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Maya medicinal plant knowledge for respiratory diseases in Yucatán, Mexico: toward an adaptive biocultural framework of pharmacopoeia organization

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ABSTRACT

Traditional Maya medicine remains a key component of local healthcare and biocultural heritage in Yucatán, Mexico, yet it is increasingly affected by socio-environmental change. While ethnobotanical studies have documented plant use, fewer have examined the underlying organization of medicinal systems. This study integrates ethnographic fieldwork with all six recognized traditional healers in two Maya communities (Tibolón and Yaxcabá) and a systematic literature review following PRISMA 2020. A consolidated database of 268 use-reports was analyzed using descriptive statistics, Informant Consensus Factor, co-occurrence network analysis, null model comparisons, and core–periphery analysis. The respiratory pharmacopoeia comprised 139 taxa across 54 families. Plant use was concentrated in a limited set of therapeutic categories, with leaves, decoction, and oral administration predominating. The flora included native (55.2%), exotic (42.2%), and regionally endemic taxa (2.6%). Network analyses revealed a structured pattern of associations among plant families and therapeutic uses. Null model comparisons showed that observed networks deviated from random expectations, with elevated clustering and reduced modularity. Core–periphery analysis identified a recurrent core of eight highly connected respiratory categories. Network and null-model analyses indicate a non-random organization of the Maya respiratory pharmacopoeia. The concentration of taxa, therapeutic categories, and use patterns, together with network and null model analyses, suggests an interconnected system shaped by ecological accessibility, sensory perception, cultural transmission, and historical incorporation of new taxa. These findings provide the basis for a preliminary theoretical framework for interpreting the Maya respiratory pharmacopoeia as an adaptive biocultural system.

Keywords: Maya traditional medicine; Respiratory diseases; Ethnobotany; Biocultural conservation; Adaptive biocultural framework..

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SIGNIFICANCE STATEMENT

This study examines medicinal plant knowledge for respiratory diseases among Maya healers in Yucatán, Mexico, integrating ethnographic fieldwork with a systematic literature review. Using network analyses, null models, and core-periphery modeling, the study identifies consistent patterns in pharmacopoeia composition, resource selection, and knowledge organization. These patterns suggest that Maya traditional medicine operates as an adaptive biocultural system structured around a stable therapeutic core and a flexible set of peripheral species. Plant selection reflects not only ecological accessibility, but also sensory evaluation, cultural transmission, and historical incorporation of new species. The limited representation of endemic taxa highlights a potentially vulnerable layer of biocultural knowledge. By proposing a data-grounded conceptual framework, this study contributes to ethnobiology and conservation by linking medicinal plant use with broader processes of knowledge resilience, adaptation, and biocultural sustainability.

INTRODUCTION

Traditional Maya medicine operates as a historically layered knowledge system in which therapeutic practices, resource management, and cultural transmission remain tightly interconnected (Argueta-Villamar et al., 1994; Hirose-López, 2018). In the Yucatán Peninsula, this system continues to play an important role in everyday healthcare, especially in rural communities, where medicinal plants remain accessible and socially embedded (WHO, 2013; Méndez-González et al., 2014; Durán-García et al., 2016).

Respiratory illnesses are among the most frequently treated conditions, reflecting both their epidemiological relevance and their recurrent place within local therapeutic knowledge (Méndez-González et al., 2014; Secretaría de Salud de Yucatán, 2024).

The historical depth of Maya medicinal plant knowledge is attested in colonial-era and early post-colonial sources. Ralph L. Roys' foundational The Ethno-Botany of the Maya (Roys, 1931; Roys, 1976) compiled and translated sixteenth- to eighteenth-century Maya medical texts from the Books of Chilam Balam and other colonial documents, documenting the extensive use of plants for respiratory and other ailments and establishing a baseline for understanding the continuity and transformation of Maya pharmacopoeias over several centuries. Earlier still, the Franciscan friar Gerónimo de Mendieta, in his *Historia eclesiástica indiana* (de Mendieta, 1870), provided one of the earliest European accounts of Indigenous medicinal practices in New Spain, including observations on plant use among the Maya of the Yucatán Peninsula. Among the most influential vernacular medical texts in Yucatán is *the Libro del Judío* (also known as *Medicina doméstica*), a compilation of plant remedies and their applications that circulated widely in the region from the eighteenth century onward (Osado, 1834). Based on colonial-era Maya sources, this compilation reflects the syncretic character of Yucatecan medicinal knowledge, blending Indigenous, European, and Afro-Caribbean therapeutic traditions.

At the same time, knowledge associated with medicinal plants for respiratory diseases is increasingly affected by land-use change, weakening intergenerational transmission, and shifting relationships with formal health systems (Can-Ortiz et al., 2017; Hirose-López, 2018; Arjona-García et al., 2021). These pressures make documentation necessary, but documentation alone is insufficient. Understanding how Yucatec Maya medicinal knowledge is organized, maintained, and adapted is equally important for ethnobiology and biocultural conservation (Gavin et al., 2015; Turner et al., 2022).

Much ethnobotanical research has documented medicinal species and uses, but fewer studies have examined broader organizational principles. In Maya medicine, plant selection reflects not only ecological availability but also sensory evaluation, therapeutic experience, historical incorporation of introduced species, and transmission through domestic and specialist networks (Ankli et al., 1999a, 1999b; Ankli et al., 2002; Escobar-Chan et al., 2024). Rather than testing existing theories in a confirmatory manner, this study adopts a theory-building approach to explore whether the respiratory pharmacopoeia reflects an integrative adaptive biocultural system (Gavin et al., 2015; Page et al., 2021). Based on existing theories, we formulated the following testable hypotheses:

- H1 (Apparency Theory). If ecological accessibility drives plant selection, then leaves (low-cost, renewable) and herbs/trees (abundant growth habits) will dominate the pharmacopoeia, and homegarden-cultivated species will be overrepresented.
- H2 (Dynamic Pharmacopoeia model). If historical incorporation of exotic species is an ongoing process, then exotic taxa will constitute a substantial proportion ($\geq$30%) of use-reports and appear among the most frequently cited species.
- H3 (Network structure). Compared to degree-preserving random null models, the observed plant family–use and use–use networks will show higher clustering (indicating therapeu-

tic integration) and lower modularity (indicating overlapping rather than compartmentalized treatment categories).

- H4 (Core–periphery organization). The therapeutic use co-occurrence network will exhibit a statistically significant core–periphery structure, with a small set of highly interconnected respiratory categories forming a stable therapeutic core.

In Yucatec Maya nosology, respiratory conditions are not understood as discrete biomedical entities but as part of a holistic framework involving humoral imbalances (hot/cold), spiritual agents (e.g., *ik* – wind/air, which can become harmful when imbalanced), and specific symptom complexes such as *ch'ak* (cutting pain). Healers (*H'men* – male specialist; *Ix'men* – female specialist; also, *herbalistas* and *parteras*) diagnose by pulse, urine, or dream interpretation, and treatment aims to restore equilibrium through plant remedies, rituals, and dietary advice. Respiratory illnesses are often associated with cold, damp, or wind exposure and may be treated with "hot" plants (e.g., *Plectranthus amboinicus*, *Cymbopogon citratus*). This background grounds our network analysis: overlapping therapeutic associations (e.g., cough, asthma, bronchitis co-occurring in the same remedy) reflect the local reality of treating related symptom complexes rather than discrete diseases.

We acknowledge that biomedical categories (e.g., "cough", "asthma") impose an etic framework. Our analyses document plant uses associated with symptom clusters recognizable from a biomedical perspective and do not claim to represent Maya diagnostic categories. Network analyses are methodological approximations, not substitutes for emic categories. Future research should incorporate Maya nosology explicitly.

MATERIAL AND METHODS

Study area and socio-environmental context

The study focused on two communities in Yucatán, Mexico: Tibolón (municipality of Sotuta) and Yaxcabá (Figure 1). Tibolón is located at 20°39'55''N, 88°56'20''W, and Yaxcabá at 20°31'26''N, 88°48'41''W. These communities lie within the seasonally dry tropical forest (SDTF) ecoregion, which has undergone substantial deforestation (Trejo and Dirzo, 2000). Currently, remaining forest fragments are small and degraded. Homegardens (*solares*) are the primary spaces for medicinal plant cultivation; each household maintains a *solar* averaging 200–500 m^2, with high plant diversity. Traditional agricultural plots (*milpas*) are still practiced but have declined due to land-use change and out-migration. In Tibolón, 85% of households reported having a *solar* with medicinal plants; in Yaxcabá, the estimate is 78% (based on our field observations and community census). This baseline is essential for interpreting Apparency Theory predictions, as accessible resources include both cultivated homegarden plants and wild forest species. Fieldwork was conducted between September 2024 and March 2025, spanning rainy and dry seasons.

Ethical considerations

The study protocol was reviewed and authorized through institutional and intercultural channels in coordination with INDEMAYA and the State Committee for Traditional Maya Medicine and Intercultural Health. Plant collection was conducted under corresponding permissions. All participants provided written informed consent in Spanish, following the International Society of Ethnobiology Code of Ethics (2006) and Mexican constitutional framework, particularly Article 2 (Cámara de Diputados del H. Congreso de la Unión, 2026).

Participant selection

Participants were selected through purposive, criterion-based sampling (Patton, 2002; Palinkas et al., 2015). Inclusion criteria were being aged ≥30 years, being recognized within the community as a traditional healer (*H'men*, *Ix'men*, herbalist, or midwife), being registered in the INDEMAYA registry of traditional healers, and actively using medicinal plants to treat respiratory illnesses. Six participants (five women and one man; age range 30–88 years, mean age 57.0 ± 21.7 years) were included: one *Ix'men*, one *H'men*, one midwife/herbalist, and three Traditional herbalists (Table 1). Because all recognized Traditional healers in the two study communities who met the inclusion criteria agreed to participate, the final sample effectively constituted a census of specialist knowledge holders at the community level. Although numerically small, this group provided in-depth, expert knowledge relevant to the study objectives (Bernard, 2011).

Ethnobotanical data collection

Semi-structured interviews lasting 60–90 minutes were conducted individually in Spanish using a guide adapted from Vera-Ku (2011). The guide included open-ended questions on: (1) local plant names in Spanish and Maya; (2) therapeutic uses for respiratory conditions; (3) plant parts used; (4) preparation methods and dosages; (5) routes of administration; (6) collection practices and collection sites; (7) perceived

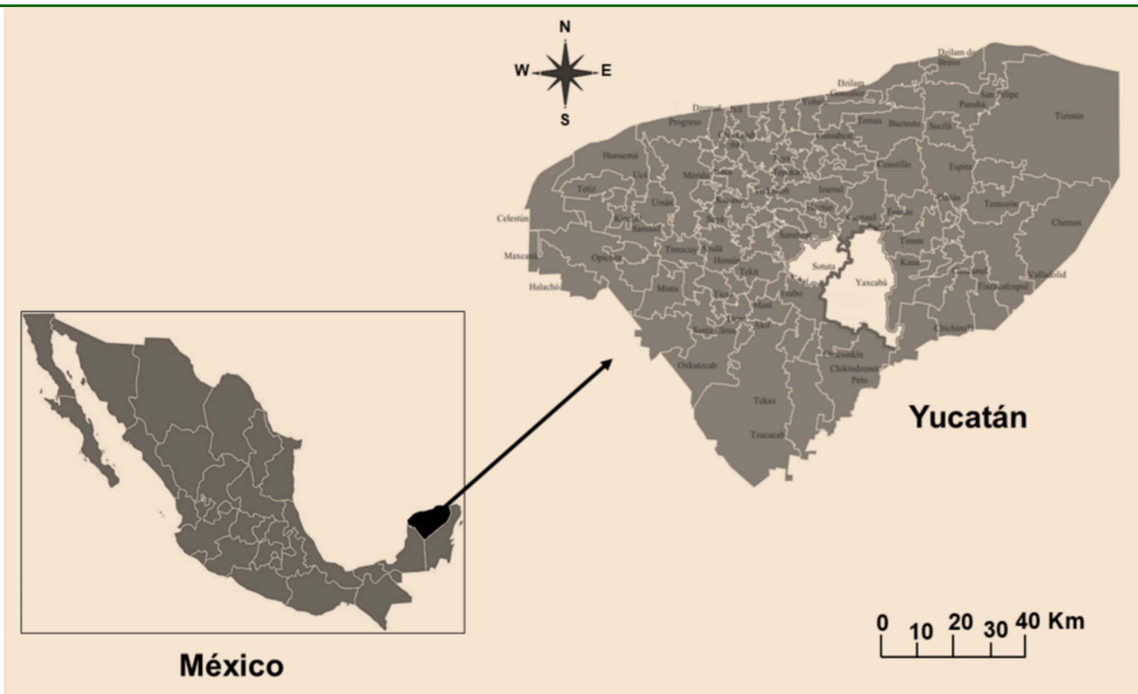

Figure 1. Location of the study area in Yucatán, Mexico. The figure shows the municipality of Yaxcabá and the locality of Tibolón, where ethnographic fieldwork with traditional Maya healers was conducted between September 2024 and March 2025. The map was prepared in QGIS Desktop 3.38.0.

changes in plant availability; (8) knowledge transmission and learning; and (9) contraindications and adverse effects. Interviews were audio-recorded with participants' permission and transcribed verbatim.

Botanical documentation

Guided walks were conducted together with participants and a botanist (LFL) in *solares* and other plant collection areas to document medicinal species and support preliminary *in situ* identification. Voucher specimens (n = 25) were collected in accordance with the Mexican Official Standard NOM-126-SEMARNAT-2000 and deposited in the *U Najil Tikin Xiw* herbarium of CICY. Complete voucher information is provided in Additional File 1. Seven commonly marketed species (*Allium sativum*, *Allium cepa*, *Zingiber officinale*, *Mentha × piperita*, *Mentha spicata*, *Ocimum basilicum*, and *Artemisia vulgaris*) were not collected as voucher specimens; instead, they were documented from participant reports and corroborated through photographic identification and consultation of botanical reference sources.

Table 1. Participant characteristics.

Participant	Age	Gender	Role	Community	Years of practice
1	88	Female	Traditional Midwife/Herbalist	Tibolón	60
2	72	Male	Traditional H'men	Tibolón	45
3	65	Female	Traditional Herbalist	Tibolón	35
4	44	Female	Traditional Herbalist	Tibolón	20
5	43	Female	Traditional Herbalist	Tibolón	18
6	30	Female	Traditional Ix'men	Yaxcabá	22
Average	57				33.33

Systematic literature review

Following PRISMA 2020 (Page et al., 2021), we searched Scopus, Web of Science, SCIELO, PubMed, Google Scholar, and JSTOR (1990–2023) for peer-reviewed articles, dissertations, and government reports on Maya ethnobotany in Yucatán documenting medicinal plant uses for respiratory conditions. Fourteen sources met inclusion criteria. The study selection procedure is described above, and the outcome of the screening process is shown in Figure 2.

Database construction

Records from fieldwork and literature were harmonized through taxonomic standardization (APG IV, 2016; WFO, 2026; POWO, 2026; Missouri Botanical Garden, 2026), synonym consolidation, recoding of respiratory indications into common categories, and normalization of ethnobotanical variables. Geographic origin (native, exotic, regionally endemic) was assigned using the *Flora of the Yucatan Peninsula* database (Centro de Investigación Científica de Yucatán, 2026) cross-checked with POWO and TROPICOS.

Fieldwork (49 use-reports from six specialists) and literature (219 use-reports from 14 sources) were integrated into a single database (Additional File 1). We acknowledge that these datasets represent different scales of knowledge: individual expert census (fine-grained, locally grounded) vs. published records (broader geographic scope but heterogeneous methods, temporal range, and reporting biases). Rather than claiming equivalence, we used the combined dataset to identify structural patterns that are robust across sources while explicitly testing for source-specific differences (see Results: comparative analysis). The literature subset shapes global network topology due to its size; fieldwork data provide local grounding and ICF values. Separate analyses by subset (Additional File 2) and chi-square comparisons are reported to assess heterogeneity. For core–periphery and null model analyses, we prioritized the full dataset but discuss source bias in Limitations.

For clarity: ICF analysis was performed exclusively on the fieldwork subset (n = 49 use-reports from six healers), while all network analyses (bipartite family-use network, use-use co-occurrence network, null model comparisons, and core-periphery analysis) were conducted on the full consolidated dataset (n = 268 use-reports); comparative analyses between subsets are reported separately in the Results section and Additional File 2.

Descriptive statistics

Analyses were conducted in R 4.2.1 (*tidyverse*, ggplot2). The unit of analysis was the use-report. Frequencies and proportions were calculated for scientific names, families, therapeutic uses, plant parts, preparation methods, administration routes, growth habits, and geographic origin.

Informant Consensus Factor (ICF)

To explore agreement among the six interviewed specialists regarding plant use by therapeutic category, the Informant Consensus Factor (ICF) was calculated following Trotter and Logan (1986): $ICF = (nur - nt)/(nur - 1)$, where nur is the number of use-reports in a category and nt is the number of taxa used for that category. ICF values range from 0 to 1, with higher values indicating greater agreement.

For ICF analysis, therapeutic uses reported in the interview subset were grouped into a reduced set of clinically related respiratory symptom categories defined in the analytical coding scheme used for the study. This recoding was applied to avoid artificial fragmentation of closely related symptoms and to obtain more interpretable consensus estimates across the six interviewed specialists. Given the small number of interviewees, ICF values were treated as exploratory indicators of consensus. Values range from 0 (no consensus, random selection) to 1 (complete consensus, all informants use same taxa).

Co-occurrence network analysis

A bipartite network of botanical families and therapeutic-use categories was constructed from the consolidated dataset. One set of nodes represented botanical families and the other therapeutic-use categories; an edge was established when a family and a therapeutic-use category co-occurred in the same use-report. Edge weights represented the frequency of co-occurrence. The network was visualized in Gephi using the ForceAtlas2 algorithm (Bastian et al., 2009; Jacomy et al., 2014), and degree centrality, betweenness centrality, and modularity were calculated as descriptive metrics. Network metrics, node-level values, and analytical outputs for the family–use and symptom-use networks are provided in Additional Files 3 and 4.

Null model analysis

For the bipartite network, 1,000 randomized matrices were generated using the Curveball algorithm (preserving row and column degrees). For the one-mode therapeutic use network, 1,000 randomized networks were generated using a double-edge swap (preserving

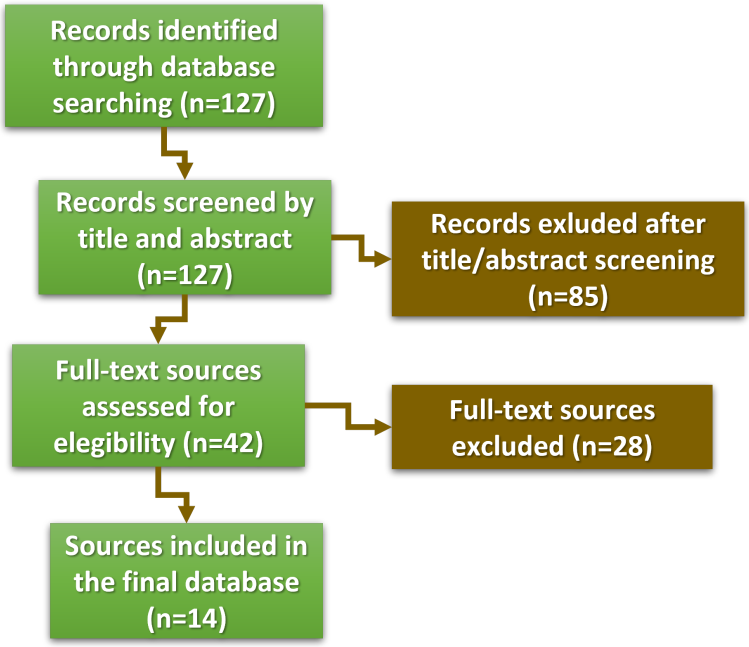

Figure 2. PRISMA flow diagram shows systematic literature review process. From 127 initial records, 14 sources were included in the final database after screening and eligibility assessment.

node degree). Observed metrics (connectance, density, average clustering coefficient, modularity, degree centralization, transitivity, average path length) were compared to random distributions; z-scores and empirical p-values were calculated.

Core–periphery analysis

We applied Borgatti–Everett continuous optimization (Borgatti and Everett, 2000). This method computes a coreness value for each node and a correlation coefficient ρ between the observed network and an idealized core–periphery matrix (where core nodes are fully connected to each other and to periphery nodes, and periphery nodes have no connections among themselves). ρ ranges from 0 (no core–periphery structure) to 1 (perfect fit). Statistical significance is assessed by comparing ρ against degree-preserving random networks. We also used k-core decomposition (Seidman, 1983) and bootstrap resampling (1,000 iterations) to assess stability of core node assignments.

RESULTS

Study selection and database composition

The literature search identified 127 potentially relevant records. After title and abstract screening, 42 sources were assessed in full text, and 14 met all inclusion criteria and were incorporated into the final database (Figure 2). These sources comprised peer-reviewed articles, a dissertation, government reports, and herbarium records.

The consolidated database comprised 268 use-reports. The fieldwork subset contributed 49 use-reports representing 32 taxa, of which 25 taxa were documented with voucher specimens, whereas the literature subset contributed 219 use-reports representing 131 taxa. The combined dataset represented 139 taxa across 54 families and corresponds to the records included in Additional File 1.

Botanical families and most frequently use-report species

The most represented botanical families were Fabaceae (32 use-reports, 12.0%), Rutaceae (23, 8.6%), Lamiaceae (21, 7.8%), and Malvaceae (17, 6.3%), which together accounted for 34.7% of all use-reports (Figure 3). Other notable families included Amaryllidaceae (13, 4.9%), Asteraceae (12, 4.5%), Poaceae (11, 4.1%), Boraginaceae (10, 3.7%), and Euphorbiaceae (10, 3.7%).

The most frequently cited species were *Cymbopogon citratus* (Poaceae, exotic; 11 use-reports, 4.1%), followed by *Plectranthus amboinicus* (Lamiaceae, exotic; 9 use-reports, 3.4%). Several native species were

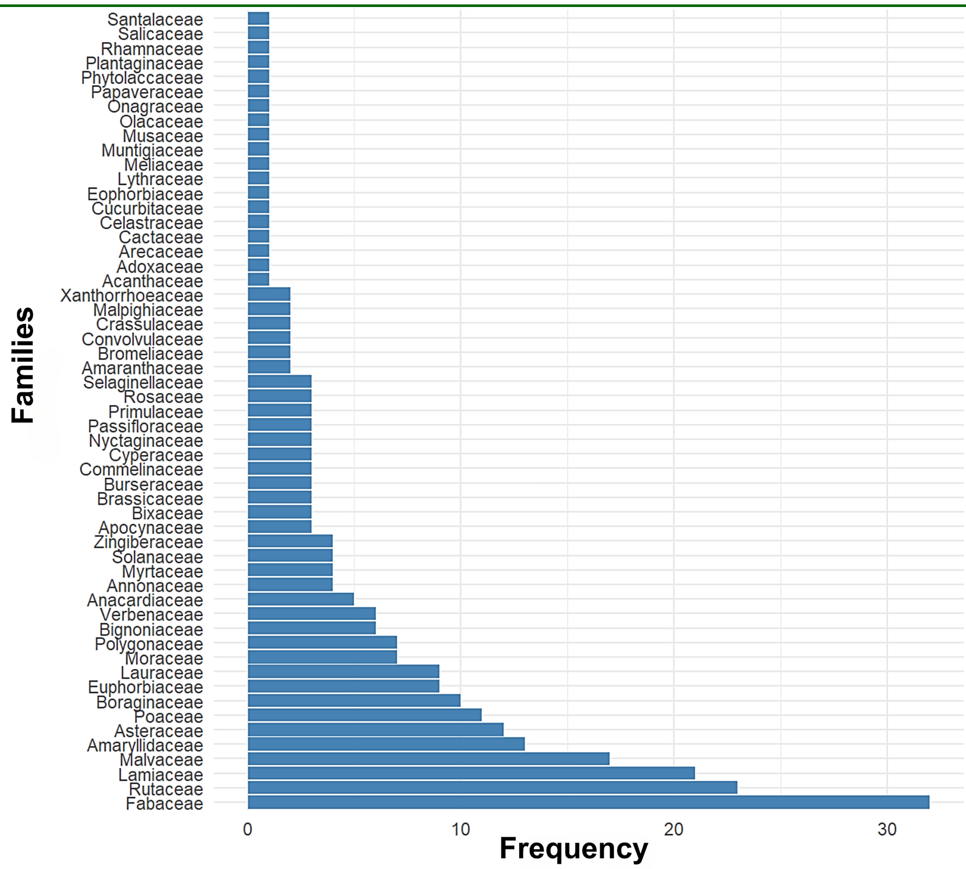

Figure 3. Distribution of use-reports (n = 268) across 54 botanical families documented in the Maya pharmacopoeia for respiratory diseases. Fabaceae, Rutaceae, Lamiaceae, and Malvaceae were the most represented families.

Table 2. Species with the highest number of use-reports for respiratory diseases (top 7).

Rank	Scientific name	Family	Origin	Use-reports	% of total
1	*Cymbopogon citratus*	Poaceae	Exotic	11	4.1
2	*Plectranthus amboinicus*	Lamiaceae	Exotic	9	3.4
3	*Bauhinia divaricata*	Fabaceae	Native	6	2.2
4	*Brosimum alicastrum*	Moraceae	Native	6	2.2
5	*Persea americana*	Lauraceae	Native	6	2.2
6	*Piscidia piscipula*	Fabaceae	Native	6	2.2
7	*Ehretia tinifolia*	Boraginaceae	Native	5	1.9
	Total (top 7)			49	18.3

also highly represented, including *Bauhinia divaricata*, *Brosimum alicastrum*, *Persea americana*, and *Piscidia piscipula* (6 use-reports each, 2.2%), as well as *Ehretia tinifolia* (5 use-reports, 1.9%). Together, these seven species accounted for 49 use-reports (18.3% of the total). The group includes both native and exotic taxa, illustrating the dynamic character of the pharmacopoeia.

Therapeutic uses

Therapeutic uses were diverse, totaling 520 therapeutic-use citations across 29 categories. Cough was the most frequently recorded therapeutic use (134 citations, 25.8%), followed by asthma (111, 21.3%), bronchitis (63, 12.1%), catarrh (54, 10.4%), and flu (41, 7.9%) (Figure 4). Because many taxa were associated with more than one respiratory condition, the total number of therapeutic-use citations exceeded the 268 use-reports in the consolidated database. Less frequent categories include cold, sinusitis, tuberculosis, throat-related conditions, and other specific respiratory symptoms.

Plant parts, preparation methods, administration routes, growth habits and geographic origin

Plant-part use was diverse, totaling 314 plant-part citations across the 268 use-reports. Leaves were the most frequently used plant part (165 citations, 52.5%), followed by fruit (25, 8.0%), aerial parts (22, 7.0%), flowers (18, 5.7%), and bark (15, 4.8%) (Figure 5 A). Roots (13, 4.1%), stems (10, 3.2%), bulbs (9, 2.9%), and latex (4, 1.3%) were less frequently reported.

Preparation methods totaled 318 citations. Decoction was the dominant preparation method (198 citations, 62.3%), followed by infusion (35, 11.0%) and juice (30, 9.4%) (Figure 5 B). Other recorded methods included poultice (9, 2.8%), syrup (9, 2.8%), maceration (7, 2.2%), roast (5, 1.6%), and inhalation (5, 1.6%).

Administration routes totaled 277 citations. Oral administration was overwhelmingly predominant (246 citations, 88.8%), followed by topical use (30, 10.8%) and rectal administration (1, 0.4%) (Figure 5 C). Herbs (94 use-reports, 35.1%) and trees (89, 33.2%) were the dominant growth habits, followed by shrubs (47, 17.5%) and shrub/tree intermediates (35, 13.1%) (Figure 5 D). Vines were minimally represented (3, 1.1%). Native taxa accounted for 148 use-reports (55.2%), exotic taxa for 113 (42.2%), and regionally endemic taxa for 7 (2.6%) (Figure 5 E). The endemic component comprised of five species: *Jatropha gaumeri*, *Bonellia flammea*, *Colubrina yucatanensis*, *Neomillspaughia emarginata*, and *Pilocarpus racemosus*.

Informant Consensus Factor (ICF) – interview data only

Analysis of interview data from the six traditional healers yielded ICF values ranging from 0.00 to 0.52 across the recoded respiratory symptom categories (Table 3). The highest consensus was observed for flu (ICF = 0.52) and sinusitis (0.50), followed by bronchitis (0.43) and dry cough (0.40). Lower values were recorded for cough (0.36), catarrh (0.26), and asthma (0.25), whereas immunomodulator showed no consensus (0.00). Given the small number of interviewees, these values should be interpreted as exploratory indicators of agreement.

Co-occurrence network analysis (full dataset)

The bipartite network of botanical families and therapeutic-use categories revealed a structured pattern of associations within the consolidated respiratory pharmacopoeia (Figure 6). Based on degree centrality, the most connected botanical families were Lamiaceae (degree = 14), Fabaceae (13), Asteraceae (10), Malvaceae (9), and Rutaceae (8). Among therapeutic-use categories, cough and asthma showed the highest degree centrality (33 each), followed by bronchitis (24), catarrh (22), and flu (21). Less connected nodes were located toward the periphery. Overall, the network displayed a clustered organization of family–use associations, presented here as a descriptive feature of the data structure.

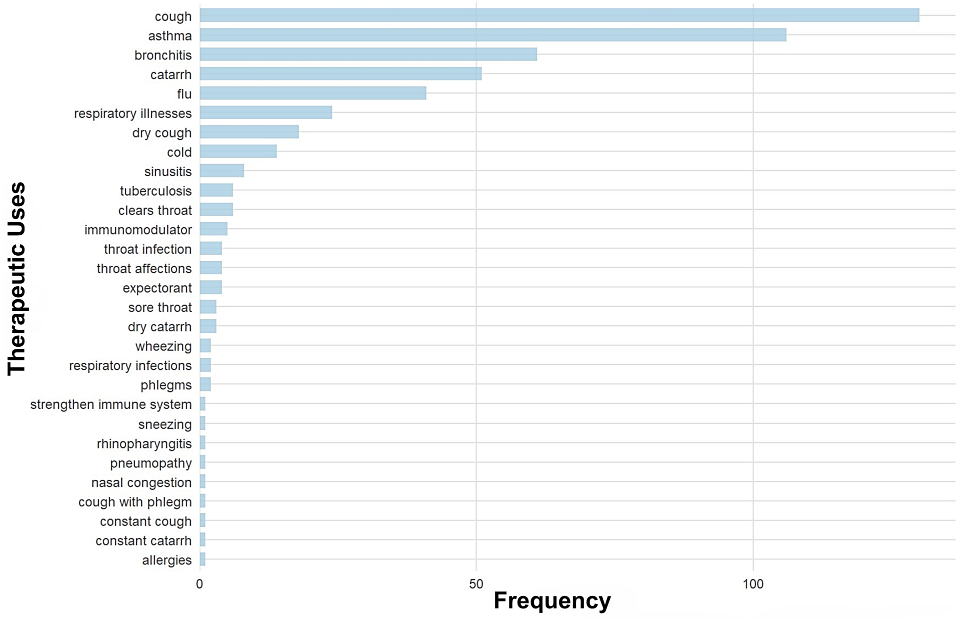

Figure 4. Frequency of therapeutic uses reported for medicinal plants used to treat respiratory diseases (n = 520 therapeutic-use citations derived from 268 use-reports). Cough (n = 134, 25.8%) was the most frequently recorded therapeutic use, followed by asthma (n = 111, 21.3%), bronchitis (n = 63, 12.1%), catarrh (n = 54, 10.4%), and flu (n = 41, 7.9%).

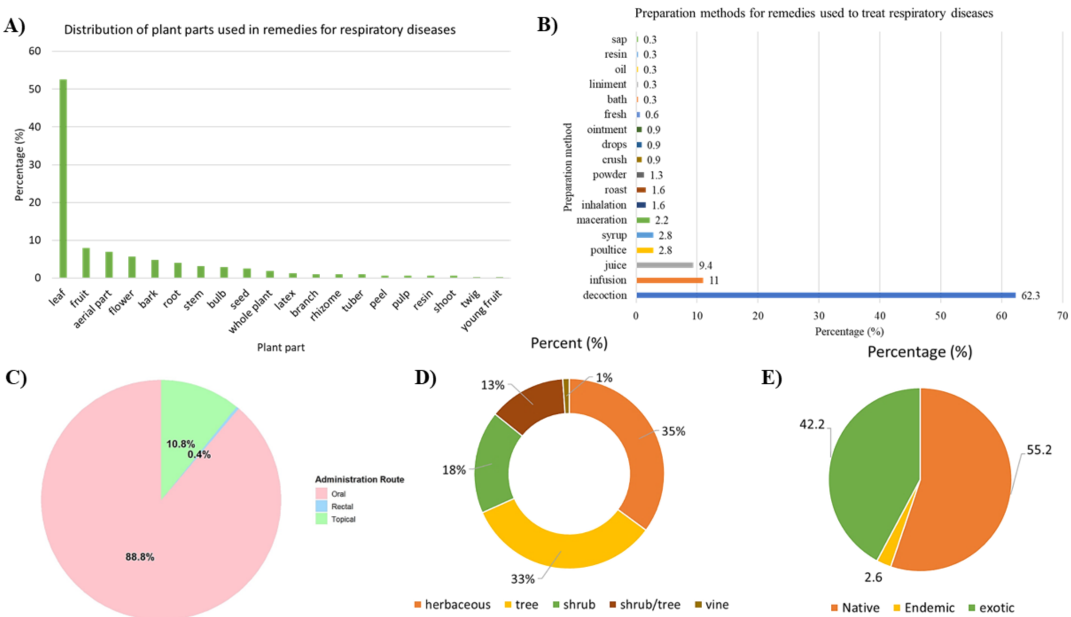

Figure 5. Multi-panel summary: A) Plant parts, B) Preparation methods, C) Administration routes, D) Growth habits, and E) Geographic origin of medicinal plant taxa.

Use–use co-occurrence network based on therapeutic-use co-occurrence

A complementary network analysis based on the co-occurrence of therapeutic-use categories within the same use-report showed a connected structure linking the main respiratory uses recorded in the consolidated database (Figure 7). The network comprised 29 coded therapeutic-use categories, of which 25 were connected by at least one co-occurrence link. The most connected categories were asthma (degree = 13), cough (12), bronchitis (10), dry cough (9), and flu (8), where degree indicates the number of direct links with other categories. In terms of weighted connectivity, that is, the cumulative strength of those links based on the number of co-occurrences, asthma and cough also occupied the most central positions, followed by bronchitis, catarrh, and flu. The strongest pairwise associations were observed between asthma and cough (weight = 61), asthma and bronchitis (47), cough and catarrh (31), cough and flu (31), asthma and catarrh (28), and bronchitis and cough (26). Less connected categories were located toward the periphery, and four categories were isolated in this coding scheme.

Null model comparison

Observed networks deviated significantly from random expectations. For the bipartite network, modularity was significantly lower than random (z = -19.44, $p < 0.001$); clustering showed a non-significant tendency to be higher (z = 1.69, p = 0.104). For the therapeutic use co-occurrence network, average clustering coefficient (z = 4.65, $p < 0.001$) and transitivity (z = 5.96, $p < 0.001$) were significantly higher than random, while modularity was significantly lower (z = -8.99, p = 0.012). These results indicate a non-random but weakly compartmentalized organization with tightly interconnected therapeutic associations.

Core–periphery structure of the therapeutic use network

The Borgatti–Everett analysis yielded a coreness fit $\rho = 0.666$ (z = 4.33, $p < 0.001$). For context, ρ quantifies the correlation between the observed network and an idealized core–periphery matrix (0 = no structure, 1 = perfect fit). Values between 0.5 and 0.7 are typically interpreted as moderate to strong evidence of core–periphery organization in social and ecological networks (Borgatti and Everett, 2000). The k-core decomposition identified a maximum 5-core. Bootstrap resampling showed high stability for asthma (95.7%), cough (95.2%), bronchitis (93.6%), and flu (91.3%), with moderate stability for cold (71.9%) and sinusitis (68.5%). These results support the presence of a cohesive recurrent therapeutic core. Complete network metrics and node-level values are provided in Additional Files 3 and 4.

Comparative analysis between the fieldwork and literature

Comparative analysis between the fieldwork and literature subsets revealed significant differences in geographic origin (χ^2 (2) = 15.67, $p < 0.001$), plant parts used (χ^2 (19) = 35.29, p = 0.0129), preparation methods (χ^2 (17) = 35.05, p = 0.0061), and the composition of the seven most represented botanical families (χ^2 (6) = 14.12, p = 0.0283). No significant difference was observed for growth habits (χ^2 (4) = 5.21, p = 0.267).

DISCUSSION

The results reveal a consistent pattern of organization within the Maya respiratory pharmacopoeia. Across multiple analytical approaches—including use-report frequencies, consensus measures, network analyses, null model comparisons, and core–periphery structure—plant uses were concentrated in a relatively limited set of taxa, therapeutic categories, and associations. The following sections examine how these

Table 3. Informant Consensus Factor (ICF) for respiratory therapeutic categories based on interview data (n = 6 healers).

Therapeutic category	Use-reports nur	Taxa nt	ICF
Flu	22	11	0.52
Sinusitis	7	4	0.50
Bronchitis	8	5	0.43
Dry cough	6	4	0.40
Cough	37	24	0.36
Catarrh	20	15	0.26
Asthma	25	19	0.25
Immunomodulator	5	5	0.00

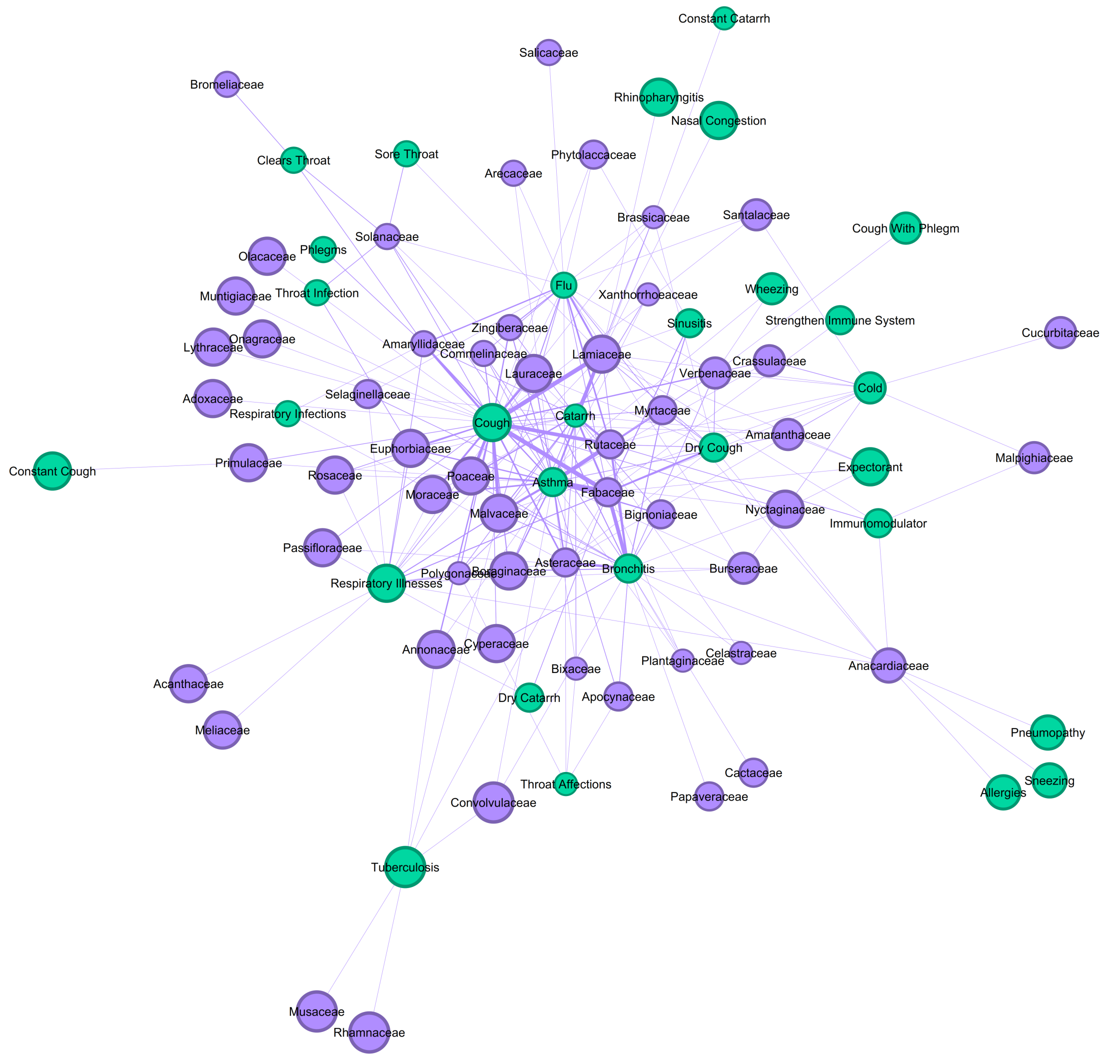

Figure 6. Bipartite co-occurrence network of botanical families and therapeutic-use categories for respiratory diseases, constructed from the consolidated dataset. Green and purple nodes represent the two node classes in the network, and edges indicate family–use associations. More connected nodes indicate families and therapeutic-use categories with broader participation in the pharmacopoeia, whereas less connected nodes indicate narrower associations.

patterns contribute to understanding the organization, transmission, and conservation of respiratory medicinal knowledge in the Yucatán Peninsula.

The patterns observed in this study resonate with historical sources that document the continuity and transformation of Maya medicinal knowledge. Roys' (1931, 1976) analysis of colonial Maya medical texts already identified a substantial repertoire of plants for respiratory conditions, many of which—such as *Piscidia piscipula* and *Brosimum alicastrum*—remain prominent in contemporary use. de Mendieta's (1870) *Historia eclesiástica indiana* offers an early European perspective on Indigenous healing practices, noting the reliance on herbal remedies and the specialized knowledge of Maya healers, a pattern that persists in the structured organization of the respiratory pharmacopoeia documented here. The *Libro del Judío* (Osado, 1834), a widely circulated vernacular pharmacopoeia, contains numerous entries for respiratory ailments—including cough, asthma, and catarrh—that overlap with the therapeutic categories identified in our consolidated database, suggesting a degree of continuity in the conceptual organization of respiratory remedies over centuries. These historical sources, to-

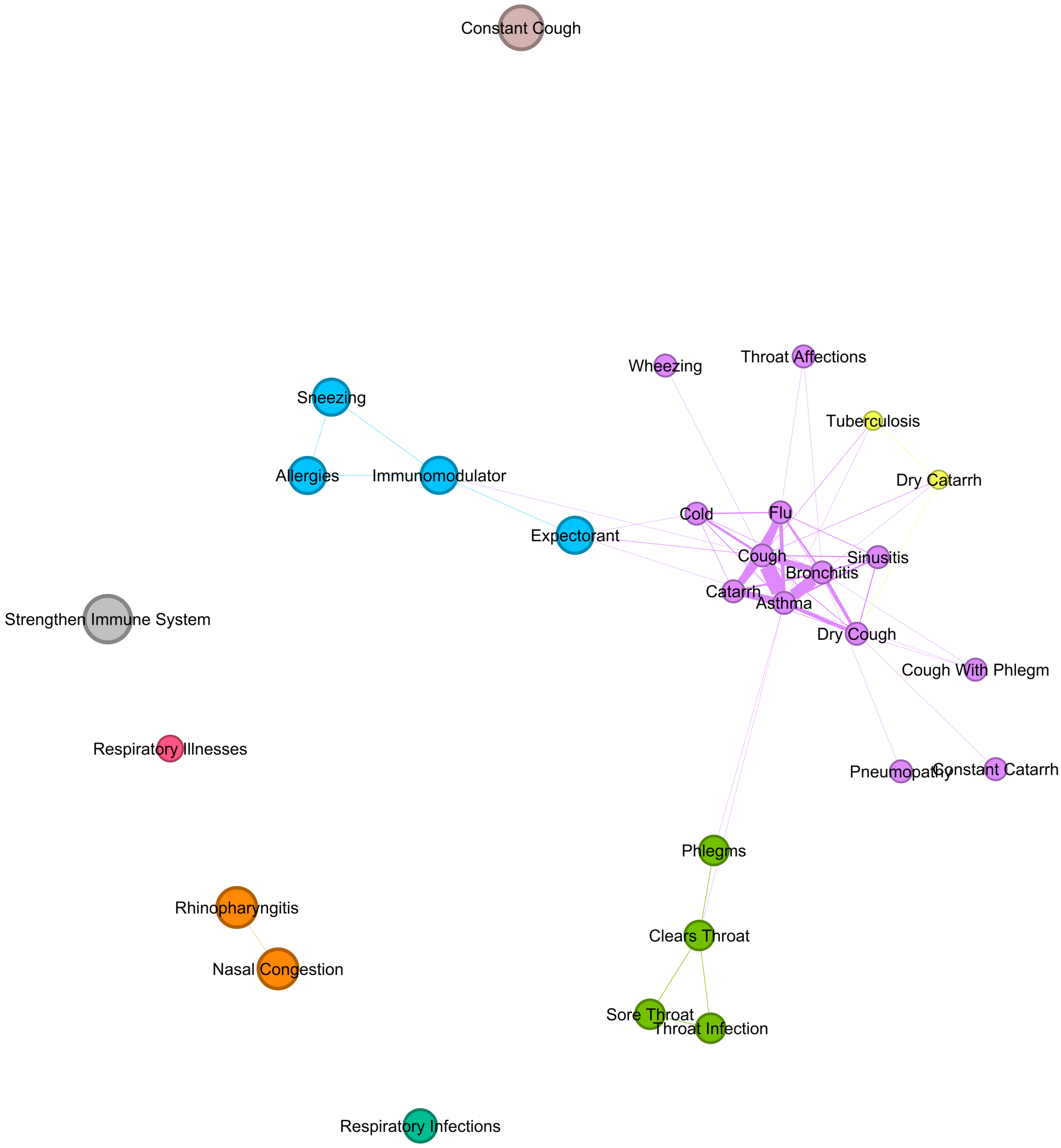

Figure 7. Use–use co-occurrence network of respiratory therapeutic-use categories in the consolidated dataset. Nodes represent therapeutic-use categories, and edges indicate co-occurrence of two categories within the same use-report. More connected nodes reflect broader overlaps in the way respiratory uses are recorded together, whereas less connected nodes indicate narrower associations.

gether with more recent ethnobotanical studies (Ankli et al., 1999a, 1999b; Hirose López, 2018; Escobar-Chan et al., 2024), provide crucial evidence for understanding the Maya respiratory pharmacopoeia as an adaptive biocultural system with a stable therapeutic core and a flexible periphery, shaped by both deep historical continuity and ongoing processes of incorporation and change, a framework that we develop throughout this study.

Structure of the respiratory pharmacopoeia

The respiratory pharmacopoeia documented in this study exhibits a non-random and highly structured organization, characterized by the concentration of use-reports in a relatively limited number of plant families, species, and therapeutic categories. A small subset of taxa accounts for a disproportionately large share of medicinal uses, suggesting the presence of a stable therapeutic core within the system. This pattern is further reflected in the recurrence of specific respiratory categories, such as cough, asthma, bronchitis, and catarrh, which concentrate most reported treatments and indicate a structured distribution of therapeutic knowledge rather than a diffuse or opportunistic use of available flora. Network analyses reinforce this interpretation by revealing clustered associations between plant families and therapeutic uses, as well as overlapping connections among symptom categories, indicating that plant selection is embedded within an organized framework of medical reasoning. Taken together, these findings indicate that plant use for respiratory diseases is distributed unevenly across taxa and therapeutic categories. Rather than being randomly distributed throughout the medicinal flora, respiratory treatments are concentrated in a relatively small subset of recurrent species, families, and symptom categories, suggesting the existence of identifiable organizational patterns within the pharmacopoeia (Gavin et al., 2015; Turner et al., 2022).

Patterns consistent with Apparency Theory

Several features of the respiratory pharmacopoeia align with Apparency Theory, which predicts reliance on abundant, accessible plant resources (Albuquerque et al., 2015). Leaves were the most used part (52% of citations), a pattern consistent with low ecological cost and documented in other systems (Albuquerque et al., 2011; Gaoue et al., 2017). The co-dominance of herbs and trees suggests use of both garden and perennial resources (Hopkins and Stepp, 2012), reinforced by cultivated species like *Cymbopogon citratus* and *Plectranthus amboinicus*. Decoction represented >60% of preparation methods, also aligning with accessibility.

However, these patterns are not solely explained by practicality. Aromatic species (e.g., *Citrus* spp., *Zingiber officinale*) are sensorially distinctive, and Maya healers value odor and taste in plant selection (Ankli et al., 1999b; Flores & Vermont, 1996). Leaves often bear glandular trichomes that produce essential oils relevant to respiratory treatment (Huchelmann et al., 2017), and decoction effectively extracts these principles (Daswani et al., 2011; Zhang et al., 2018). Thus, the prominence of leaves and decoction reflects a combination of accessibility, sensory recognition, phytochemistry, and local therapeutic logic.

The same reasoning explains the mixed biogeographic composition: 42.2% of use-reports involve exotic taxa, and introduced species rank among the most cited (Table 2). Plant selection is shaped not only by ecological availability but also by historical incorporation through intercultural exchange. Maya medicine is syncretic, integrating Indigenous, European, and African knowledge (Escobar-Chan et al., 2024). The respiratory pharmacopoeia therefore links patterns predicted by Apparency Theory with those of the Dynamic Pharmacopoeia model.

Endemic species: a potentially vulnerable component

Within this broader and adaptive respiratory pharmacopoeia, the endemic component stands out as its most geographically restricted layer. As shown in (Figure 5 E), regionally endemic species accounted for only 2.6% of all use-reports and comprised five species. Numerically, this is a small fraction of the pharmacopoeia; bioculturally, however, it is especially significant because the continued use of these taxa depends not only on the persistence of localized plant populations, but also on the knowledge systems that identify, manage, and transmit them.

This low representation likely reflects both ecological and epistemic factors. Endemic species have narrower geographic distributions than widespread native taxa or cultivated exotics, which reduces their accessibility and visibility in everyday therapeutic practice. In the Yucatán Peninsula, several endemic taxa are associated with dry forest habitats that have undergone substantial land-use change (Trejo and Dirzo, 2000), further increasing their vulnerability. At the same time, knowledge linked to endemic plants may be more localized, specialized, or selectively transmitted than knowledge associated with more widespread medicinal taxa. Studies of knowledge change suggest that the most restricted and context-dependent domains of traditional knowledge are often the most vulnerable under conditions of social and environmental transformation (Reyes-García et al., 2013; Hirose-López, 2018).

Even so, the presence of five endemic species in a pharmacopoeia focused specifically on respiratory diseases is itself meaningful. It indicates that geographically restricted taxa remain part of therapeutic practice, even if only marginally in quantitative terms, and suggests that the pharmacopoeia includes not only a resilient core of widely used taxa, but also a narrower layer of more localized biocultural knowledge. From a conservation perspective, this endemic component deserves particular attention, because it may be especially sensitive to both habitat loss and the interruption of intergenerational knowledge transmission. This contrast between a broadly shared medicinal core and a more restricted layer of specialized knowledge also provides a useful bridge to the following discussion of consensus and knowledge structure.

Knowledge structure and consensus

The Informant Consensus Factor (ICF) values suggest variable levels of agreement among the interviewed specialists across respiratory therapeutic categories. Higher values were observed for flu, sinusitis, bronchitis, and dry cough, whereas lower values were recorded for cough, catarrh, and asthma (Table 3), indicating that some respiratory conditions are treated with a more restricted and recurrent set of shared remedies, while others involve a broader and more variable therapeutic repertoire. Given the small number of interviewees, these values are best interpreted as exploratory indicators of agreement rather than as strict measures of therapeutic standardization (Trotter and Logan, 1986; Heinrich et al., 1998).

The moderate bootstrap stability values observed for cold (71.9%) and sinusitis (68.5%), while still above the 50% threshold indicating meaningful structure, are lower than those for core conditions such as asthma, cough, and bronchitis. This difference may reflect that cold and sinusitis occupy a more ambiguous position within Maya respiratory nosology, often overlapping with other symptom categories. Cold and sinusitis may also be treated with a more diverse or context-dependent set of remedies compared to the more consistently associated core conditions.

The network analyses reinforce this interpretation by showing that variability and structure coexist rather than excluding one another. In the bipartite family–use network, some families, particularly Fabaceae, Lamiaceae, and Rutaceae, were linked to multiple therapeutic categories, whereas others occupied more peripheral positions with fewer associations (Figure 6). Likewise, the use–use network showed that major respiratory categories such as asthma, cough, bronchitis, and flu were strongly interconnected (Figure 7). This interconnected pattern suggests that respiratory complaints are treated as related symptom complexes rather than as fully discrete disease categories, and that many remedies are recorded in connection with overlapping respiratory conditions rather than strictly disease-specific indications.

The combined evidence from consensus and network analyses suggests that agreement and variability coexist within the respiratory pharmacopoeia. Some taxa and therapeutic categories are broadly shared among practitioners, whereas others occupy more restricted positions within the medicinal repertoire. This pattern highlights the coexistence of common and specialized domains of knowledge within the system.

The observed null-model deviations support H3, whereas the Borgatti–Everett and k-core analyses support H4.

Integration of primary and secondary data

Integrating fieldwork and literature records made it possible to compare locally documented specialist knowledge with previously published ethnobotanical evidence from the Yucatán Peninsula. As shown in Additional File 2, both subsets converged in several key structural patterns: leaves were the predominant plant part used, decoction was the dominant preparation method, and Fabaceae, Rutaceae, and Lamiaceae were among the most represented families. These consistencies support the robustness of the merged database for identifying general patterns in the respiratory pharmacopoeia rather than patterns restricted to a single source of evidence.

At the same time, the comparison also revealed meaningful differences between subsets. The most notable concerned geographic origin, with a significantly higher proportion of use-reports involving exotic taxa in the fieldwork dataset than in the literature dataset (χ^2 (2) = 15.67, $p < 0.001$; Additional File 2). This contrast likely reflects sampling context. The present fieldwork was conducted largely in solares, where cultivated and introduced species are common and actively managed, whereas many ethnobotanical studies in the region emphasize wild flora, forest environments, or vegetation surveys. Under those conditions, cultivated exotic species may be underrepresented in inventories that prioritize wild-collected plants or native vegetation.

This difference suggests that the apparent predominance of native taxa in parts of the ethnobotanical literature may partly reflect research focus and sampling strategy rather than the actual absence of exotic species from traditional medical practice. In this sense, integrating primary and secondary data not only expands regional coverage, but also reveals how medicinal floras are shaped both by plant-use patterns and by the environments in which researchers choose to document them, a pattern likewise observed when ethnobotanical information is contrasted across different source types (Cámara-Leret et al., 2014; Souza et al., 2017). This comparative perspective helps clarify the broader conservation implications of the pharmacopoeia and the context in which it is maintained.

Biocultural conservation implications

Safeguarding the Maya respiratory pharmacopoeia requires protecting not only plant species but also the socio-ecological contexts where knowledge is practiced and renewed. *Solares* (homegardens) are central spaces for cultivating, using, and learning about medicinal plants, acting as *in situ* reservoirs of biocultural diversity. Conservation strategies must therefore support healer networks, household plant management, and broader landscapes (Gavin et al., 2015).

Regionally endemic species account for only 2.6% of use-reports (five taxa), forming a small but bioculturally significant layer. Their low representation reflects ecological restriction and localized knowledge transmission, not lack of value. Documentation, local monitoring, and participatory strategies with healers as knowledge authorities are especially important for this vulnerable component (Reyes-García et al., 2013; Hirose-López, 2018).

The predominance of women knowledge holders (83.3%; Table 1) underscores the need for gender-conscious conservation. Women play central roles in managing domestic medicinal knowledge, a fact that should inform research and policy (Howard, 2003; Pfeiffer & Butz, 2005). Prominent culturally important taxa (e.g., *Cymbopogon citratus*, *Plectranthus amboinicus*, *Piscidia piscipula*) suggest aligning community cultivation and local conservation with intercultural health approaches (Almaguer González et al., 2014; Garibaldi & Turner, 2004). Taken together, these observations underscore that conservation efforts should address both biological resources and the social contexts through which medicinal knowledge is maintained and transmitted. Protecting medicinal plants without considering healer networks, homegardens, and local knowledge systems would preserve only part of the biocultural processes that sustain the pharmacopoeia (Albuquerque et al., 2015; Gavin et al., 2015).

Toward an adaptive biocultural theory of Maya traditional medicine The patterns documented here indicate that the Maya respiratory pharmacopoeia cannot be fully explained by single-factor models of resource selection. While some features align with Apparency Theory (predominance of leaves and accessible resources), other findings point to a more complex organization integrating ecological, cultural, and historical dimensions (Albuquerque et al., 2015; Gaoue et al., 2017).

The significant presence of exotic species, the structured yet overlapping therapeutic categories, and the central role of homegardens and healer networks show that plant selection is driven by multiple criteria: accessibility, sensory perception, perceived efficacy, cultural familiarity, and historical incorporation (Alencar et al., 2010; Medeiros et al., 2017; Ankli et al., 1999b; Flores & Vermont, 1996). This supports interpreting Maya traditional medicine as an adaptive biocultural system organized around a stable therapeutic core and a flexible, dynamic periphery (Heinrich et al., 1998; Gavin et al., 2015).

The coexistence of native, exotic, and endemic taxa reinforces this dual structure. Exotic incorporation represents adaptive expansion, not knowledge erosion (Alencar et al., 2010; Medeiros et al., 2017; Escobar-Chan et al., 2024), while low endemic representation reveals a more restricted, vulnerable layer (Reyes-García et al., 2013; Hirose-López, 2018). Thus, Apparency Theory and the Dynamic Pharmacopoeia model remain useful but partial; the evidence supports a more integrative interpretation of Maya medicinal systems as adaptive, historically dynamic, and structurally organized biocultural systems.

These broader conservation and health implications should nevertheless be interpreted with caution. First, the fieldwork component was based on a small number of participants (n = 6). Although this sample represents all recognized healers in the two study communities and therefore provides strong local-level insight, it limits broader generalization across the Yucatán Peninsula and the wider Maya region. The integration of literature records expanded the regional scope of the study, but heterogeneity in methods, temporal range, and reporting practices remains an important constraint.

Second, the study is geographically focused and cross-sectional. As such, it provides a detailed snapshot of medicinal knowledge in two communities, but does not directly capture historical change, intergenerational dynamics, or long-term transformation of the pharmacopoeia. Third, the use of biomedical categories such as cough, asthma, and bronchitis introduce an etic framework that may not fully correspond to Maya ethnomedical concepts. This limitation is especially relevant for the interpretation of both consensus values and network structure, since both analyses depend on the way therapeutic categories are defined. Finally, the consensus and network analyses should be understood as exploratory and descriptive tools rather than as confirmatory models of therapeutic logic. Additionally, the specific set of respiratory categories elicited in the fieldwork interviews may have been influenced by the structure and phrasing of the interview guide. Although the guide was designed to be open-ended and to allow healers to describe their own categories, the prompts used inevitably shape which conditions are discussed and how they are coded, potentially affecting both consensus values and network structure.

In addition, this study documents medicinal knowledge and patterns, but does not experimentally evaluate efficacy or safety. Future research should therefore combine ethnobotanical, ethnographic, pharmacological, and ecological approaches, including multi-community comparisons, participatory research with healers, longitudinal studies of knowledge transmission, closer attention to emic illness categories, and ethnopharmacological investigation of frequently cited respiratory taxa (Jiménez-Balam et al. 2019; Muñoz-

Cázares et al. 2023). Taking together, these approaches would help clarify not only which plants are used, but also how therapeutic reasoning, ecological change, and knowledge transmission interact over time. This also provides the basis for a concise final synthesis of the article's main contribution.

CONCLUSION

The Maya respiratory pharmacopoeia documented in this study exhibits a structured pattern of organization characterized by the concentration of medicinal knowledge in a limited set of plant families, species, and therapeutic categories, together with a smaller component of more specialized and less widely shared knowledge. The coexistence of native, exotic, and endemic taxa highlights the dynamic nature of the pharmacopoeia and suggests that medicinal plant selection is shaped by multiple interacting ecological, cultural, and historical factors. These findings contribute to understanding how traditional medicinal knowledge is organized, maintained, and adapted over time. They further suggest that biocultural conservation should focus not only on medicinal plant resources, but also on the socio-ecological contexts that sustain knowledge transmission, including homegardens, healer networks, and local management practices. Future comparative studies across therapeutic domains and communities will be essential to determine whether the patterns identified here represent broader organizational features of Maya traditional medicine.

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DATA AVAILABILITY

The datasets supporting the conclusions of this article are included within the article and its additional files (Additional File 1: complete ethnobotanical database; Additional File 2: comparison of field work and literature subsets; Additional File 3: Complete network metrics and Additional File 4: Complete network datasets). Voucher specimens are deposited in the *U Najil Tikin Xiw herbarium*, with collector L. Ferrer and collection numbers MVK-076 to MVK-120. Gephi project files and exported network files are available from the corresponding author upon reasonable request.

DECLARATIONS

Ethics approval and consent to participate: This study was approved by the relevant ethics and cultural authorities associated with Traditional Maya and intercultural medicine in Yucatán, including institutional coordination with INDEMAYA. Collection activities were conducted under the corresponding environmental and institutional permissions. All participants provided written informed consent prior to participation. Community consent was obtained through meetings with local authorities and traditional healer associations in both municipalities. The study was conducted in accordance with the International Society of Ethnobiology Code of Ethics (International Society of Ethnobiology, 2006).

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

CONTRIBUTION STATEMENT

Conceived of the presented idea: LFL, MVK.
Carried out the experiment: LFL, MAPP.
Carried out the data analysis: LFL, MVK.
Wrote the first draft of the manuscript: LFL.
Review and final write of the manuscript: MVK, LFL, MAPP.
Supervision: MVK, ELOV.

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DISCLOSURE OF AI USE

During manuscript preparation, the authors used the AI-assisted functionalities available in SciSpace to facilitate statistical workflow, computational execution, and interpretation of analytical outputs, which were independently verified using R to confirm the reproducibility of the results. During manuscript revision, ChatGPT (OpenAI) was used to assist with improving language clarity, manuscript organization, and auditing results in databases. The intellectual direction of the study, including the research questions, theoretical framework, methodological decisions, interpretation of results, and scientific conclusions, was determined exclusively by the authors. All AI-generated suggestions were critically evaluated, modified when necessary, and incorporated only after author review and approval. The authors take full responsibility for the content of the manuscript.

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Additional Files

Add File 1. https://ethnobioconservation.com/ebc/article/view/1321/548

Add File 2. Summary of the ten most represented botanical families by species richness, use-reports, and geographic-origin composition of use-reports.

Family	Species (n)	Use-reports (n)	% Native	% Exotic	% Endemic
Fabaceae	18	32	62,5	34,4	3,1
Rutaceae	8	23	26,1	73,9	0
Lamiaceae	7	21	28,6	71,4	0
Malvaceae	6	17	70,6	29,4	0
Amaryllidaceae	5	13	0	100	0
Asteraceae	6	12	75	25	0
Poaceae	4	11	18,2	81,8	0
Boraginaceae	4	10	100	0	0
Euphorbiaceae	5	10	60	20	20
Verbenaceae	3	9	100	0	0

Add File 3. https://ethnobioconservation.com/ebc/article/view/1321/549

Add File 4. https://ethnobioconservation.com/ebc/article/view/1321/550