuários	Roque et al. 2010; Santos et al. 2018
Lamiaceae	*Lippia alba*	Usado no preparo de chás e infusões, especialmente para problemas respiratórios	Oliveira et al. 2010; Magalhães et al. 2019

Na região da Caatinga, as espécies lenhosas são de grande importância medicinal, constituindo um elemento essencial da assistência médica tradicional em comunidades locais, utilizadas no tratamento de uma ampla gama de problemas de saúde (MAGALHÃES et al., 2019; SILVA et al., 2024). Espécies como *Astronium urundeuva*, *Amburana cearensis*, *Anadenanthera colubrina*, *Sideroxylon obtusifolium*, *Ziziphus joazeiro*, *Anacardium occidentale* e *Schinopsis brasiliensis* são altamente valorizadas na região, utilizadas no tratamento de doenças respiratórias e digestivas, problemas de pele e sintomas em geral (SILVA; ALBUQUERQUE, 2005; ALBUQUERQUE et al., 2007; MAGALHÃES et al., 2019).

De acordo com Albuquerque et al., (2012), a fitofisionomia predominante na da Caatinga favorece a seleção de plantas lenhosas como recurso medicinal, conforme a Hipótese da Sazonalidade Climática. Esta hipótese prevê que em ambientes sazonais como a Caatinga, as pessoas tendem a selecionar os recursos perenes disponíveis ao longo do ano, como a casca do fuste de espécies lenhosas, em detrimento às folhas, por exemplo, que encontram-se disponíveis em poucos meses (ALBUQUERQUE et al., 2006).

Com relação à composição fenólica e ao uso da casca como recurso medicinal, a família Fabaceae também pode ser considerada a mais importante. As famílias Anacardiaceae, Burseraceae e Apocynaceae também são significativas, refletindo tanto o interesse científico quanto o uso medicinal tradicional da casca neste bioma (Tabela 3).

Tabela 3. Famílias e espécies frequentemente estudadas em relação à composição fenólica e uso da casca como recurso medicinal na Caatinga.

Família	**Espécie**	**Principais descobertas sobre fenólicos da casca**	**Referências**
Fabaceae	*Libidibia ferrea*	Alto teor de fenólicos e taninos na casca; a inoculação com AMF aumenta os flavonoides e os taninos	Lins et al. 2019; Amorim et al. 2021
	Mimosa caesalpiniaefolia	Extratos de casca com alto teor de fenólicos e atividade antifúngica	Lins et al. 2019; Silva et al. 2021
	Poincianella pyramidalis	Casca rica em derivados de ácido gálico e elágico; alto efeitos antioxidantes e anti-inflamatórios	Moraes et al. 2020
	Cenostigma microphyllum	A casca contém fenóis e taninos significativos, embora menos do que as folhas	Albergaria et al. 2021
Anacardiaceae	*Anacardium occidentale*	Casca rica em fenólicos e óleos essenciais com atividade antifúngica	Silva et al. 2021
Burseraceae	*Commiphora leptophloeos*	Óleos essenciais e extratos de casca ricos em fenólicos e flavonoides	Pinto et al. 2023
Apocynaceae	*Aspidosperma pyrifolium*	Alto teor de tanino nos ramos e na casca	Lins et al. 2019

O uso e o conhecimento sobre plantas medicinais lenhosas estão profundamente enraizados nas tradições locais, sendo as espécies nativas as mais frequentemente utilizadas, embora existam espécies exóticas também importantes localmente (ALBUQUERQUE; OLIVEIRA, 2007; MEDEIROS et al., 2013). Entretanto, espécies medicinais importantes são frequentemente as mais vulneráveis devido à sobreexploração e à perda de habitat, com algumas listadas como ameaçadas de extinção, tais como *Schinopsis brasiliensis* e *Astronium urundeuva* (ALBUQUERQUE; OLIVEIRA, 2007; SILVA et al., 2022; 2024).

3 ARTIGO 1

Is there a relationship between the concentration of phenolic compounds and the versatility of medicinal plants in the Caatinga biome?

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Research

Abstract

Background: This study investigates whether the concentration of phenolic compounds—specifically phenols, tannins, and flavonoids—correlates with the medicinal versatility of woody plant species in the Caatinga, a seasonally dry tropical forest in northeastern Brazil. Given the well-documented bioactivity of phenolic compounds, we tested the hypothesis that higher concentrations are associated with a broader range of medicinal uses.

Methods: We selected 20 woody medicinal plant species and classified them into high- and low-versatility groups based on their Relative Importance (RI) values drawn from the ethnobotanical literature. Stem bark samples were collected from Catimbau National Park, Pernambuco, Brazil. Methanolic extracts were analyzed for total phenolics using the Folin–Ciocalteu assay, for tannins using casein precipitation, and for flavonoids using the aluminum chloride complexation method.

Results: Contrary to our hypothesis, no statistically significant differences in phenolic compound concentrations were observed between high- and low-versatility groups. While highly versatile species such as *Astronium urundeuva* (232.85 mg TAE/100 g DM) and *Anadenanthera colubrina* (254.24 mg TAE/100 g DM) exhibited elevated levels of total phenolics, some less versatile species—Mimosa tenuiflora (244.86 mg TAE/100 g DM) and *Schinopsis brasiliensis* (219.85 mg TAE/100 g DM) — showed similarly high values. A comparable pattern was observed for tannins, while flavonoid concentrations did not vary significantly between groups.

Conclusions: Although phenolic compounds contribute to the pharmacological potential of medicinal plants, their concentrations alone do not account for greater medicinal versatility in the Caatinga. Other factors—such as ecological availability, cultural preferences, and traditional knowledge systems—likely play a more decisive role. These findings highlight the need for integrative approaches in ethnopharmacological research that move beyond chemical profiles alone.

Keywords: Phytochemistry; Tannins; Seasonal dry forests; Ethnobotany; Ethnopharmacology; Flavonoids; Phenols; Plant chemicals; Woody Plants

Background

Contemporary research has increasingly emphasized the pharmacological relevance of secondary metabolites produced by plants, particularly phenolic compounds such as tannins, flavonoids, and coumarins. These molecules exhibit a broad spectrum of biological activities—including anti-inflammatory, antioxidant, antimicrobial, and antifungal effects—which support their importance as therapeutic agents and their influential role in shaping human medicinal plant use (Rahman et al. 2021; Kumar et al. 2019; Albuquerque et al. 2020; Durazzo et al. 2019).

Plants biosynthesize secondary metabolites, as integral components of their physiological processes, which are essential for survival and reproduction in diverse environments. These compounds may be upregulated in response to biotic and abiotic stressors, including herbivory, pathogen attack, water deficit, low soil fertility, or salinity. The type and intensity of metabolite production vary across species and are shaped by environmental pressures (Isah 2019; Yang et al. 2018).

Interest in the phytochemical and ethnopharmacological aspects of plant use has been growing within ethnobotanical research, particularly as it relates to local ecological knowledge (Castro et al. 2014; Ribeiro et al. 2014). The Caatinga biome, a seasonally dry tropical forest characterized by irregular rainfall and pronounced environmental stress, offers edaphoclimatic conditions favorable for the biosynthesis of phenolic compounds, including tannins and flavonoids (Albuquerque et al. 2012).

Such compounds have been consistently identified in numerous plant species widely used in traditional medicine in the Caatinga, with their therapeutic effectiveness often attributed to these phytochemicals (Almeida et al. 2005, 2011; Araújo et al. 2008). Furthermore, studies have suggested significant correlations between phenolic content and the pharmacological efficacy of medicinal plants (Amorim et al. 2021; Chaves et al. 2013; Sobrinho et al. 2011).

The medicinal value of a plant is often assessed by its versatility, which refers to the range of therapeutic uses attributed to it. This versatility can be quantified using the Relative Importance Index (RI), which integrates both the number of body systems treated and the number of therapeutic uses cited, serving as a proxy for cultural salience and medicinal relevance (e.g., Albuquerque et al. 2007; Bennett & Prance 2000; Souza et al. 2016).

A systematic review encompassing 385 woody medicinal angiosperms from the Caatinga revealed a strong association between high RI values and their widespread popular use, reinforcing the utility of the RI metric for identifying culturally and pharmacologically important plants with bioprospecting potential (see Albuquerque et al. 2007). Several Caatinga plant species are known to accumulate substantial levels of phenolic compounds. *Mimosa tenuiflora* (Willd.) Poir., commonly known as black jurema, is rich in total phenolics, flavonoids, and tannins (Silva et al. 2017). *Cenostigma microphyllum* (Mart. ex G. Don) Gagnon & G.P. Lewis also contains high concentrations of phenolics and tannins, particularly in its leaves (Albergaria et al. 2021). Similarly, *Libidibia ferrea* (Mart. ex Tul.) L.P. Queiroz (pau-ferro or jucá) contains bioactive phenolics, such as gallic acid, and flavonoids, including kaempferol and quercetin (Castro et al., 2014). Other species, including *Sideroxylon obtusifolium* (Roem. & Schult.) T.D. Penn. and *Schinopsis brasiliensis* Engl., are also reported to contain diverse phenolic compounds (Castro et al. 2014).

In light of the recognized pharmacological properties of phenolic compounds and their diverse biological functions (Sun et al. 2023), it is plausible to hypothesize that plants with higher medicinal versatility also exhibit higher concentrations of these compounds. However, this potential relationship remains unexplored in the context of the Caatinga. To address this gap, the present study investigates whether the concentrations of phenolic compounds - specifically total phenols, tannins, and flavonoids - are associated with the medicinal versatility of woody plant species used by local communities in the Caatinga. We hypothesize that more versatile species exhibit higher concentrations of these bioactive compounds. By bridging the fields of chemical ecology and ethnopharmacology, this pioneering study aims to deepen our understanding of the phytochemical underpinnings of traditional plant use in a uniquely adapted ecosystem.

Materials and Methods

Plant species

To investigate whether the concentration of phenolic compounds explains the versatility of medicinal tree species, we utilized a list of medicinal tree species from Caatinga, as published by Campos & Albuquerque (2021). These authors calculated the Relative Importance Index (RI) for 147 species, including woody species, palm trees, and cacti, used medicinally in the Caatinga. RI values ranging from 0 to 2 indicate species versatility, with values closer to 2 indicating higher versatility for medicinal use (Bennett & Prance 2000). The relative importance index (RI) was calculated using the formula IR = ((REL MP + REL BS)/2) × 100, where MP represents the number of medicinal properties and REL MP is the relative value of the medicinal properties normalized to a maximum of 1. BS refers to the number of body systems treated, and REL BS is the relative value of the body systems treated normalized to a maximum of 1. We selected 20 woody plant species from this list to perform phytochemical analyses, focusing on the quantification of total phenols, tannins, and flavonoids. We classified ten species as the most versatile, with RI values closer to 2, and ten species as the least versatile, with RI values closer to 1 (Table 1).

Table 1. List of woody medicinal plants from the Caatinga selected according to Relative Importance (RI) values, from Campos & Albuquerque (2021).

Family	Species	Popular name	Relative Importance Index (RI)	Voucher	Herbarium
Anacardiaceae	*Astronium urundeuva* (M.Allemão) Engl.	Aroeira	1.94	92517	IPA
Fabaceae	*Libidibia ferrea* (Mart. ex Tul.) L.P.Queiroz	Pau-ferro	1.74	91696	IPA
Fabaceae	*Anadenanthera colubrina* (Vell.) Brenan	Angico	1.69	91649	IPA
Olacaceae	*Ximenia americana* L.	Ameixa-da-praia	1.37	91787	IPA
Bignoniaceae	*Handroanthus impetiginosus* (Mart. ex DC.) Mattos	Ipê-roxo	1.27	86867	IPA
Anacardiaceae	*Anacardium occidentale* L.	Cajueiro	1.26	93683	IPA
Rhamnaceae	*Sarcomphalus joazeiro* (Mart.) Hauenschild	Juazeiro	1.23	82935	IPA
Fabaceae	*Hymenaea courbaril* L.	Jatobá	1.22	91630	IPA
Sapotaceae	*Sideroxylon obtusifolium* (Roem. & Schult.) T.D.Penn.	Quixaba	1.18	84076	IPA
Fabaceae	*Cenostigma pyramidale* (Tul.) Gagnon & G.P.Lewis	Caatingueira	1.09	55339	UFP
Apocynaceae	*Aspidosperma pyrifolium* Mart. & Zucc.	Pereiro	0.92	93686	IPA
Fabaceae	*Mimosa tenuiflora* (Willd.) Poir.	Jurema preta	0.74	82895	UFP
Burseraceae	*Commiphora leptophloeos* (Mart.) J.B.Gillett	Amburana-de-cambão	0.72	91663	IPA
Anacardiaceae	*Schinopsis brasiliensis* Engl.	Baraúna	0.62	91697	IPA
Fabaceae	*Senegalia bahiensis* (Benth.) Seigler & Ebinger	Calumbi	0.36	91697	IPA
Fabaceae	*Peltogyne pauciflora* Benth.	Pau-de morro	0.29	93435	IPA
Fabaceae	*Piptadenia retusa* (Jacq.) P.G.Ribeiro, Seigler & Ebinger	Jurema branca	0.21	91656	IPA

Malpighiaceae	*Byrsonima gardneriana* A.Juss.	Murici	0.21	93437	IPA
Erythroxylaceae	*Erythroxylum revolutum* Mart.	Quebra-facão	0.15	91560	IPA
Fabaceae	*Pityrocarpa moniliformis* (Benth.) Luckow & R.W. Jobson	Catanduva	0.14	91651	IPA

Collection of plant material Samples of the listed species (Table 1) were collected within Catimbau National Park (8°24'00″″ " to 8°36'35" S; 37°0'30" to 37°1'40"″ W), during the dry season (October/2021), within the permanent study plots of the PELD Catimbau Project (Long-Term Ecological Project) (see https://www.peldcatimbau.org/). Voucher material of the species collected in the Park was deposited in the IPA herbarium (Dárdano de Andrade Lima) and the UFP herbarium (Geraldo Mariz - Federal University of Pernambuco).

This Park, located in Pernambuco, Northeast Brazil, has a hot, semi-arid climate (BSh, according to the Köppen classification) (Alvares *et al.* 2013). Indigenous populations and surrounding rural communities sustain a subsistence relationship with the region's flora, engaging in activities such as hunting, logging, collecting firewood, and utilizing plant resources (Rito *et al.* 2017). The samples consisted of stem bark, the primary resource used for therapeutic purposes due to its perennial nature (see Albuquerque *et al.*, 2012). At least three individuals of each species were selected, spaced 3–5 m apart. Bark samples were collected from each individual, forming a composite sample of 500 g. Bark samples were collected at breast height (approximately 1.30 m above ground level) from all individuals of the species. The samples were placed in labeled paper bags and dried in an oven with forced air circulation at 25 °C. Subsequently, they were processed at the Plant Physiology Laboratory (UFPE) using a Willey knife mill (R-TE-650/1, Tecnal) to obtain a powder.

Preparation of crude extract for phytochemical analysis

Bark powder (500 mg) from each species was extracted in 50 mL beakers containing 25 mL of 80% methanol (v/v). The use of an 80% (v/v) methanolic solvent ensures the wide extraction of phenolic compounds, as these compounds exhibit varying polarities (Dai & Mumper 2010; Spigno *et al.* 2007). The mixture was gently boiled (below the boiling temperature of the solvent) on a hot plate (TE-0851; Tecnal, Männedorf, Switzerland) for 30 min. Extracts were filtered using qualitative filter paper (Unifil 80 g/m2) in 50 mL volumetric flasks. The residues were washed with an additional 25 mL of 80% (v/v) methanol solvent, filtered again, and the final volume of the flask was adjusted using the same solvent (Amorim *et al.* 2012). Extractions for each species were conducted in triplicate for subsequent analysis of total phenols, tannins, and flavonoids.

Determination of the Total Phenolic (TPC) and Total Tannin Content (TTC)

The total phenolic content (TPC) was determined using the Folin-Ciocalteu method (Amorim *et al.* 2012). Aliquots of the extracts (0.125 – 0.25 mL) were pipetted into 25 mL volumetric flasks. Subsequently, 1.25 mL of 10% (v/v) Folin-Ciocalteu reagent and 7.5% (w/v) aqueous sodium carbonate solution (2.5 mL) were added. The final volume of the flasks was filled with deionized water, and the samples were left to react in the dark for 30 min. Absorbance was measured at 760 nm using a Genesys 10S spectrophotometer (Thermo Fisher Scientific, Waltham, MA, USA). Total tannin content (TTC) was quantified using the residual phenol content obtained via the casein precipitation method, followed by the Folin-Ciocalteu method with some modifications (Amorim *et al.* 2012). Aliquots of the extracts (6 mL) were pipetted into Erlenmeyer flasks containing 1 g of casein powder and 12 mL of deionized water. The samples were mechanically stirred for three hours at room temperature and were protected from light. After filtration, aliquots of the resulting solution were used to quantify residual phenols via the Folin-Ciocalteu method. The amount of TTC was determined by comparing the total and residual phenols. TPC and TTC were estimated using the calibration curve obtained by preparing a standard tannic acid solution (0.1 mg/mL). TPC and TTC were expressed in milligrams of tannic acid equivalents per gram of dry matter (mg TAE/100 g DM). The calibration equation for tannic acid was $y = 0.154 x + 0.076$ ($R^2 = 0.977$).

Determination of Total Flavonoid Contents (TFC)

The total flavonoid content (TFC) was determined using a previously described method (Amorim *et al.* 2012). Aliquots of the extracts (1 mL) were pipetted into 25 mL volumetric flasks. Then, 0.6 mL of glacial acetic acid and 10 mL of 20% (v/v) methanolic pyridine solution were added, followed by 2.5 mL of 5% (w/v) methanolic aluminum chloride solution. The final volume of each flask was filled with deionized water and shaken appropriately. The reaction was performed in the dark for 30 min, and the absorbance was measured at 420 nm using a spectrophotometer. The TFC was estimated using the calibration curve obtained by preparing the standard rutin solution (0.5 mg/mL). The amount of TFC was expressed in milligrams of rutin equivalents per gram of dry matter (mg RE/100 g DM). The calibration equation for rutin was $y = 0.518x + 0.046$ ($R^2 = 0.999$).

Data analysis

Species were divided into two groups based on RI values:

Group 1: The ten most versatile plants with RI > 1 (high);

Group 0: The ten less versatile plants, with RI < 1 (low), as shown in Table 1.

Data were analyzed for normality using the Shapiro-Wilk test and homoscedasticity using the Bartlett test. Subsequently, Analysis of Variance (ANOVA) was conducted to compare the average levels of each compound class (total phenols, tannins, and flavonoids) between the two plant groups (high and low RI). Statistical analyses were performed using the R software at a significance level of 5% ($p < 0.05$). Principal component analysis (PCA) was performed to identify potential clusters. Data were transformed (logarithm) for standardization owing to the different scale magnitudes. The importance level of each PC was determined using the Broken-stick method, where eigenvalues exceeding the expected values were retained for interpretation. Analyses were performed using OriginPro 2018 software.

Results

Content of phenolic compounds

The total amounts of the phenols, tannins, and flavonoids are listed in Table 2. Among the most versatile plants, *Anadenanthera colubrina* exhibited the highest total phenol content (254.244 mg TAE/100 g DM) and was the third species listed, based on its relative importance value (RI = 1.69). As for the species *Astronium urundeuva*, which has the highest relative importance value on the list (RI = 1.94), it presented 232.846 mg TAE/100 g DM (Table 2).

Table 2. Average content of phenolic compounds (total phenols, tannins, and flavonoids) with standard deviation, quantified in woody medicinal plants listed as more versatile (RI > 1) and less versatile (RI < 1), collected in the Catimbau National Park, PE – Brazil. (n = 3/species). RI= Relative Importance.

Species	RI	Total phenols (mg TAE/100 g DM)	Tannins (mg TAE/100 g DM)	Flavonoids (mg RE/100 g DM)
Astronium urundeuva	1.94	232.846 ± 1.598	159.931 ± 3.663	2.010 ± 0.129
Libidibia ferrea	1.74	164.556 ± 1.841	163.483 ± 1.393	1.214 ± 0.037
Anadenanthera colubrina	1.69	254.244 ± 1.008	244.104 ± 0.977	1.511 ± 0.595
Ximenia americana	1.37	175.525 ± 6.786	131.921 ± 7.680	2.257 ± 0.019
Handroanthus impetiginosus	1.27	57.450 ± 0.950	49.572 ± 1.187	1.920 ± 0.012
Anacardium occidentale	1.26	138.125 ± 4.329	106.684 ± 5.886	1.720 ± 0.032
Sarcomphalus joazeiro	1.23	10.475 ± 0.397	8.591 ± 0.879	0.329 ± 0.030
Hymenaea courbaril	1.22	110.996 ± 1.153	105.768 ± 1.312	1.974 ± 0.423
Sideroxylon obtusifolium	1.18	96.000 ± 2.344	92.991 ± 2.790	0.745 ± 0.102
Cenostigma pyramidale	1.09	90.716 ± 2.077	88.679 ± 2.385	1.447 ± 0.094
Aspidosperma pyrifolium	0.92	46.303 ± 1.948	38.403 ± 1.252	1.079 ± 0.031
Mimosa tenuiflora	0.74	244.857 ± 6.045	199.099 ± 1.998	2.231 ± 0.046
Commiphora leptophloeos	0.72	63.674 ± 3.444	62.965 ± 3.544	1.083 ± 0.059
Schinopsis brasiliensis	0.62	219.847 ± 6.599	208.164 ± 6.564	2.904 ± 0.145
Senegalia bahiensis	0.36	23.453 ± 1.011	18.646 ± 1.202	0.993 ± 0.002
Peltogyne pauciflora	0.29	102.446 ± 2.557	96.686 ± 2.240	0.949 ± 0.027
Piptadenia retusa	0.21	24.770 ± 0.408	21.564 ± 0.329	0.501 ± 0.011
Byrsonima gardneriana	0.21	192.232 ± 24.021	187.711 ± 21.572	1.041 ± 0.128
Erythroxylum revolutum	0.15	84.996 ± 2.705	79.336 ± 2.562	1.113 ± 0.029
Pityrocarpa moniliformis	0.14	126.232 ± 1.033	122.621 ± 1.077	0.982 ± 0.068

In contrast, among the less versatile plants, *Mimosa tenuiflora*, ranked twelfth due to its assigned RI value (RI = 0.74), showed a high total phenol content (244.857 mg TAE/100 g DM), similar to *A. colubrina*. Additionally, *Schinopsis brasiliensis* (RI = 0.62), also listed among the less versatile species, exhibited a total phenol content of 219.847 mg TAE/100 g DM, which was comparable to that of *A. urundeuva*, considered a more versatile species. Similar trends were observed for tannin levels. Among the most versatile plants, *A. colubrina* and *Libidibia ferrea* (third and second positions according to RI values) exhibited 244.104 mg and 163.483 mg TAE/100 g DM), respectively. Contrary to the least versatile plants, *S. brasiliensis* and *M. tenuiflora* (fourteenth and twelfth positions according to the RI values) exhibited 208.164 mg and 199.099 mg TAE/100 g DM, respectively (Table 2).

The species with the highest flavonoid levels within the most versatile group were *Ximenia americana* (RI = 0.37) and *A. urundeuva* (2.257 and 2.010 mg RE/100 g DM, respectively). Similarly, in the less versatile group, *S. brasiliensis* and *M. tenuiflora* exhibited 2.904 mg and 2.231 mg RE/100 g DM, respectively, which were comparable to those found in the more versatile species (Table 1).

Phenol concentration and medicinal plant versatility

The variation in phenolic compound levels among plant samples, grouped according to the relative importance index (RI), was analyzed using principal component analysis (PCA) (Figure 1). The analysis indicates that more versatile species (high RI) tend to cluster in the positive region of PC1 (87.7%), being associated with higher tannin and total phenol levels, while less versatile species (low RI) present greater dispersion in the graph, with less association with phenolic compounds, especially tannins. However, it is possible to observe an overlap between the ellipses, which represent 95% confidence, indicating that the groups share similar characteristics in part of the data, specifically in the levels of phenolic compounds in both groups.

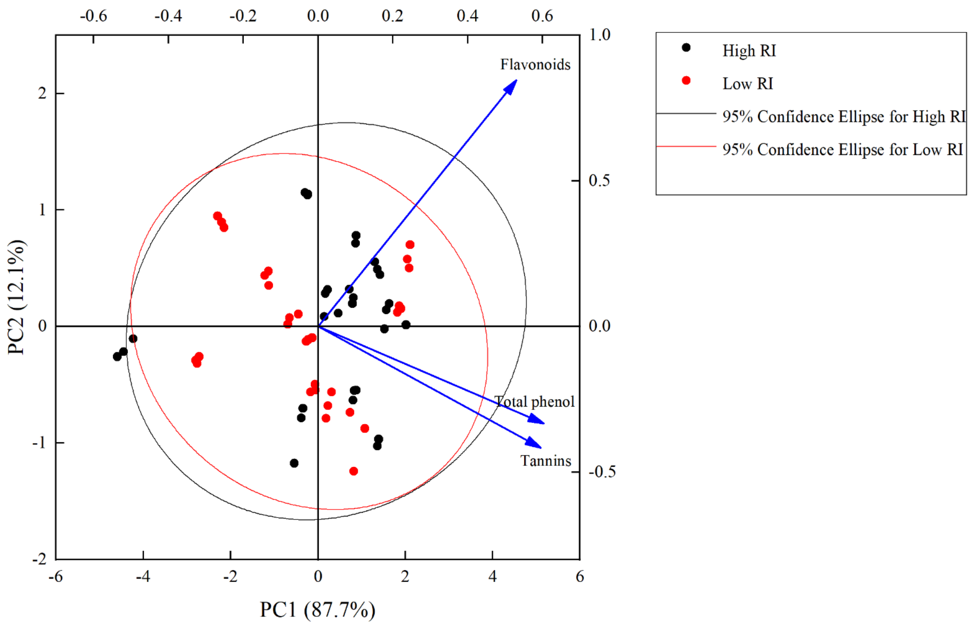

Figure 1. Principal component analysis (PCA) based on the entire data set of phenols, tannins, and flavonoids in groups of woody medicinal plants in relation to versatility (high and low RI), collected in the Catimbau National Park, Brazil (n = 3/species). RI = Relative Importance Index.

According to Figure 2, the group of species with the highest (RI) presented higher average contents of total phenols, tannins, and flavonoids compared to the group with low RI. However, according to the analysis of variance (*p*-values), there were no significant differences in the total amounts of phenols, tannins, or flavonoids between the plant groups (Table 3).

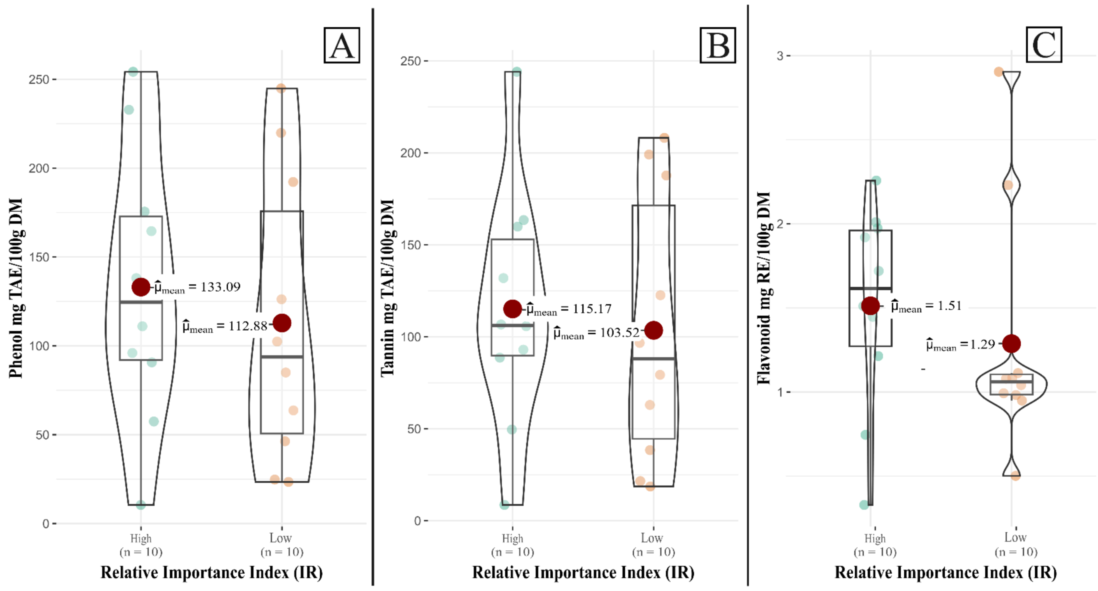

Figure 2. Average content of total phenols (A), tannins (B), and flavonoids (C) in groups of woody medicinal plants in relation to versatility (high and low RI), collected in the Catimbau National Park, Brazil. RI= Relative Importance.

The amount of phenols in the group with the highest versatility was 133.093 ± 75.910 mg TAE/100 g DM, while in the group with the lowest versatility, it was 112.881 ± 80.854 mg TAE/100 g DM (Figure 2A). A similar pattern was observed for total tannins among plant groups, with the amount in the most versatile group being 115.172 ± 65.199 mg TAE/100 g DM, and in the least versatile group it was 103.519 ± 73.011 mg TAE/100 g DM (Figure 2B). The same trend was observed for flavonoids. The mean value for the group with the highest versatility was 1.513 ± 0.606 mg RE/100 g DM, while in the group with the lowest versatility, it was 1.288 ± 0.714 mg RE/100 g DM (Figure 2C). Details of the statistical analyses are presented in Table 3.

Table 3. Average content of phenolic compounds (total phenols, tannins, and flavonoids) followed by standard deviation (SD) along with p-value (ANOVA) in the groups of most versatile (high RI) and least versatile (low RI) woody medicinal plants collected in the National Park of Catimbau, PE - Brazil. RI= Relative Importance. (n = 3/species).

Phenolic content	**RI**	**Mean (± SD)**	***p* (< 0.05)**
Total phenols (mg TAE/100 g DM)	Hight	133.093 ± 75.910	0.571
	Low	112.881 ± 80.854	
Tannins (mg TAE/100 g DM)	Hight	115.172 ± 65.199	0.711
	Low	103.519 ± 73.011	
Flavonoids (mg RE/100 g DM)	Hight	1.513 ± 0.606	0.457
	Low	1.288 ± 0.714	

Discussion

The initial hypothesis of this study, based on prior research (see Araújo et al. 2008; Siqueira et al. 2012), proposed that medicinal plants with higher versatility in the Caatinga would exhibit elevated concentrations of phenolic compounds. Contrary to this expectation, our findings revealed no statistically significant differences in phenolic content between species with high and low Relative Importance (RI) values. This divergence from the original hypothesis may reflect the intricate and context-dependent nature of the relationship between chemical composition and therapeutic use in ethnobotanical systems.

Our results are consistent with Monteiro et al. (2014), who also reported no direct correlation between tannin concentration and plant use value. Such findings reinforce the argument that chemical richness alone cannot fully explain patterns of medicinal plant use. Instead, cultural preferences, ecological availability, and the structure of local medical systems must be considered in a more integrative framework.

One plausible explanation for these results lies in the scale of previous studies. Earlier work often focused on localized contexts, assessing whether specific bioactivities could be linked to the presence of phenolic compounds in particular plants (see Albuquerque et al. 2012; Araújo et al. 2008). In contrast, our study aimed to test this association at a broader regional level, using an updated and comprehensive database of medicinal species in the Caatinga (Campos & Albuquerque, 2021). However, the phytochemical data generated here did not corroborate the hypothesized pattern, underscoring the complexity of chemical ecology and ethnopharmacology.

The case of *Sarcomphalus joazeiro* illustrates this well. Despite being among the most versatile species in our dataset, it exhibited low phenolic concentrations (Table 2). Previous studies attribute its pharmacological efficacy to saponins rather than phenolics (Andrade et al. 2019a, 2019b), exemplifying how bioactivity may result from compound classes not examined in this study.

Other examples further complicate the relationship between phenolic content and versatility. *Anadenanthera colubrina*, with the third-highest RI value (1.69), exhibited the highest levels of total phenols and tannins. In contrast, less versatile species such as *Mimosa tenuiflora* (RI = 0.74) and *Schinopsis brasiliensis* (RI = 0.62) also showed exceptionally high concentrations of these compounds, comparable to those in *A. colubrina* and *Astronium urundeuva*, both high-RI species (Table 1). Notably, *M. tenuiflora* and *A. colubrina* have been widely studied for their antioxidant, anti-inflammatory, antimicrobial, and wound-healing activities.

In *A. colubrina*, ethanolic leaf extracts have demonstrated potent antioxidant and anti-inflammatory effects, attributed to their high phenolic content (Junior et al. 2020). The bark extract has also shown promise in managing diabetes mellitus (Costa et al. 2020). Likewise, *M. tenuiflora* exhibited elevated levels of total phenols and flavonoids in this study, aligning with previous research that indicates its antimicrobial activity, likely due to the presence of flavonoids and tannins (Ferreira et al. 2021). Moreover, its bark extract has been shown to inhibit aflatoxin B1 production, which is attributed to condensed tannins (Hernandez et al. 2021). Conversely, *Byrsonima gardneriana*, a species with a low RI (0.21), exhibited phenolic levels comparable to *A. colubrina* (Table 3), further challenging the assumption that versatility and phenolic content are directly linked.

Similarly, no significant differences were found in flavonoid content between high- and low-RI groups. Flavonoids, although widespread in the Fabaceae family, were present at concentrations approximately 80% lower than those of total phenols and tannins. This trend supports Araújo et al. (2008), who found no clear link between flavonoid levels and indications for anti-inflammatory use across different plant groups.

This study represents the first attempt to systematically assess the relationship between phenolic content—specifically total phenols, tannins, and flavonoids—and medicinal versatility among woody Caatinga species at a regional scale. Among the most versatile species, *Ximenia americana* and *A. urundeuva* showed the highest flavonoid concentrations. However, less versatile species such as *S. brasiliensis* and *M. tenuiflora* also had comparably high levels (Table 2), emphasizing again that phenolic abundance alone does not explain medicinal importance.

A. urundeuva, the species with the highest RI (1.94), also exhibited the highest levels of total phenols and flavonoids. It is one of the most extensively studied Caatinga species in terms of phenolic composition and pharmacological activity. Its bark extract is rich in phenolics and exhibits strong antioxidant activity (Sousa et al. 2022), with documented antiviral and antifungal properties (Cecilio et al. 2016; Oliveira et al. 2017). *S. brasiliensis* (RI = 0.62), despite being less versatile, is traditionally used to treat pain, inflammation, and infections. Research has confirmed its high phenolic content and associated pharmacological properties, including antioxidant, anti-inflammatory, analgesic, and antimicrobial activities (Linhares et al. 2022; Santos et al. 2017, 2018; Luz et al. 2018).

In *X. americana* (RI = 1.37), phenolic compounds, including condensed tannins, flavonols, and flavone glycosides, have been linked to antioxidant, antibacterial, and antiaging effects (Bakrim et al. 2022). A comparative analysis of its aqueous and methanolic extracts revealed that the aqueous extract had the highest phenolic content and antioxidant activity. In contrast, the methanolic extract demonstrated stronger anti-inflammatory effects (Shettar et al., 2015).

The findings from this study also contribute to our understanding of chemical ecology in arid and semi-arid environments. In such regions, plants often invest more in the synthesis of high-molecular-weight phenolics, such as tannins, which provide robust protection against environmental stressors. In contrast, flavonoids tend to be synthesized in smaller quantities and are more commonly concentrated in leaves (Feeny 1976; Gottlieb 1987). Our results confirm that tannins predominate in the Caatinga, aligning with previous observations (Araújo et al. 2008).

Taken together, these results suggest that the concentrations of total phenols, tannins, and flavonoids are not decisive predictors of a species' medicinal versatility. Instead, versatility is shaped more by the contextual dynamics of local medical systems and cultural knowledge, which influence how species are selected and valued. The RI values observed in this study reflect a relatively balanced distribution of high and low versatility across the sampled species, independent of phenolic content.

Declarations

List of abbreviations: ANOVA: Analysis of Variance; CPI: Conservation Priority Index; PCA: Principal component analysis; TFC: Total Flavonoid Content; TPC: Total Phenolic Content; TTC: Total Tannin Content.

Ethical Approval and Participant Consent: Not applicable.

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4 ARTIGO 2

Precipitation dynamics and phenolic compound accumulation in woody medicinal plants of the Caatinga

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Abstract:

Climate change impacts ecological interactions in tropical ecosystems, with significant reductions in precipitation projected for seasonally dry forests such as the Brazilian Caatinga. This study investigates how rainfall variation affects the production of phenolic compounds in woody medicinal plants of the Caatinga, where these compounds play essential roles in both ecological functions and medicinal applications. Stem bark samples of ten species were collected from abundant medicinal plant species in Catimbau National Park, northeastern Brazil, across plots characterized by contrasting rainfall regimes (low and high precipitation). Phenolic content was quantified using the Folin-Ciocalteu method, tannins by casein precipitation, and flavonoids by aluminum chloride complexation. Analyses were conducted at the community level and for species-specific variations between rainfall regimes. Contrary to our initial hypothesis, reduced precipitation did not result in increased phenolic compound production. At the community level, total phenolic content and tannin concentrations were higher in high-rainfall areas, while flavonoid levels showed no significant differences. However, 40% of the species exhibited higher flavonoid levels under low-rainfall conditions. For *Cenostigma microphyllum* and *Senegalia piauhiensis,* no significant variation in total phenolic content or tannins was observed across rainfall gradients. Similarly, the flavonoid content of *C. microphyllum*, *Jatropha mutabilis*, and *Pityrocarpa moniliformis* remained unchanged between rainfall regimes. These findings indicate that reduced precipitation negatively affects the production of total phenolics and tannins in Caatinga plants, which may alter their ecological roles and medicinal value under future climate change scenarios.

Keywords: Chemical Ecology; Climatic Seasonality; Flavonoid; Phenolic Compounds; Rainfall; Tannins; Tropical Dry Forest

1. Introduction

Climate change has become an increasing global concern, as evidenced by the above-average rise in global temperatures over the past five years (Lindsey and Dahlman, 2020; Tollefson, 2020). These changes significantly impact the dynamics of ecosystem services worldwide, affecting human well-being (Pecl et al., 2017). In tropical regions, a substantial reduction in precipitation levels is projected, particularly in seasonally dry forests (Wright, 2005; Stan and Sanchez-Azofeifa, 2019). These forests are characterized by low annual precipitation (<1,800 mm/year), pronounced seasonality, and predominantly deciduous vegetation, forming a global biome covering approximately 2,700,000 km² (Pennington et al., 2000; Queiroz et al., 2017).

The Brazilian Caatinga, a major component of this biome, represents the largest contiguous area of seasonally dry tropical forest, exhibiting high species richness and endemism. It spans approximately 849,516 km², corresponding to 31% of the Neotropical seasonally dry forest biome (Queiroz et al., 2017; Fernandes et al., 2020). Projections indicate an increase in aridity within the Caatinga, with an estimated 22% reduction in precipitation (Marengo et al., 2017; Mendes et al., 2020). The availability of water and the soil's capacity for water retention are crucial in these environments, serving as key environmental filters that influence plant distribution . Consequently, such climatic projections raise concerns regarding ecosystem stability (Moro et al., 2015; Silva et al., 2018).

Additionally, the human population inhabiting the Caatinga is highly dependent on local natural resources for subsistence, akin to other semiarid regions (Singh, 1998; Albuquerque et al., 2012). The utilization of plants as primary medicinal resources by local communities is well documented (Albuquerque et al., 2007; Albuquerque et al., 2018). The seasonal nature of the region drives the selection of perennial resources, such as the bark of woody plants, which are extensively used for medicinal purposes (Albuquerque, 2006).

Given the anticipated increase in aridity, the structure and functioning of naturally dry ecosystems are expected to be affected, impacting ecosystem service provision and, consequently, the stability of human populations relying on these ecosystems (Oliveira et al., 2020). These environmental changes may also influence plant biology in the region, potentially altering their availability and use by local communities.

Plants in seasonally dry forests typically exhibit increased carbon-to-nitrogen ratios due to water scarcity , leading to higher concentrations of carbon-based structural compounds, such as phenolics (Pringle et al., 2011; Silva et al., 2015; Prescott et al., 2020). This trend aligns with the resource availability hypothesis, which posits that plants in resource-limited environments allocate more resources toward chemical defenses (Coley et al., 1985; Stamp, 2003). Phenolic compounds play a critical role in protecting plants against high ultraviolet radiation, reducing water loss, and providing chemical defense against herbivores and pathogens (Kessler and Kalske, 2018; Pang et al., 2021). Plants in the Caatinga are likely to exhibit elevated levels of phenolic compounds in response to the region's edaphoclimatic conditions (Gobbo-Neto and Lopes, 2007; Araújo et al., 2012; Siqueira et al., 2012; Albuquerque et al., 2020). Additionally, the medicinal properties of these plants are largely attributed to the presence of phenolic compounds, particularly tannins (Araújo et al., 2008; Almeida et al., 2011).

In the context of climate change, it is predicted that reductions in species richness and change in the composition of key medicinal plant species in the Caatinga will occur (Silva et al., 2022). Research on the effects of climate change on the synthesis of phenolic compounds has gained prominence due to their ecological and medicinal significance (Gupta et al., 2019; Srivastava et al., 2021; Sun et al., 2023). Previous studies have investigated phenolic compound synthesis in medicinal plants of the Caatinga in relation to climatic seasonality and variable precipitation levels (Monteiro et al., 2006; Araújo et al., 2015; Albergaria et al., 2021).

However, it is essential to understand the dynamics of synthesis of these compounds in Caatinga plants, given that there is variation in precipitation levels within this ecosystem, in addition to its vulnerability to climate change, which can also impact the availability of these resources. Thus, this study aimed to investigate the effects of rainfall variation on the synthesis of phenolic compounds (total phenols, tannins, and flavonoids) in woody medicinal plant communities of the Caatinga. We hypothesized that phenolic compound content would be higher in areas with lower precipitation, exhibiting a significant increase in concentration under reduced rainfall conditions.

2. Materials and Methods

2.1. Study Sites

This study was conducted in Catimbau National Park (8°24′00″ to 8°36′35″ S, 37°09′30″ to 37°14′40″ W), a protected area of approximately 62,300 hectares located in the state of Pernambuco, Northeastern Brazil. The park represents a typical Caatinga dry forest ecosystem, encompassing the full range of precipitation variability observed within this phytogeographic domain, with annual rainfall ranging from 480 to 1100 mm (Machado et al., 2017) and an average temperature of 23°C (Rito et al., 2017). The study area comprises twenty permanent plots (50 m × 20 m each), established under the International Long-Term Ecological Research (ILTER) project (https://www.peldcatimbau.org/). The plots, located at least two kilometers apart, are distributed along a precipitation gradient. Plot selection was based on mean annual precipitation values previously identified through the WorldClim database (www.worldclim.org), with values ranging from 510 mm to 940 mm. The selected plots were: R70 (533 mm), P08 (578 mm), P25 (588 mm), P04 (591 mm), P10 (647 mm), P11

(673 mm), R17 (866 mm), R20 (888 mm), R45 (897 mm), P27 (903 mm), P30 (913 mm), and R37 (940 mm) (see Rito et al., 2017).

Precipitation was considered a key variable due to its significant influence on vegetation composition and structure. It is the primary determinant of tree density in seasonally dry forests, surpassing other climatic factors (Crowther et al., 2015), and is widely used as an indicator in climate change projections (Houghton, 2001).

2.2. Collection of Plant Material

Given the historical anthropogenic modifications, plant community composition differs among plots along the precipitation gradient (Rito et al., 2017). Species selection was based on previous phytosociological surveys (https://www.peldcatimbau.org/), identifying most abundant species per plot. Thus, ten species simultaneously present in the sampled plots were selected (Table 1). For each selected species, bark samples were collected from three individuals spaced 3–5 meters apart. A standardized sampling approach was employed: bark was obtained at breast height (~1.30m) for tree species and from the central stem region for shrub species shorter than 1.50m. Each sample weighed approximately 500g and was intended for phytochemical analysis.

Bark was chosen as the tissue based on the hypothesis that seasonal climatic variations influence secondary metabolite production, and because bark is a primary source of medicinal extracts for local communities due to its perennial availability (Albuquerque, 2006). In an attempt to minimize possible biases, bark samples of the species were collected in April 2022, during the rainy season. Thus, possible differences in the concentration of phenolic compounds predominantly reflect the natural variation in precipitation between plots, minimizing the influence of water stress factors in the dry season. The accumulated rainfall in April 2022 was 243 mm, with moderate drought, according to a bulletin from the Pernambuco Water and Climate Agency (APAC, 2022).

Samples were stored in labeled paper bags and dried in an oven at 25°C, with forced air circulation. Subsequently, the material was transported to the Plant Physiology Laboratory at UFPE , where it was ground in a Willey knife mill (R-TE-650/1 - Tecnal) to obtain a fine powder. Further details on species distribution across rainfall categories, quantified compounds, and sample sizes are presented in Table S1. The list of collected species is provided in Table 1.

Table 1. List of woody medicinal plant species collected in plots under different rainfall levels, located in Catimbau National Park, Pernambuco, Brazil.

Family	Species	Popular name
Annonaceae	*Annona leptopetala* (REFr.) H.Raine	Araticum
Burseraceae	*Commiphora leptophloeos* (Mart.) JBGillett	Umburana-de-cambão
Bignoniaceae	*Handroanthus impetiginosus* (Mart. ex DC.) Mattos	Ipê-roxo
Euphorbiaceae	*Jatropha mutabilis* (Pohl) Baill.	Pinhão-bravo
Fabaceae	*Cenostigma microphyllum* (Mart. ex G.Don) Gagnon & GPLewis	Catingueira-miúda
	Chloroleucon foliolosum (Benth.) GPLewis	Arapiraca
	Peltogyne pauciflora Benth.	Pau-de-morro
	Pityrocarpa moniliformis (Benth.) Luckow & RWJobson	Canzenzo
	Senegalia bahiensis (Benth.) Seigler & Ebinger	Calumbi
	Senegalia piauhiensis (Benth.) Seigler & Ebinger	Jurema-branca

2.3. Soil sampling

A total of 10 composite soil samples were collected from plot areas with different precipitation. Each sampling point consisted of 5 subsoil samples collected in close proximity to the plants, each 3–5 m apart, at a depth of 0.0–0.20 m. The samples were later taken to the Soil Environmental Chemistry Laboratory of the Federal Rural University of Pernambuco for analysis. Soil characterization was performed using conventional methods, measuring chemical, physical and soil fertility parameters (Teixeira et al., 2017; Nascimento et al., 2021).

2.3. Preparation of crude extract for phytochemical analysis

Bark powder (500 mg per species) was placed in 50 mL beakers and extracted with 25 mL of 80% (v/v) methanol. The extraction was performed by gently boiling the samples on a hot plate (TE-0851 – Tecnal) for 30 minutes. The extracts were filtered through qualitative filter paper (80 g/m^2) into 50 mL volumetric flasks.

Residues were washed with an additional 25 mL of 80% methanol, filtered again, and the final volume was adjusted with the same solvent (Amorim et al., 2012). Each extraction is performed in triplicate. The resulting extracts were used to quantify total phenols, tannins, and flavonoids.

2.4. Quantification of total phenols (TF) and total tannins (TT)

Total phenol content (TF) was determined using the Folin-Ciocalteu method, with modifications (Amorim et al., 2012). Aliquots (0.125 mL - 0.25 mL) of plant extracts were transferred to 25 mL volumetric flasks, followed by the addition of 1.25 mL of 10% (v/v) Folin-Ciocalteu reagent and 2.5 mL of 7.5% (w/v) sodium carbonate solution. The final volume was adjusted with distilled water and mixed thoroughly. After 30 minutes of reaction in darkness, absorbance was measured at 760 nm using a previously calibrated spectrophotometer with a quartz cuvette. Deionized water was used as a blank.

Total tannin (TT) content was quantified based on the difference between total phenols and non-complexed residual phenols, determined via the casein precipitation method followed by the Folin-Ciocalteu method (Amorim et al., 2012). Extract aliquots (6ml) were mixed with 1 g of casein and 12 mL of distilled water in Erlenmeyers flasks. The mixture were shaken for 3 hours at room temperature in darkness, then filtered through qualitative filter paper (80 g/m^2) into 25 mL volumetric flasks. Residues were washed, filtered again, and the final volume was adjusted with distilled water. Aliquots (0.375-0.75 mL) of this solution were used to quantify residual phenols following the Folin-Ciocalteu method.

TF and TT concentrations were calculated using a calibration curve generated with a tannic acid standard solution (0.1 mg/mL). Results were expressed as milligrams of tannic acid equivalents per gram of dry matter (mg TAE/100 g DM). The calibration equation for tannic acid was $y = 0.154 x + 0.076$ ($R^2 = 0.977$).

2.5. Quantification of total flavonoids (TFL)

Total flavonoid content (TFL) was determined following Amorim et al. (2012). Aliquots (1 mL) of plant extracts were transferred to 25 mL volumetric flasks, followed by the addition of 0.6 mL of glacial acetic acid, 10 mL of 20% (v/v) methanolic pyridine solution, and 2.5 mL of 5% (w/v) methanolic aluminum chloride solution.. The final volume was adjusted with distilled water and mixed thoroughly. After 30 minutes of reaction in darkness, absorbance was measured at 420 nm using a glass cuvette. Deionized water was used as a blank.

TFL concentrations were determined using a calibration curve generated with a rutin standard solution (0.5 mg/mL). Results were expressed as milligrams of rutin equivalents per gram of dry matter (mg RE/100 g DM). The calibration equation for rutin was y = 0.518 x + 0.046 (R^2 = 0.999).

2.6. Data analysis

Plots were categorized into two precipitations regimes: low rainfall (533 - 737 mm) and high rainfall (738 - 940 mm), with six plots in each category. Compound levels were analyzed at the plant community level to assessed total concentrations across precipitation categories.

Variations in total phenol and tannin were assessed using Analysis of Variance (ANOVA), followed by the Student-Newman-Keuls test. Flavonoid levels were analyzed using the Mann-Whitney U test. Species-level variations were also examined between rainfall categories. Statistical analyses were conducted using Statistica 8.0 software at a significance level of $p < 0.05$, following test-specific assumptions. Furthermore, a correlation analysis was performed between the precipitation values of the plots and the soil moisture data.

3. Results

Our findings do not support the hypothesis that phenolic compound synthesis is enhanced in low-rainfall areas. Instead, we observed that the levels of total phenols (p = 0.0241) and tannins (p = 0.0316) were significantly influenced by precipitation. In contrast, no significant differences were detected in the total flavonoid content between the two precipitation regimes (p = 0.6140) (Table 2).

As show in Table 2, total phenol and tannin concentration were higher in the high-rainfall areas. In low-rainfall plots, the total phenol content was 107.73 mg TAE/100g DM, whereas in high-rainfall plots, it reached 144.27 mg TAE/100g DM. A similar pattern was observed for tannins, with 96.36 mg TAE/100g DM, in low rainfall areas compared to 126.31 mg TAE/100g DM in high-rainfall areas. The total flavonoid content exhibited minimal variation between precipitation regimes, with 1.35 mg RE/100g DM in low-rainfall areas and 1.51 mg RE/100g DM in high-rainfall areas (Table 2).

Table 2. Concentration of phenolic compounds (total phenols, tannins, and flavonoids) in woody medicinal plant communities across two precipitation regimes (low and high-rainfall) in Catimbau National Park, Pernambuco, Brazil.

Phenolic compound contents	**Rainfall category**	**Average**	***p* (< 0.05)**
Total phenols	Low	107.73 ± 4.89 a	0.024077
(mg TAE/100g DM)	High	144.27 ± 6.27 b	
Tannins	Low	96.36 ± 4.41 a	0.031572
(mg TAE/100g DM)	High	126.31 ± 5.23 b	
Flavonoids*	Low	1.35 ± 0.03 a	0.614011
(mg RE/100g DM)	High	1.51 ± 0.06 a	

Different letters with the same column indicate statistically significant differences ($p < 0.05$) in compound concentrations between precipitations regimes. Total phenols and tannins were analyzed using Analysis of Variance (ANOVA) followed by the Student-Newman-Keuls test, while flavonoids were assessed using the Mann-Whitney U test. Compound concentrations are expressed as tannic acid equivalents (TAE) for phenols and tannins and rutin equivalents (RE) for flavonoids.

We also analyzed species-specific differences in compound concentrations between the two precipitation regimes (Figure 1). The species-level patterns mirrored the trends observed at the community level. In *Cenostigma microphyllum* and *Senegalia piauhiensis*, no significant differences were detected in total phenol and tannin contents between low and high-rainfall areas (Figure 1A, B). Similarly, flavonoid content did not vary significantly between precipitation regimes in *C. microphyllum*, *Jatropha mutabilis,* and *Pityrocarpa moniliformis* (Figure 1C).

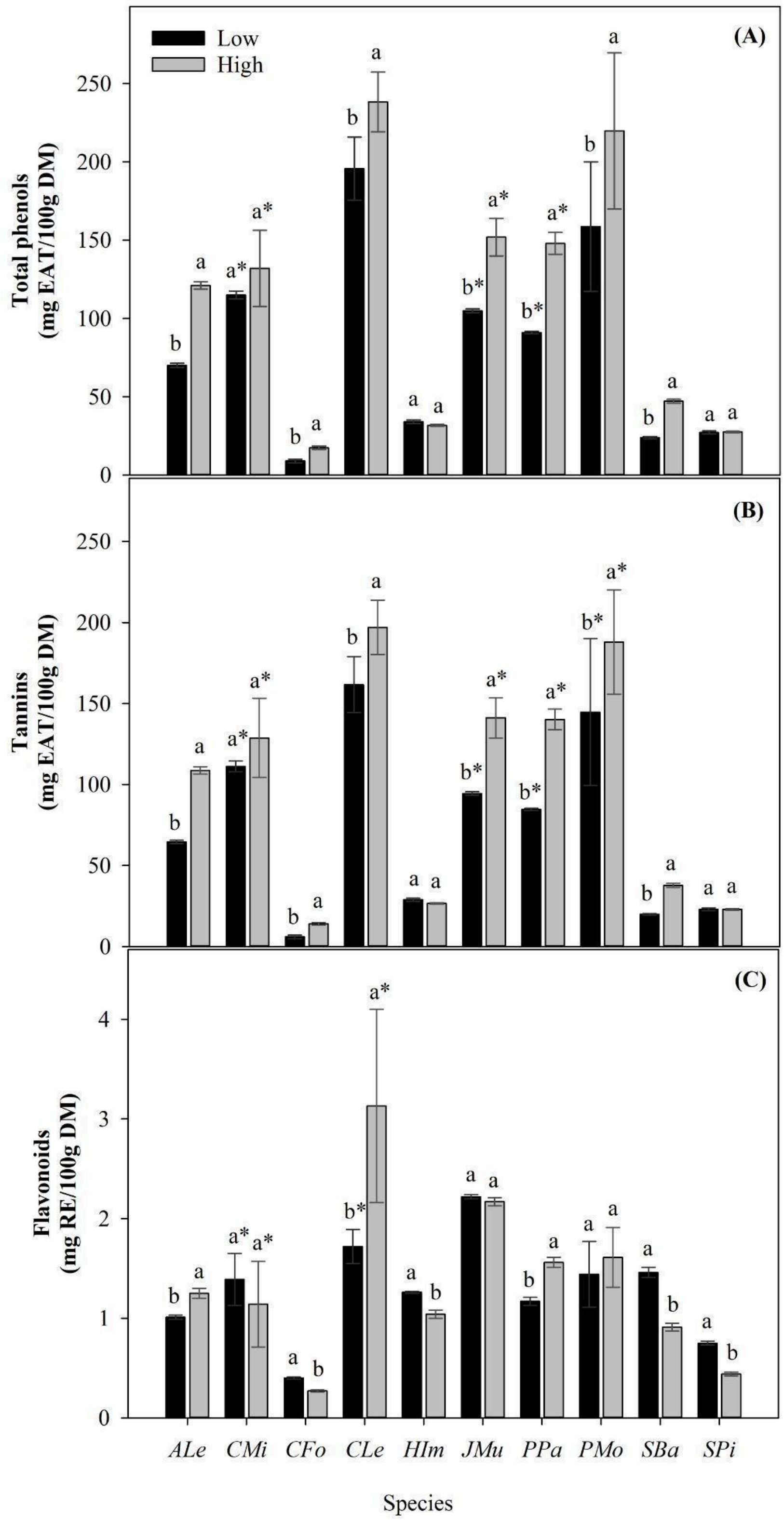

Figure 1. Concentrations of phenolic compounds (total phenols, tannins, and flavonoids) in woody medicinal plant species across two precipitation regimes (low and high- rainfall) in Catimbau National Park, Pernambuco, Brazil. Different letters indicate statistically significant differences ($p < 0.05$) in

compound levels within species between precipitation regimes, based on ANOVA followed by the Student-Newman-Keuls test or the Mann-Whitney U test. Compound concentrations are expressed as tannic acid equivalents (TAE) for phenols and tannins and rutin equivalents (RE) for flavonoids. Species abbbreviations: *ALe - Annona leptopetala*; *CMi - Cenostigma microphyllum*; *CFo - Chloroleucon foliolosum*; *CLe - Commiphora leptophloeos*; *HIm - Handroanthus impetiginosus*; *JMu - Jatropha mutabilis*; *PPa - Peltogyne pauciflora*; *PMo - Pityrocarpa moniliformis*; *SBa - Senegalia bahiensis*; *SPi - Senegalia piauhiensis*.

Soil moisture values varied considerably among samples, ranging from 0.14% to 1.29% (Table S2). The lowest moisture content was recorded in samples P10 (0.14%) and R70 (0.25%), plots with the lowest precipitation, with 643 mm and 533 mm, respectively. In the wetter plots, samples R37 (940 mm) and R45 (897 mm) presented the highest soil moisture values, 1.29% and 0.72%, respectively. The correlation analysis between precipitation and soil moisture is moderate (r = 0.37), but not statistically significant (p = 0.24) (Figure 2).

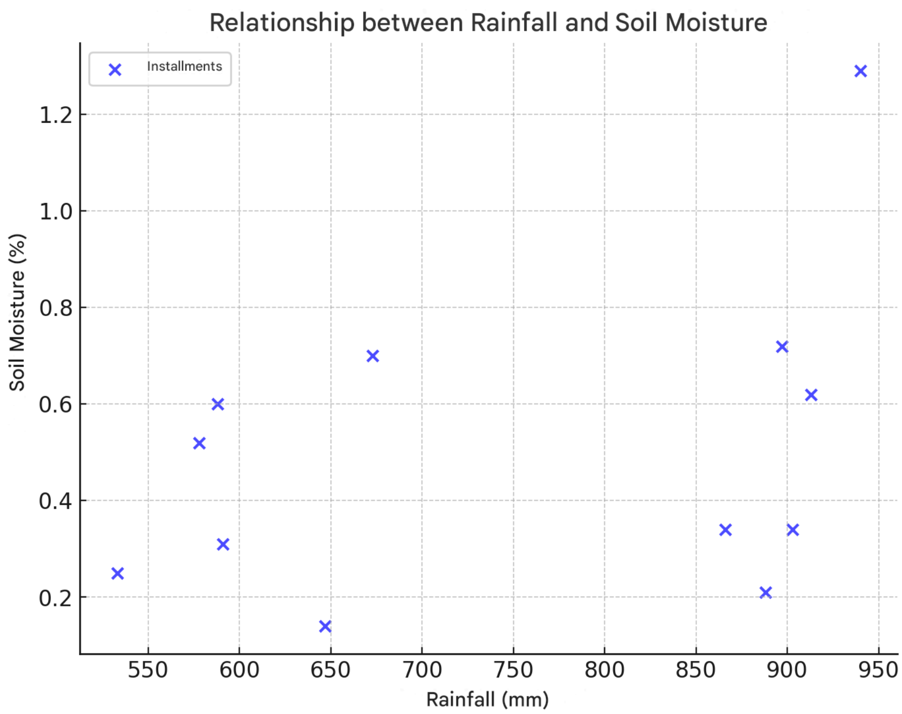

Figure 2. Correlation analysis between soil moisture and precipitation corresponding to each of the plots analyzed in two precipitation regimes (low and high precipitation) in Catimbau National Park, Pernambuco, Brazil.

4. Discussion

The production of phenolic compounds in plants is well documented as being influenced by abiotic factors and environmental constraints (Sun et al., 2023). The Caatinga biome is characterized by pronounced climatic seasonality, which suggests a potential relationship between this seasonality and increased synthesis of phenolic compounds, particularly tannins, in plant species from this region (Araújo et al., 2012). Given projections of increasing aridity in these areas (Rito et al., 2017), this study investigated the concentrations of total phenols, tannins, and flavonoids in plant communities subjected to contrasting precipitation regimes (low and high rainfall). Based on the "resource availability" hypothesis, we initially predicted that phenolic compound synthesis would be greater in regions with lower precipitation. However, our findings did not support this assumption, these results suggest that additional factors must be considered when applying this hypothesis to the synthesis of phenolic compounds in these ecosystems.

At the community level, total phenol and tannin concentrations were significantly higher in areas with greater precipitation (Table 2). The total phenol content in high rainfall areas (144.27 mg TAE/100g DM) was 25.33% greater than in low rainfall areas (107.73 mg TAE/100g DM). A similar pattern was observed for tannins, with concentrations 23.71% higher in high rainfall areas (126.31 mg TAE/100 g DM) compared to low rainfall areas (96.36 mg TAE/100 g DM). Although these differences were statistically significant, the relatively small percentage variation suggests that phenolic compound synthesis is broadly distributed across plant communities in this region, reinforcing the role of precipitation as a key driver in the biosynthesis of these compounds.

A systematic review on the effects of water deficit on phenolic compound production in medicinal plants, found that the common assumption that phenolic compound synthesis increases under low water availability is overlay simplistic, as it fail to account for the complexity of environmental interactions and species specific responses (Albergaria et al., 2020). This aligns with our findings. Additionally, ecological factors such as plant phenology, seasonality, and precipitation levels have been shown to influence the chemical composition of medicinal plants (Yao et al., 2016; Ribeiro et al., 2019).

Under conditions of increased water availability, whether due to seasonal rainfall or higher relative humidity, deciduous species in seasonally dry forests tend to extend their leaf retention period (Teodoro et al., 2022; Medeiros et al., 2024). In the same study area, it was found that deciduous woody species tend to have more resource-conservative leaf trait in areas with greater water availability (Yule et al., 2024). Since phenolic compound synthesis is a common defensive strategy in environments where herbivory risk of and resource availability fluctuate seasonally (Karban, 2011), prolonged leaf presence may contribute to the observed increase in total phenols and tannins in high rainfall areas. Supporting this perspective, a study conducted in a tropical dry forest found higher phenolic concentrations during the rainy season in deciduous species (Silva et al., 2020), corroborating our findings.

Flavonoid concentrations were not significantly influenced by precipitation at the community level (Table 2). These compounds were present in markedly lower concentrations approximately 90% lower than phenols and tannins. While plants in arid and semi-arid environments generally invest in the production of high-molecular-weight secondary metabolites such as phenols and tannins, flavonoids are also synthesized in the regions (Almeida et al., 2005; Araújo et al., 2008). Structurally based on 2-phenylchromone nucleus, flavonoids are low molecular-weight, highly bioactive compounds that function as antioxidants at low concentrations (Agati et al., 2012; Wang et al., 2018), whereas phenols and tannins typically require higher concentrations for enhanced biological activity (Almeida et al., 2011). Furthermore, this study analyzed stem bark samples, which aligns with the hypothesis of climatic seasonality influencing phytochemical composition (de Albuquerque, 2006). This could explain the lower flavonoid concentrations in bark samples at the community level, contributing to the observed lack of statistical significance (Table 2).

Our results contribute to an expanding body of research investigating the effects of precipitation, on the phenolic composition of medicinal plants. Similar patterns have been reported in studies of desert species. Gull et al., (2018) found that total phenolic content in *Capparis* species from desert regions of Pakistan was higher during the rainy season across different plant structures (fruits, bark, and roots). Likewise, in a Mediterranean forest, long-term amplified drought simulations led to a decrease in phenolic compound levels in *Quercus pubescens* compared to natural drought conditions. The authors attributed this reduction to the antioxidant role of phenolic compounds, which undergo oxidation and degradation under prolonged drought stress (Laoué et al., 2023).

Conversely, Kumar et al., (2017) reported that reduced precipitation was associated with increased phenolic compound synthesis in *Aloe vera* plants from drier regions, contradicting our findings. meta-analysis by Sun et al. (2023) suggested that phenolic concentrations in medicinal and aromatic plants tend to increase under decreasing precipitation, although some studies have reported a positive correlation between water availability and phenolic compound synthesis.

At the species level, variations in total phenol, tannin, and flavonoid concentrations were observed between rainfall areas (low and high). In 70% of the species, analyzed, higher total phenol and tannin levels were found in high-rainfall plots, whereas 40% of the species exhibited greater flavonoid concentrations in low-rainfall areas (Figure 1).

Previous studies on the effects of precipitation on phenolic compound concentrations in medicinal plants from the Caatinga have reported species-specific responses. Monteiro et al. (2006) found that tannin concentrations in *Astronium urundeuva* and *Anadenanthera colubrina* varied with climatic seasonality, with higher levels occurring during the dry season. However, *A. urundeuva* exhibited higher tannin concentrations in leaves, whereas *A. colubrina* had greater concentrations in bark. Similarly, Araújo et al. (2015) observed that the main phenolic compounds in *A. colubrina* bark showed only slight seasonal variation. Albergaria et al. (2021) concluded that total phenol and tannin levels were significantly higher in leaves than in bark for *Cenostigma microphyllum*, with no significant differences in response to varying precipitation levels.

As shown in Fig. 2, the correlation analysis between precipitation and soil moisture is moderate ($r = 0.37$), but not statistically significant ($p = 0.24$). This means that there is a tendency for higher precipitation to be associated with wetter soils, but the relationship is not strong enough to be considered conclusive.

The values obtained in the analyzed parameters are in agreement with previous studies, which indicate that Caatinga soils are, in general, not very fertile and retain little water (Pinheiro et al., 2017). In this study, the soils presented high acidity (above 3.0 cmolc/dm^3), low levels of potassium, calcium and organic carbon (O.C. - ideal above 20 g/kg) with high levels of aluminum (above 0.1 cmolc/dm^3) (Table S2). The moisture values of the samples range from 0.14% to 1.29%, indicating a dry soil. In fact, in the Caatinga, the soil usually has moisture content below 10% due to the characteristics of the region, being shallow, with low water retention and high evaporation (Andrade et al., 2017; Pinheiro et al., 2017).

Therefore, the analysis of the soils of the plots reinforces the influence of rainfall in regulating the synthesis of phenolic compounds, indicating that rainfall is a determining factor for plant metabolism. The rapid drainage of water in the soil can create a cycle of absorption and metabolic response in plants, activating the synthesis of phenolic compounds more dynamically as rainfall events occur.

To the best of our knowledge, this is the first study to investigate the effects of a rainfall gradient on phenolic compound synthesis in medicinal plant communities in the Caatinga. Our results do not support the hypothesis that reduced precipitation associated with climate change would enhance phenolic compound production in these species. Instead, we found that total phenol and tannin concentrations were higher in areas with greater precipitation. These findings highlight the potential ecological and socioeconomic consequences of increasing aridity, which may compromise ecosystem resilience and the livelihoods of local communities on medicinal plants.

In the same region, reduced precipitation has been linked to lower plant diversity, making drier areas more vulnerable (Rito et al., 2017). Predictive models suggest that increasing aridity could lead to the disappearance of key medicinal plant species (Silva et al., 2022). Although these studies did not assess phytochemical composition, when combined with our findings, they suggest that rising aridity could impact both the synthesis of phenolic compounds and the availability of medicinal species.

A potential decline in plant diversity due to increasing aridity may intensify anthropogenic pressure on remaining species (Silva et al., 2019). Such changes could disrupt socio-ecological systems dependent on medicinal plant resources (Albuquerque et al., 2019; Gupta et al., 2019; Silva et al., 2022).

Therefore, by demonstrating that phenolic compound synthesis is higher in high rainfall areas, our findings underscore the need to consider the combined effects of climate change and anthropogenic pressures on Caatinga medicinal flora. This understanding is critical for developing conservation strategies that ensure the sustainability of medicinal plant resources and the resilience of local communities.

CRediT authorship contribution statement

Marcela Maria Albuquerque-Silva: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Arthur Vinícius da S. Cabral:** Investigation, Formal analysis, Data curation. **Marciel Teixeira de Oliveira:** Writing – review & editing, Supervision, Data curation, Formal analysis. **Antonio Fernando M. de Oliveira:** Writing – review & editing, Methodology. **Ulysses Paulino Albuquerque:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors have declared that no competing interests exist.

Data availability

Data will be made available upon reasonable request.

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Supplementary Material

Table S1. List of woody medicinal plant species followed by the levels of total phenols, tannins and flavonoids quantified by precipitation category, number of individuals and sampled plot/precipitation (according to Rito et al., 2017) collected in Catimbau National Park - PE, Brazil.

Species	Precipitation category	Total phenols (mg TAE/100g DM)	Tannins (mg TAE/100g DM)	Flavonoids (mg RE/100g DM)	Number individuals	Sampled plot/precipitation
Annona leptopetala	Low	70.10 ± 1.33 b	64.52 ± 1.10 b	1.01 ± 0.02 b	3	R70/533
	High	121.05 ± 2.38 a	108.62 ± 2.30 a	1.25 ± 0.05 a	3	R37/940
Cenostigma microphyllum	Low	115.02 ± 2.45 a*	111.13 ± 3.37 a*	1.39 ± 0.26 a*	6	R70/ 533 P11/ 673
	High	131.95 ± 24.33 a*	128.78 ± 24.43 a*	1.14 ± 0.43 a*	6	R45/897 P27/903
Chloroleucon foliolosum	Low	8.98 ± 1.17 b	5.96 ± 1.13 b	0.40 ± 0.01 a	3	P10/ 647
	High	17.44 ± 1.09 a	13.93 ± 0.87 a	0.27 ± 0.01 b	3	P30/ 913
Commiphora leptophloeos	Low	195.66 ± 20.14 b	161.65 ± 17.27 b	1.72 ± 0.17 b*	6	P08/ 578 P04/ 591
	High	238.24 ± 19.05 a	197.00 ± 16.75 a	3.13 ± 0.97 a*	6	R20/888 R37/940
Handroanthus impetiginosus	Low	34.05 ± 1.17 a	28.84 ± 0.94 a	1.26 ± 0.01 a	3	R70/ 533
	High	31.76 ± 0.55 a	26.59 ± 0.50 a	1.04 ± 0.04 b	3	R45/897
Jatropha mutabilis	Low	104.90 ± 1.17 b*	94.40 ± 1.03 b*	2.22 ± 0.02 a	3	R70/ 533
	High	151.92 ± 12.00 a*	141.20 ± 12.13 a*	2.17 ± 0.04 a	3	R20/888
Peltogyne pauciflora	Low	91.01 ± 0.80 b*	84.61 ± 0.70 b*	1.17 ± 0.04 b	3	P04/ 591
	High	147.94 ± 6.97 a*	140.24 ± 6.38 a*	1.56 ± 0.05 a	3	R20/888
Pityrocarpa moniliformis	Low	158.62 ± 41.34 b	144.71 ± 45.44 b*	1.44 ± 0.33 a	12	R70/ 533 P08/ 578 P04/ 591

						P11/ 673
	High	219.73 ± 49.81 a	187.95 ± 32.10 a*	1.61 ± 0.30 a	12	R17/866 R20/888 P30/ 913 R37/940
Senegalia bahiensis	Low	23.86 ± 0.64 b	19.82 ± 0.51 b	1.46 ± 0.05 a	3	P08/ 578
	High	47.19 ± 1.23 a	37.74 ± 1.28 a	0.91 ± 0.04 b	3	R17/866
Senegalia piauhiensis	Low	27.21 ± 1.00 a	22.88 ± 0.83 a	0.75 ± 0.02 a	3	P04/ 591
	High	27.52 ± 0.52 a	22.88 ± 0.56 a	0.44 ± 0.02 b	3	R17/866

Different letters in the same column indicate differences in the significance level ($p < 0.05$) for the compound quantified at the species level between the precipitation areas (low and high). Differences analyzed according to the premises of each test: ANOVA subsequent by Student-Newman-Keuls test; or by the test U Mann-Whitney*. TAE = tannic acid equivalents and RE = rutin equivalents.

Table S2. Soil properties collected in plots under different precipitation levels, located in Catimbau National Park, Pernambuco, Brazil.

Sampled plot/precipitation	pH (water)	Ca	Mg	Al	Na	K	P	O.C.	O.M.	H+Al	MC
	1 : 2.5	cmol$_c$ dm^{-3}					mg dm^{-3}	g kg^{-1}		cmol$_c$ dm^{-3}	%
R70/533	5.26	2.00	0.00	0.15	0.01	0.08	11.88	10.92	18.82	2.02	0.25
P08/578	4.46	0.70	0.35	0.25	0.01	0.06	7.52	10.88	18.76	3.64	0.52
P25/588	6.65	4.50	0.00	0.00	0.03	0.41	47.14	9.35	16.11	1.21	0.60
P04/591	5.15	2.50	0.00	0.05	0.02	0.10	13.18	15.90	27.42	2.67	0.31
P10/647	6.37	1.50	0.00	0.00	0.01	0.09	12.97	6.08	10.48	0.81	0.14
P11/673	5.31	1.00	0.15	0.15	0.01	0.12	17.20	8.12	14.00	1.37	0.70
R17/866	4.81	1.00	0.00	0.15	0.01	0.08	8.06	12.86	22.18	2.99	0.34
R20/888	5.09	2.50	0.00	0.15	0.03	0.08	11.47	15.76	27.17	2.18	0.21
R45/897	5.15	4.00	0.00	0.05	0.02	0.11	20.34	33.20	57.24	4.04	0.72
P27/903	4.93	1.90	0.00	0.10	0.01	0.09	13.32	10.70	18.44	2.83	0.34
P30/913	4.59	1.70	0.00	0.54	0.03	0.09	7.31	25.50	43.96	5.66	0.62
R37/940	4.38	0.70	0.40	1.08	0.04	0.12	2.81	29.53	50.91	9.22	1.29

Parameters: pH (water); Calcium (Ca); Magnesium (Mg); Aluminum (Al); Sodium (Na); Potassium (K); Phosphorus (P); Organic Carbon (O.C.); Organic Matter (O.M.); H+Al (potential acidity) and Soil moisture content (%).

5 CONSIDERAÇÕES FINAIS

O presente trabalho buscou explorar diferentes fatores relacionados à composição fenólica em plantas medicinais da Caatinga. Essa região apresenta um filtro ambiental bem característico, o que parece ter impulsionado as plantas na convergência da síntese majoritária de compostos fenólicos, especialmente os de alto peso molecular como taninos. Paralelamente, às pessoas que habitam a região tem uma relação histórica estabelecida no uso dos recursos para subsistência, incluindo as plantas medicinais. As indicações terapêuticas, tais como antiinflamatória, antimicobriana, antifúngica e cicatrizante, foi atribuída a presença de compostos fenólicos de espécies medicinais importantes em sistemas médicos locais da região. Apesar da ampla atividade biológica, os resultados revelaram que fenois, taninos e flavonoides totais, não influenciam na versatilidade, do ponto de vista fitoquímico, dessas espécies. A versatilidade é fortemente influenciada por fatores culturais, sendo relativa a contextos locais específicos, como a dinâmica das comunidades humanas e a disponibilidade de espécies vegetais. Foi evidenciada uma ampla variação nos valores de importância relativa entre os grupos das espécies estudadas, o que sugere uma distribuição equilibrada entre plantas mais e menos versáteis dentro da flora medicinal a nível regional.

Além disso, os dados apontaram que a síntese de compostos fenólicos tende a ser maior em áreas com maior pluviosidade, reforçando que a disponibilidade hídrica atua como um fator modulador na produção desses compostos. Já é bem estabelecido que a dinâmica biológica da Caatinga é fortemente influenciada pela disponibilidade hídrica, portanto, mesmo contrariando as expectativas, a maior síntese de fenólicos em áreas de maior pluviosidade é explicada, pois esses compostos estão envolvidos na defesa anti-herbivoria, possivelmente durante a rebrota das folhas, bem como nos processos e floração e maturação dos frutos, evidenciando a importância dos compostos fenólicos na manutenção e sobrevivência dessas espécies. Portanto, diante do cenário de mudanças climáticas e pressões antrópicas crescentes, os resultados reforçam a importância de integrar conhecimentos ecológicos, fitoquímicos e etnobotânicos na compreensão da dinâmica das comunidades vegetais da Caatinga e manutenção da flora medicinal, com implicações na resiliência dos sistemas socioecológicos da região.

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ANEXO A - CERTIDÃO DO PROJETO NA PLATAFORMA SisGen

Ministério do Meio Ambiente
CONSELHO DE GESTÃO DO PATRIMÔNIO GENÉTICO

SISTEMA NACIONAL DE GESTÃO DO PATRIMÔNIO GENÉTICO E DO CONHECIMENTO TRADICIONAL ASSOCIADO

Certidão

Cadastro nº A3F792C

Declaramos, nos termos do art. 41 do Decreto nº 8.772/2016, que o cadastro de acesso ao patrimônio genético ou conhecimento tradicional associado, abaixo identificado e resumido, no Sistema Nacional de Gestão do Patrimônio Genético e do Conhecimento Tradicional Associado foi submetido ao procedimento administrativo de verificação e não foi objeto de requerimentos admitidos de verificação de indícios de irregularidades ou, caso tenha sido, o requerimento de verificação não foi acatado pelo CGen.

Número do cadastro:	**A3F792C**
Usuário:	**Marcela Maria Albuquerque Silva**
CPF/CNPJ:	**075.507.564-14**
Objeto do Acesso:	**Patrimônio Genético**
Finalidade do Acesso:	**Pesquisa**

Espécie

Título da Atividade:	**Quantificação de compostos fenólicos em plantas medicinais da caatinga**

Equipe

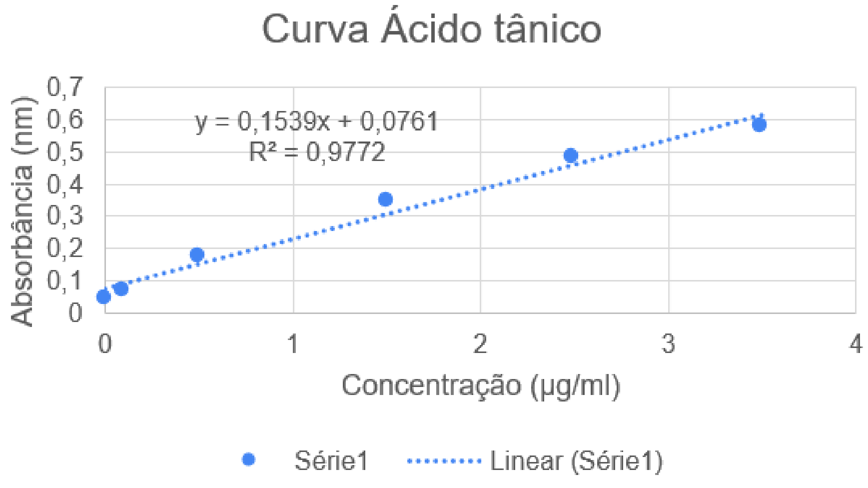
Marcela Maria Albuquerque Silva	**INDEPENDENTE**

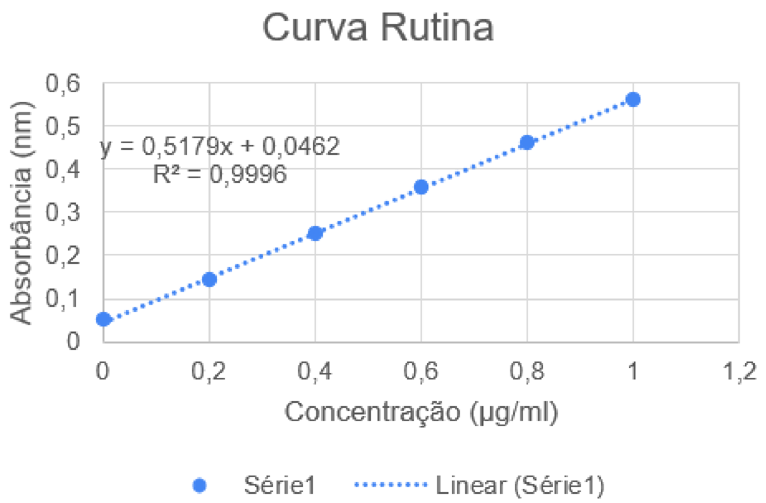
Data do Cadastro:	**07/10/2024 14:02:56**
Situação do Cadastro:	**Concluído**

Conselho de Gestão do Patrimônio Genético
Situação cadastral conforme consulta ao SisGen em **10:23** de **04/08/2025**.

SISTEMA NACIONAL DE GESTÃO DO PATRIMÔNIO GENÉTICO E DO CONHECIMENTO TRADICIONAL ASSOCIADO - SISGEN

ANEXO B - GRÁFICOS DAS CURVAS DE CALIBRAÇÃO COM CONCENTRAÇÕES CRESCENTES DE ÁCIDO TÂNICO (QUANTIFICAÇÃO DE FENÓIS E TANINOS) E RUTINA (QUANTIFICAÇÃO DE FLAVONOIDES)





ANEXO C - NORMAS PARA SUBMISSÃO DE MANUSCRITO AO PERIÓDICO

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To facilitate review, the authors must send a list of three (3) possible reviewers, specialists in the subject of the article, with their respective email addresses. This does not necessarily imply that the suggested specialists will be the reviewers of the manuscript, this decision being at the discretion of the editor.

ANEXO D - NORMAS PARA SUBMISSÃO DE MANUSCRITO AO PERIÓDICO FLORA

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