Ethnomedicinal knowledge and geographic patterns of medicinal plants used for Leishmaniasis management in Southeastern Morocco: Integrating GIS, multivariate statistics, and machine learning

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Research

Abstract

Background: Leishmaniasis remains a major public health concern in Morocco, where medicinal plants continue to play an important role in traditional healthcare. This study aimed to document the medicinal plants used for leishmaniasis management in the Draa-Tafilalet region and to evaluate the influence of sociodemographic and geographical factors on ethnomedicinal knowledge and practices.

Methods: A cross-sectional ethnobotanical survey was conducted across the main provinces of the region using structured questionnaires in 2023. Correspondence analysis, Geographic Information System (GIS)-based mapping, and machine-learning approaches were applied to characterize spatial variation and identify the factors influencing medicinal plant selection.

Results: Women represented 58.62% of respondents, while participants aged ≤22 and 23-38 years each accounted for 44% of the sample. Most respondents were single (77%), economically active (81.6%), and university-educated (78%). However, 59% reported no knowledge of medicinal plants, and 64% were unable to identify any medicinal species. Further, 61 medicinal plant species were documented, with *Rosmarinus officinalis* (18 citations), *Lawsonia inermis* (12), and *Origanum compactum* (8) being the most frequently reported. Errachidia recorded the highest plant diversity (29.03%), whereas no medicinal plants were reported from Rissani. Leaves (40%) and decoction (46%) were the predominant plant part and preparation method, respectively. GIS and correspondence analyses revealed pronounced geographical heterogeneity in medicinal plant use among provinces. Machine Learning Identified High- and Low-Priority Medicinal Plants.

Conclusions: This study represents the first comprehensive ethnobotanical assessment covering the entire Draa-Tafilalet region, integrating GIS, multivariate, and machine learning analyses to identify spatial and sociodemographic determinants

of medicinal plant utilization. These findings provide a valuable foundation for biodiversity conservation, ethnopharmacological research, and the development of affordable plant-based strategies for leishmaniasis management.

Keywords: Leishmaniasis; Ethnobotany; Medicinal plants; Drâa-Tafilalet; Geographic Information System (GIS); machine learning; traditional knowledge.

Background

Morocco possesses one of the richest ethnobotanical heritages in the Mediterranean basin, where the use of medicinal plants has been deeply rooted in traditional healthcare practices for centuries (Elachouri *et al.* 2021). This knowledge, transmitted across generations, encompasses a wide diversity of plant species used to manage infectious, digestive, respiratory, dermatological, metabolic, renal, and reproductive disorders, among many other human ailments (Haouari *et al.* 2018, Chaachouay *et al.* 2022). Ethnobotanical investigations have documented considerable floristic diversity and highlighted the cultural importance of herbal medicine in both rural and urban communities (Achour *et al.* 2022). Nevertheless, research efforts remain geographically uneven, with the majority of studies concentrated in northern, northeastern, eastern, and southern Morocco, including the Rif, Taza, and Souss regions (Teixidor-Toneu *et al.* 2016, Bencheikh *et al.* 2021, Chaachouay *et al.* 2022). In contrast, southeastern Morocco, particularly the Drâa-Tafilalet region, has received comparatively limited scientific attention despite its considerable floristic diversity, longstanding reliance on traditional medicine, and relatively constrained socioeconomic conditions. Expanding ethnobotanical research in this region is therefore essential for systematically documenting and preserving indigenous ethnomedicinal knowledge, safeguarding culturally important therapeutic practices, and providing a scientific basis for future pharmacological and phytochemical investigations.

Moroccan ethnobotanical knowledge encompasses a rich diversity of medicinal plants traditionally employed in the management of parasitic diseases. Numerous plant-based remedies have been documented for the treatment of intestinal helminthiasis, *Ascaris* infections, *Toxoplasma gondii*, *Blastocystis* spp., and a range of other parasitic diseases affecting both humans and animals (Chaoua *et al.* 2025, Elkoraichi *et al.* 2025). Experimental investigations have increasingly supported these traditional practices, demonstrating the antiparasitic potential of extracts from species such as *Origanum compactum*, *Trigonella foenum-graecum*, *Punica granatum*, and *Euphorbia officinarum* through in vitro and in vivo assays, including reduced parasite viability, apoptosis-like effects, and decreased parasite burden (Boutoub *et al.* 2022, Chaoua *et al.* 2025, Elkoraichi *et al.* 2025). Nevertheless, studies investigating medicinal plants for parasite management in Morocco remain relatively scarce and are geographically restricted, with most research conducted in selected northern and southern regions or focused on specific parasites (Bourouache *et al.* 2021, Chaoua *et al.* 2025). Consequently, several regions, particularly southeastern Morocco, remain comparatively understudied despite their considerable floristic diversity and longstanding reliance on traditional herbal medicine. This knowledge gap underscores the need for broader and more systematic ethnobotanical and pharmacological investigations to document traditional medicinal practices and evaluate their therapeutic potential.

Leishmaniasis is among the oldest recognized parasitic diseases, with historical records spanning several millennia, from descriptions in ancient civilizations to its modern characterization in parasitology (Steverding 2017). Currently, it is endemic in tropical, subtropical, and Mediterranean regions, affecting millions of people across more than 90 countries (Torres-Guerrero *et al.* 2017, Wamai *et al.* 2020). The disease occurs mainly as cutaneous, mucocutaneous, and visceral leishmaniasis, each characterized by distinct clinical manifestations ranging from self-limiting skin ulcers to life-threatening systemic infection (Torres-Guerrero *et al.* 2017, Mokni 2019). In Morocco, cutaneous and visceral leishmaniasis remain major public health concerns, caused predominantly by *Leishmania major*, *L. tropica*, and *L. infantum*, with expanding endemic foci influenced by urbanization and climate change (Kholoud *et al.* 2018, Laboudi *et al.* 2018, Hakkour *et al.* 2019, El mazini *et al.* 2022, Harkat *et al.* 2026). Despite the availability of pentavalent antimonials and other antiparasitic drugs, treatment remains limited by toxicity, prolonged administration, high cost, therapeutic failures, and emerging drug resistance. These limitations emphasize the urgent need to identify safer, more effective, and affordable therapeutic alternatives, including bioactive compounds derived from medicinal plants (Torres-Guerrero *et al.* 2017, Mokni 2019).

Medicinal plants have long been used in Moroccan traditional medicine to manage cutaneous leishmaniasis, particularly in endemic regions such as Sefrou, northwestern Morocco, and other areas where access to conventional treatment may be limited (Zeouk *et al.* 2020, El-Mouhdi *et al.* 2023). Ethnobotanical surveys have documented the use of numerous species, including *Salvia verbenaca*, *Origanum compactum*, *Artemisia herba-alba*, *Marrubium vulgare*, *Lawsonia inermis*, and *Rosmarinus officinalis*, which are applied topically or administered as infusions and decoctions to promote lesion healing and alleviate symptoms (Zeouk *et al.* 2020, El-Mouhdi *et al.* 2023). Pharmacological studies have validated part of this traditional

knowledge, demonstrating significant in vitro leishmanicidal activity of *Salvia verbenaca* and several medicinal plant extracts against different *Leishmania* promastigotes, with notable growth inhibition and parasite mortality (Et-Touys *et al.* 2016, Bouyahya *et al.* 2018, Zeouk *et al.* 2020). Reviews of African medicinal plants further highlight promising in vivo and experimental evidence supporting their antileishmanial potential (Et-Touys *et al.* 2017). Nevertheless, the number of Moroccan studies remains limited and geographically concentrated, leaving many endemic regions insufficiently investigated (Soussi *et al.* 2023, El-Ghazouani *et al.* 2024, Radi *et al.* 2024, Jaouad *et al.* 2025). Future research should therefore expand ethnobotanical and pharmacological surveys to underexplored areas, particularly socioeconomically disadvantaged regions where expensive conventional drugs are less accessible. In addition, greater attention should be given to the influence of sociodemographic factors, including age, gender, education, occupation, and residence, on the selection, knowledge, and utilization of medicinal plants for leishmaniasis management. Equally, future research should integrate new technologies, such as machine learning and GIS-based tools, to facilitate the analysis and mapping of big data from field surveys.

Leishmaniasis remains a significant public health challenge in Morocco, particularly in southeastern endemic areas where access to conventional therapies can be limited, and traditional medicine continues to play an important role. However, systematic evidence on medicinal plants used against leishmaniasis and the factors influencing their selection in the Drâa-Tafilalet region remains scarce. This study aimed to document medicinal plant species traditionally used to manage leishmaniasis and to assess how sociodemographic characteristics and geographic location shape ethnomedicinal knowledge and plant-use patterns. The study provides a novel regional synthesis by integrating ethnobotanical surveys with GIS, correspondence analysis, and machine-learning approaches to identify spatial and sociodemographic patterns. The findings are suggested to establish a baseline for prioritizing culturally important species, conserving biodiversity and traditional knowledge, guiding ethnopharmacological research, and supporting the development of accessible, evidence-based plant-derived strategies for leishmaniasis management.

Materials and Methods

Study area

The study was conducted in the Drâa-Tafilalet region of southeastern Morocco, the country's largest administrative region, encompassing approximately 88,836 km² (Figure 1). The region comprises five provinces: Errachidia, Midelt, Tinghir, Zagora, and Ouarzazate. It is bordered by the Oriental region to the northeast, Béni Mellal-Khenifra to the northwest, Marrakech-Safi and Souss-Massa to the west, and Algeria to the east and southeast. Geographically, Drâa-Tafilalet encompasses a highly heterogeneous landscape shaped by pronounced altitudinal, climatic, and geomorphological gradients. Its physical environment includes the High Atlas and Anti-Atlas mountain ranges, extensive desert plains, rocky plateaus, alluvial valleys, palm groves, and oasis agroecosystems. Major river valleys, particularly those of the Ziz, Drâa, and Ghéris, support localized irrigated agriculture and densely vegetated oasis systems within an otherwise predominantly arid environment. This marked environmental heterogeneity generates substantial spatial variation in vegetation composition, water availability, land use, and human settlement patterns, providing a particularly suitable setting for investigating geographical variation in ethnobotanical knowledge and medicinal-plant use.

The climate of the region is predominantly arid to hyper-arid, characterized by prolonged, hot summers and cold winters, particularly at higher elevations in the mountainous areas. Annual precipitation is generally scarce and highly variable, ranging from less than 100 mm in desert areas to approximately 250 mm at higher elevations, while summer temperatures frequently exceed 40°C (Ben Salem & El Alami El Filali 2024). High evapotranspiration rates, coupled with the irregular and limited distribution of rainfall, contribute to persistent water scarcity and exert a strong influence on vegetation distribution and composition.

Despite these challenging environmental conditions, the region supports a distinctive and diverse flora comprising species and plant communities well adapted to prolonged drought and water stress (Mohamed et al 2026). The vegetation is primarily composed of xerophytic shrubs, steppe communities, desert grasses, and oasis agroecosystems dominated by date palms (*Phoenix dactylifera*). Aromatic and medicinal plants, including rosemary (*Rosmarinus officinalis*), thyme (*Origanum compactum*), lavender (*Lavandula multifida*), and henna (*Lawsonia inermis*), are widely distributed and have a long-standing history of use in traditional medicine (Eddouks *et al.* 2020). The interplay between environmental heterogeneity, drought-adapted plant diversity, and deeply rooted ethnobotanical practices makes the Drâa-Tafilalet region a particularly suitable setting for investigating the traditional use of medicinal plants in the management of leishmaniasis.

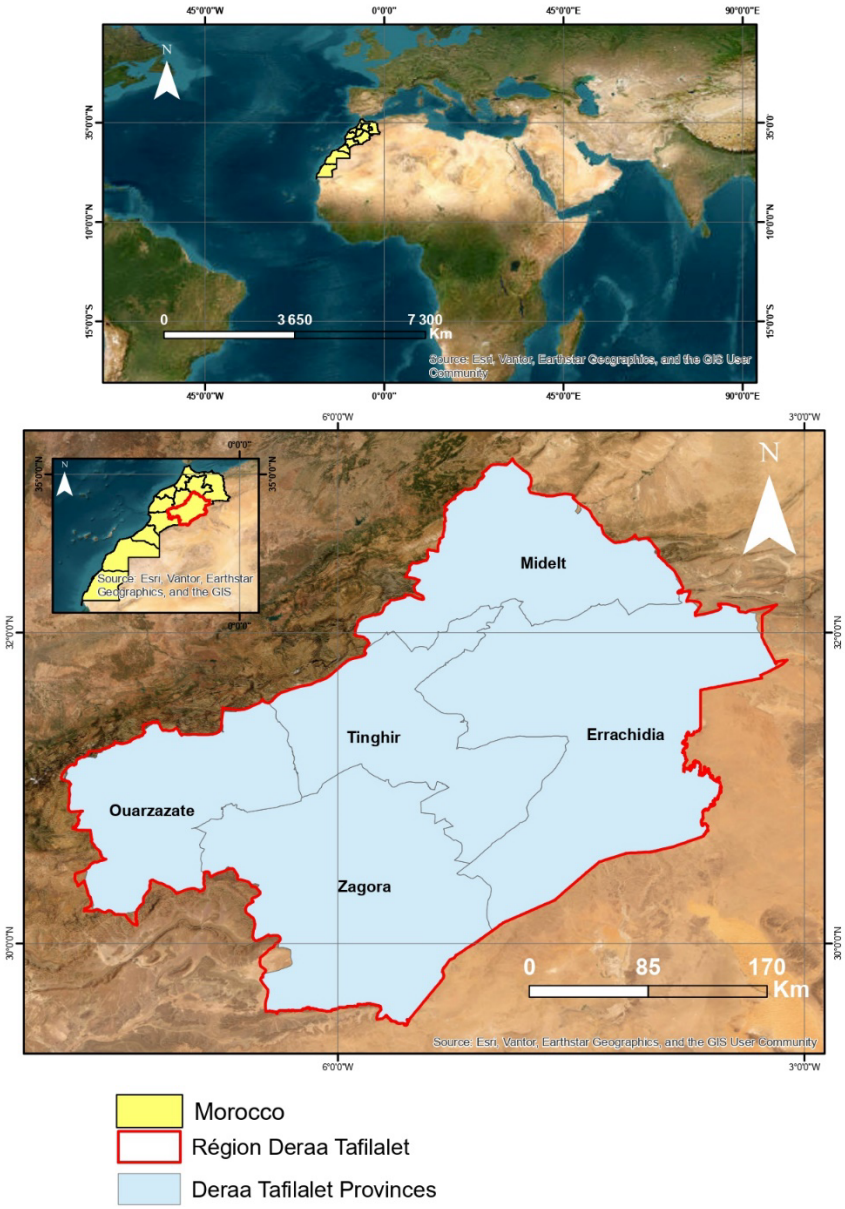

Figure 1. Drâa-Tafilalet region and its provinces in southeastern Morocco

Preparation of the questionnaire

The questionnaire was developed following established ethnobotanical survey protocols and tailored to document traditional medicinal knowledge related to leishmaniasis (Asante-Kwatia *et al.* 2023, Bouzabata *et al.* 2024). This approach ensured methodological consistency and facilitated comparison with previous ethnobotanical studies. It comprised structured and open-ended questions covering sociodemographic characteristics, medicinal plant knowledge, and therapeutic practices, thereby enabling both standardized data collection and documentation of culturally specific information. Participants were asked to report vernacular plant names, treated ailments, plant parts used, and preparation and administration methods, including decoction, infusion, powder, and fumigation (bkhour), to characterize medicinal practices comprehensively. Questions were formulated to ensure comparability among respondents while allowing detailed descriptions of traditional practices. The questionnaire was subsequently reviewed and refined before field implementation to minimize ambiguity, improve response consistency, and ensure completeness of the collected information.

A purposive sampling strategy was employed to recruit participants from selected localities of the Drâa-Tafilalet region because individuals with relevant knowledge of traditional medicinal practices were the primary target population. Participants were eligible if they resided in the study area and possessed knowledge or experience concerning medicinal plant use, thereby increasing the likelihood of obtaining reliable ethnobotanical information. Recruitment across the selected

localities improved the geographical representation of local knowledge. Participant availability and eligibility determined the final sample, while the inclusion of 174 respondents provided a sufficiently broad representation of ethnobotanical knowledge for subsequent analysis.

Collection of Sociodemographic Data

Sociodemographic data were collected through face-to-face interviews using the standardized questionnaire. Before each interview, study objectives and data use were explained, followed by verbally informed consent. Participation was voluntary, with confidentiality and anonymity maintained to encourage reliable responses. Variables included gender, age, marital status, education, occupation, and residence, selected because they may influence the acquisition, transmission, and retention of traditional medicinal knowledge. Gender was classified as men or women to assess potential differences in knowledge. Age was grouped into ≤22, 23-38, 39-54, and ≥55 years to examine intergenerational patterns. Marital status (single, married, divorced) reflected potential household influences, while education (illiterate, primary, secondary, higher) assessed the role of formal schooling. Occupation (employed, unemployed, retired) enabled socioeconomic comparisons, and residence captured geographical variation.

Medicinal plants

Ethnobotanical Data Collection

Ethnobotanical information was obtained through face-to-face, semi-structured interviews with volunteer participants from the selected provinces of the Drâa-Tafilalet region. This approach was chosen because direct interaction facilitates clarification of vernacular terminology, reconstruction of preparation practices, and documentation of knowledge that may not be captured by closed questions. Interviews followed a standardized sequence to ensure comparability among respondents while retaining flexibility to record locally specific information.

Following the introductory questions, participants were first asked whether they recognized or used medicinal plants for treating health conditions. This screening question established their level of familiarity and determined whether the subsequent detailed questions were applicable. Respondents who reported relevant knowledge were then asked to identify the medicinal plants by vernacular name, followed by questions concerning the ailments treated, to establish the therapeutic relevance of each species. For every reported plant-ailment association, information was subsequently recorded on the plant part used (e.g., leaves, flowers, fruits, seeds, roots, or whole plant), because different organs may have distinct medicinal applications and harvesting implications. Participants were then asked about preparation methods (e.g., decoction, infusion, powder, or fumigation [bkhour]) and administration routes, allowing characterization of how remedies were traditionally prepared and used. Where applicable, additional information on the source or availability of the plant was recorded.

Data quality was controlled at three stages. Immediately after each interview, questionnaires were checked for missing responses, ambiguous entries, and internal inconsistencies. Unclear vernacular names or contradictory responses were revisited with participants during the same or subsequent encounters whenever feasible. Plant names were cross-checked against published floristic references and, where necessary, verified through repeated interviews to minimize identification errors. Finally, validated responses were assigned standardized codes and entered into a digital database, with entries checked against the original questionnaires to detect transcription or coding errors before statistical analysis.

Calculation of Ethnobotanical Indices

Three complementary indices were calculated to quantify the ethnobotanical importance of the reported medicinal plants. Frequency of Citation (FC) was defined as the number of respondents who independently reported using a given species, providing a direct measure of its prevalence within local medicinal knowledge. Relative Frequency of Citation (RFC) was calculated as $RFC = FC/N$, where N is the total number of respondents, thereby standardizing citation frequency and enabling comparisons among species. Use Value (UV) was calculated as $UV = \Sigma U/N$, where ΣU represents the total number of use reports recorded for each species. These indices were selected to characterize both the prevalence and relative importance of medicinal plants. Because each respondent reported only one use per species in the present dataset, ΣU was equivalent to FC; consequently, UV and RFC yielded identical values. This equivalence reflects the structure of the collected data rather than redundancy in the calculations.

Data analysis

Categorical variables describing participants' sociodemographic characteristics, habitation zone (urban, suburban, and rural), medicinal-plant knowledge (yes/no), ability to nominate medicinal species (yes/no), plant parts used, and preparation modes were summarized as frequencies and percentages. Associations between categorical variables were assessed using Pearson's

chi-square (χ^2) test, selected because it evaluates whether observed frequencies differ significantly from those expected under independence. We set statistical significance at $p < 0.05$.

To identify similarities in medicinal-plant utilization among sampled provinces, a hierarchical clustering heatmap was generated using the reported plant parts, preparation modes, and number of medicinal species. Ward's minimum-variance method with Euclidean distance was used to group localities with similar ethnomedicinal profiles. Simultaneous row and column clustering helped identify geographic patterns and associations among utilization variables.

A Correspondence Analysis (CA) was conducted to examine associations between provinces and respondents' sociodemographic characteristics (gender, age class, education, occupation, and marital status). CA was selected because it is specifically suited to contingency tables containing categorical variables and provides a low-dimensional representation of their associations. Eigenvalues, inertia, and the percentage of variance explained by each dimension were calculated.

The spatial distribution of respondents was assessed in QGIS 3.40 by aggregating participants according to province and habitation zone. Graduated-symbol maps and kernel density estimation were used to visualize sampling coverage and areas of greater participant concentration, providing a spatial assessment of survey representation.

Finally, ethnobotanical importance was evaluated using PCA followed by K-means clustering based on standardized FC, RFC, and UV values. PCA reduced dimensionality and identified major patterns of variation, whereas K-means classified species into homogeneous groups. The optimal cluster number was determined using silhouette analysis. Statistical analyses were conducted in SPSS 25.0 and Python 3.12, while graphical outputs were produced using GraphPad Prism 5.3.8 and Python libraries (Scikit-learn, NumPy, Pandas, and Matplotlib).

Results and Discussion

Sociodemographic features of participants

In the Draa-Tafilalet region, the socio-demographic profile of the respondents revealed clear differences according to gender and age (Table 1). Women constituted most participants, accounting for 58.62% of the sample, whereas men represented 41.32% (Table 1). Age distribution showed that the youngest respondents (≤22 years) and those aged 23-38 years were equally the most represented, each contributing 44% of the study population. By contrast, the intermediate age category (39-54 years) and the oldest group (>55 years) each accounted for only 6%, demonstrating a significantly lower representation. On the other hand, the Correspondence Analysis showed a geographical disparity in participants' age. Respondents from Tinghir, Rissani, Midelt, and Arfoud were predominantly 23-38 years old, whereas participants from Errachidia, Goulmima, and Zagora were mainly ≤22 years old. In contrast, Tinejdad was distinguished by a predominance of older respondents (39-54 years and >55 years).

Marital status and occupational characteristics further highlighted the predominance of economically active young adults in the study area. Single participants represented 77% of the respondents, substantially exceeding married individuals (20%) and divorced participants (3%). Similarly, economically active individuals constituted 81.6% of the sample, whereas unemployed respondents accounted for only 18.4%, and no retired participants were recorded.

Educational attainment was generally high among respondents, with 78% reporting higher education, considerably exceeding the proportions with secondary level (10%), no formal education (7%), or primary education (5%). However, Correspondence Analysis showed notable spatial differences among sampled sites.

Participants from Tinghir, Zagora, Midelt, Rissani, Arfoud, and Ouarzazate were predominantly university-educated. In comparison, respondents from Goulmima exhibited a mixed educational profile, with primary and secondary education being the most common. Conversely, Tinejdad differed markedly from the other cities, as illiteracy represented the dominant educational status.

Table 1. Sociodemographic features of participants from Deraa-Tafilalte (* denotes statistically different at p<0.05: *<**<***)

Sociodemographic Parameter	Category	Number of Participants (n)	Percentage (%)
Gender	Men	72	41.38*
	Women	102	58.62**
Age (years)	≤22	77	44.25**
	23-38	76	43.68**
	39-54	11	6.32*
	≥55	10	5.75*
Marital Status	Single	134	77.01***
	Married	35	20.11**
	Divorced	5	2.87*
Education Level	Primary	9	5.17*
	Secondary	18	10.34**
	Higher education	137	78.74***
	Illiterate (No formal education)	10	5.75*
Occupation	Retired	0	0*
	Employed (Economically active)	142	81.61***
	Unemployed	32	18.39**

The three-dimensional Correspondence Analysis (CA) revealed clear associations between cities and respondents' sociodemographic characteristics, with the first three axes explaining 64.7%, 22.7%, and 7.0% of the total inertia, respectively (94.4% cumulative) (Figure 2). Tinghir was strongly associated with higher education, respondents aged 23-38 years, and unemployed individuals, whereas Tinejdad and Goulmima were closely related to married, non-schooled, and older respondents. Further, Er-Rachidia was positioned near the ≤22-year age group, indicating a younger respondent profile. In contrast, Midelt, Arfoud, Rissani, Ouarzazate, and Zagoura occupied intermediate positions, reflecting more balanced sociodemographic characteristics without a strong association with any specific variable.

Sociodemographic characteristics are recognized as key determinants of health-seeking behavior, knowledge transmission, and the selection of medicinal plants for leishmaniasis management. In the present study, women were more represented than men, while young respondents (≤22 and 23-38 years) were equally represented. Most participants were single, economically active, and highly educated. Correspondence analysis revealed marked geographical heterogeneity, indicating that medicinal-plant knowledge and healthcare practices were not uniformly distributed across the study area but were associated with differences in demographic and socioeconomic profiles among localities.

Comparable geographical and demographic variations have been reported in previous Moroccan investigations, although these studies were generally restricted to a limited number of localities and participants. In Sefrou, Zùeouk *et al.* (2020) interviewed only 16 traditional herbalists, who were predominantly male (87.5%), older than 60 years (43.8%), and largely illiterate (56.3%), contrasting sharply with our younger and highly educated population. Similarly, El-Mouhdi *et al.* (2023) surveyed 14 cutaneous leishmaniasis patients from El Hajeb Province, where participants were mainly men (57.1%), aged 18-64 years (mean 49 years), and predominantly rural residents (78.6%), all of whom initially relied on traditional remedies before seeking medical care. At a broader spatial scale, Fellah *et al.* (2020) demonstrated that poverty significantly influenced the distribution of cutaneous leishmaniasis in Moulay Yacoub Province, highlighting the importance of socioeconomic inequalities in disease epidemiology and access to healthcare. Similar contrasts have been reported in Algeria: Amari *et al.* (2021) found a predominance of women (68%) among 100 inhabitants of Ain Sekhouna, whereas Bouzabata *et al.* (2024) recorded a predominantly male population (95.2%) among 21 herbalists from Annaba and El Tarf, with a mean age of 53.4 years and extensive professional experience. These differences suggest that ethnomedicinal knowledge is strongly context-dependent and shaped by locality, occupation, age structure, and access to formal healthcare rather than reflecting a uniform regional tradition.

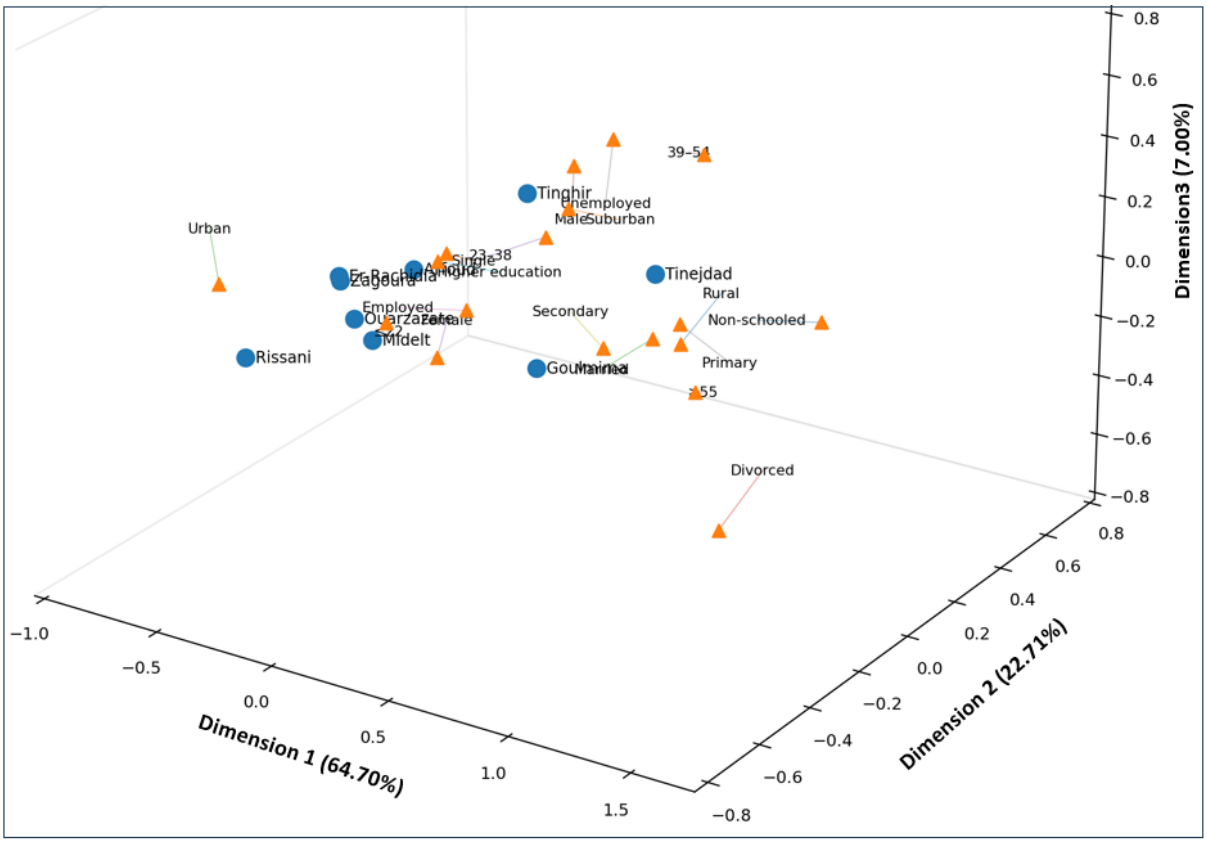

Figure 2. 3-dimensional Correspondence Analysis (CA) of associations between sociodemographic features and sampled provinces.

This investigation extends previous research in several important ways. Unlike earlier Moroccan and Algerian studies, which focused on single cities, provinces, or specific groups such as herbalists or patients, this survey covered multiple provinces across the Drâa-Tafilalet region, providing a broader spatial representation of the local population. The integration of GIS-based mapping with correspondence analysis enabled visualization of geographical differences in sociodemographic characteristics and their relationship with medicinal-plant knowledge and utilization, while machine-learning approaches helped identify the relative contribution of these variables. Such spatial heterogeneity has important implications for both biodiversity conservation and traditional healthcare: locally preferred medicinal species may experience uneven harvesting pressure, requiring conservation strategies that consider differences in demand and availability among localities. At the same time, documenting geographically concentrated knowledge is essential for preserving traditional therapeutic practices and identifying communities where knowledge transmission may be vulnerable. This multidisciplinary framework therefore provides a more comprehensive understanding of how demographic, educational, and socioeconomic factors shape traditional leishmaniasis management in underserved regions where access to conventional antileishmanial treatment may remain constrained by economic and geographic barriers.

Habitation of participants

The distribution of participants according to habitat type in the Draa-Tafilalet region showed a nearly balanced pattern across the three residential settings (Figure 3). Suburban residents constituted the largest proportion of respondents (34%), only slightly exceeding those living in rural and urban areas, each representing 33% of the study population. The minimal difference among these categories indicates that the survey achieved a relatively even representation of participants from different living environments.

The correspondence Analysis of results showed more pronounced geographical variations among sampled cities. Participants from Goulmima and Tinejdad were predominantly from rural areas, whereas those from Tinghir mainly resided in suburban settings. In contrast, respondents from Errachidia, Rissani, Midelt, Arfoud, Ouarzazate, and Zagora were primarily urban residents.

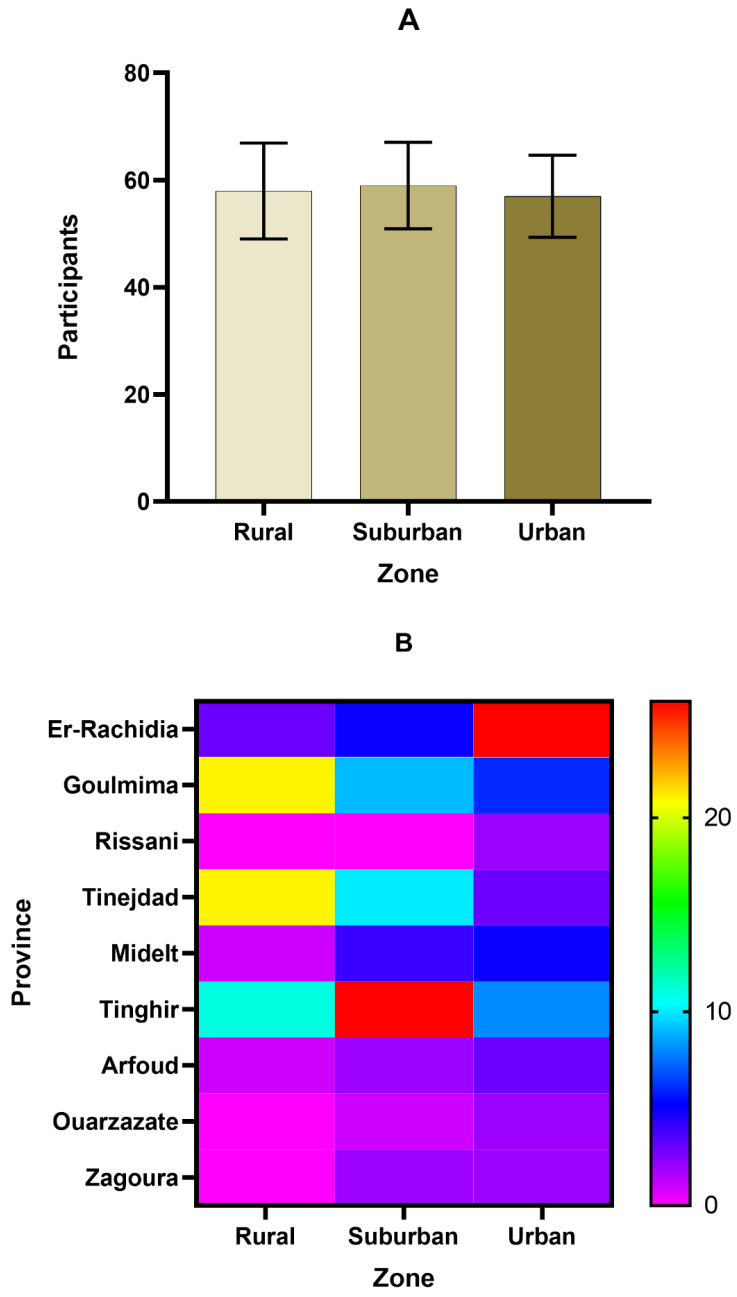

Figure 3:.Habitation zone of sampled participants in Deraa-Tafilalte (A: Comparison between zones, B: heatmap of habitation zones in sampled provinces).

The residential environment constitutes an important ecological determinant of leishmaniasis transmission because it mediates interactions among human populations, sand fly vectors, reservoir hosts, vegetation, and land-use conditions (Borges *et al.* 2022; Khosravi *et al.* 2025). The geographical differentiation observed across the Drâa-Tafilalet region is therefore likely to reflect contrasting ecological and socioeconomic contexts rather than a simple rural-urban gradient. Rural predominance in Goulmima and Tinejdad may be associated with oasis agriculture, dispersed settlements, livestock husbandry, and closer contact with natural or peridomestic habitats that can support vector and reservoir populations. In contrast, the stronger urban orientation of Errachidia, Rissani, Midelt, Arfoud, Ouarzazate, and Zagora may reflect population concentration, infrastructure development, and progressive transformation of natural habitats. Tinghir's intermediate suburban configuration may represent a transitional landscape in which agricultural, peri-domestic, and urban environments coexist. Such landscape contrasts can modify not only exposure to vectors but also the availability, accessibility, and use of medicinal plants, potentially contributing to the spatial structuring of traditional healthcare knowledge.

These observations are broadly compatible with previous Moroccan studies showing that leishmaniasis transmission responds differently to environmental contexts. Visceral leishmaniasis has historically been associated with rural environments, although urban expansion can progressively create suitable conditions for transmission (Kahime *et al.* 2017). Similarly, associations between cutaneous leishmaniasis and urbanization have been documented in central Morocco and Sefrou Province (El Omari *et al.* 2020; Talbi *et al.* 2020), whereas Amane *et al.* (2022) reported substantially greater risk of anthroponotic cutaneous leishmaniasis among rural populations. Rather than being contradictory, these findings emphasize that residence alone is unlikely to determine transmission risk; its effect depends on vector ecology, host availability, housing characteristics, environmental disturbance, and human mobility. The spatial patterns identified here consequently support a landscape-based interpretation in which different localities may combine distinct ecological pressures and healthcare practices.

The broader geographical coverage of the present investigation provides an opportunity to move beyond single-focus interpretations and examine how traditional healthcare practices respond to heterogeneous southeastern Moroccan environments. Integrating spatial and multivariate approaches helps identify locality-specific contexts in which medicinal-plant knowledge is maintained, transformed, or potentially lost. From a conservation perspective, this heterogeneity suggests that medicinal-plant management should be geographically targeted, particularly where frequently used species coincide with habitat degradation or increasing harvesting pressure. From a public-health perspective, recognizing these spatially differentiated practices can facilitate culturally appropriate leishmaniasis interventions that complement, rather than replace, conventional prevention and treatment.

Knowledge of medicinal plants

Knowledge

Figure 4A illustrates the distribution of participants according to their knowledge of medicinal plants in the Draa-Tafilalet region. The results indicate that most respondents (59%) reported not knowing medicinal plants. In contrast, 41% of the participants stated that they were familiar with medicinal plants.

Figure 4B further presents the distribution of respondents based on their ability to identify or cite medicinal plants. A higher proportion of participants (64%) were unable to name any medicinal plants, whereas only 36% were able to cite at least one medicinal plant. These findings indicate that the proportion of respondents lacking practical knowledge of medicinal plants was greater than the proportion of those who could identify or report specific medicinal plant species.

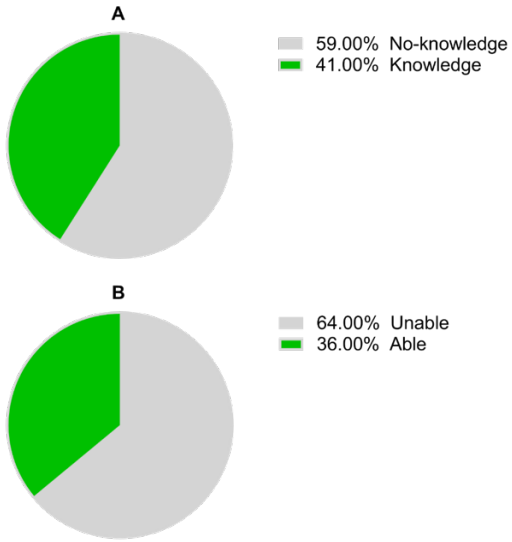

Figure 4. Knowledge of medicinal plants among participants (A: Comparison of knowledge in medicinal plants, B: Ability to name used medicinal plants).

Medicinal plants have constituted an essential component of Moroccan traditional medicine for centuries, with knowledge being transmitted across generations and remaining particularly important in the management of infectious and parasitic diseases (Elachouri 2018, Merrouni *et al.* 2021). In the present study, however, 59% of respondents reported not knowing medicinal plants, and an even greater proportion (64%) were unable to identify a single medicinal species. These findings

may reflect the predominance of young participants in our survey, despite their generally high educational level, suggesting that formal education does not necessarily ensure the preservation of traditional ethnobotanical knowledge, which is mainly acquired through family and community experience (Bouyahya *et al.* 2017, Kachmar *et al.* 2021, El-Mernissi *et al.* 2023).

Previous Moroccan studies have extensively documented the diversity and traditional uses of medicinal plants (Bouyahya *et al.* 2017, Balahbib *et al.* 2020, Merrouni *et al.* 2021, El-Mouhdi *et al.* 2023), but only one investigation specifically assessed community knowledge of leishmaniasis and medicinal plants. In central Morocco, (Mounia *et al.* 2022) evaluated knowledge, attitudes, and practices in a single endemic area, whereas our study provides the first regional-scale assessment across the entire Draa-Tafilalet region, encompassing both rural and urban communities. This broad geographical coverage offers a more representative understanding of the spatial variability of medicinal plant knowledge and establishes a valuable baseline for future ethnobotanical conservation and public health initiatives.

Use of medicinal plants

Diversity of medicinal plants

In sampled provinces of the Drâa-Tafilalet region, Errachidia exhibited the highest richness with 36 species (29.03%), followed by Goulmima (26; 20.97%), Tinghir (24; 19.35%), and Tinejdad (21; 16.94%). Midelt accounted for 11 species (8.87%), whereas Zagoura (4; 3.23%) and Arfoud (2; 1.61%) contributed marginally (Figure 5). No medicinal plants were recorded in Erissani (0%), indicating pronounced spatial variation in medicinal plant diversity across the surveyed provinces.

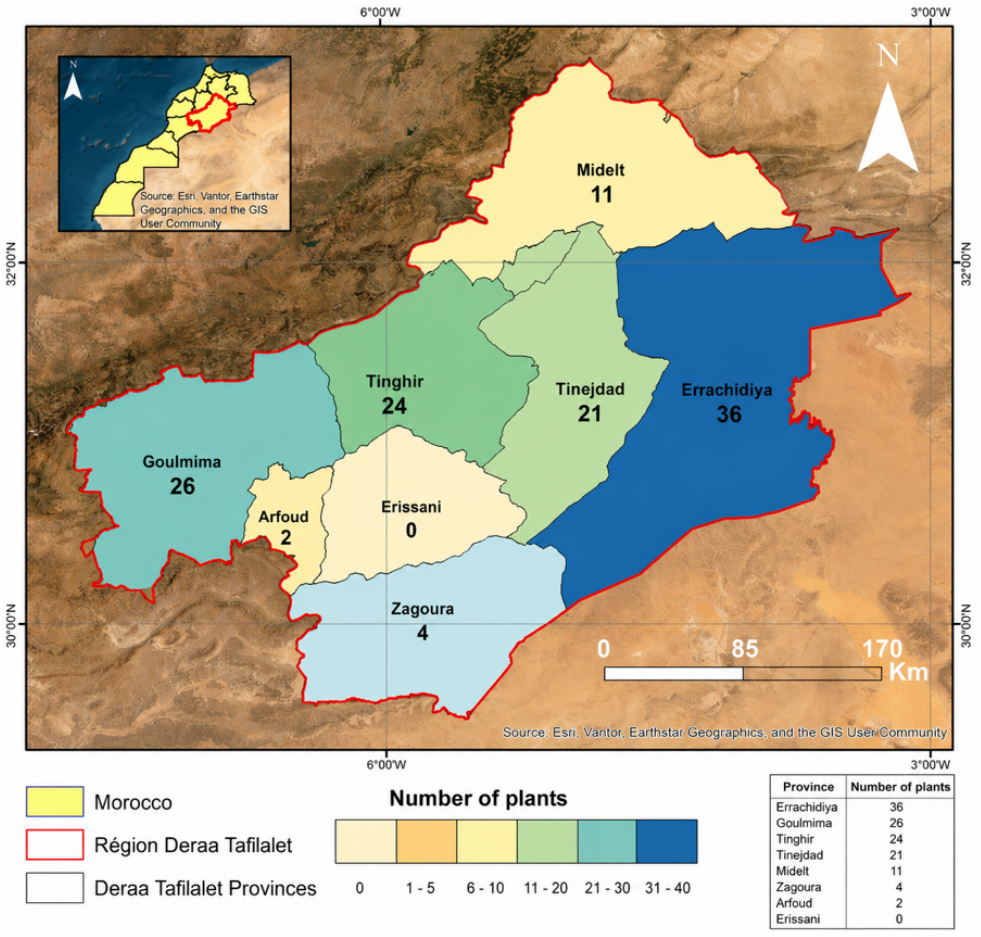

Figure 5. Mapping of recorded medicinal plants in sampled provinces of Deraa-Tafilalte

The ethnobotanical survey documented a diverse range of medicinal plants used by the respondents, although citation frequencies varied considerably among species. *Rosmarinus officinalis* exhibited the highest ethnobotanical importance (FC = 18; RFC = UV = 0.36), followed by *Lawsonia inermis* (FC = 12; RFC = 0.24), *Origanum compactum* (FC = 8; RFC = 0.16), and both *Lavandula multifida* and *Mentha pulegium* (FC = 6; RFC = 0.12) (Table 2).

Conversely, numerous species showed low citation frequencies (RFC = 0.02-0.08), suggesting localized or occasional use. Several plants, including *Pinus sylvestris*, *Lippia citriodora*, *Juniperus thurifera* var. *africana*, *Citrullus colocynthis*, and *Glycyrrhiza glabra*, were not reported by any respondent, indicating either limited local knowledge or infrequent therapeutic application. Overall, the distribution of FC, RFC, and UV values reveals that only a few species dominate traditional medicinal practices, whereas many others are retained as complementary remedies with relatively low cultural prominence (Table 2).

Table 2. Frequency of Citation (FC), Relative Frequency of Citation (RFC), and Use Value (UV) of medicinal plants reported by respondents.

Vernacular name	**Scientific name**	**FC**	**RFC**	**UV***
Saffron	*Crocus sativus* L.	5	0.1	0.1
Henna / Black henna	*Lawsonia inermis* L.	13	0.26	0.26
Thyme	*Origanum compactum* Benth.	8	0.16	0.16
Lavender	*Lavandula multifida* L.	6	0.12	0.12
Rose	*Rosa* spp.	2	0.04	0.04
Bay laurel	*Laurus nobilis* L.	3	0.06	0.06
Rosemary	*Salvia rosmarinus* Spenn.	18	0.36	0.36
Fennel	*Foeniculum vulgare* Mill.	1	0.02	0.02
Hibiscus	*Hibiscus sabdariffa* L.	1	0.02	0.02
Onion / Onion seed	*Allium cepa* L.	3	0.06	0.06
Eucalyptus	*Eucalyptus* spp.	2	0.04	0.04
Cinnamon	*Cinnamomum verum* J.Presl	1	0.02	0.02
Cactus	*Opuntia ficus-indica* (L.) Mill.	1	0.02	0.02
Olive	*Olea europaea* L.	5	0.1	0.1
Pennyroyal	*Mentha pulegium* L.	6	0.12	0.12
White horehound	*Marrubium vulgare* L.	2	0.04	0.04
Carob	*Ceratonia siliqua* L.	1	0.02	0.02
Chamomile	*Anthemis stiparum* Pomel	1	0.02	0.02
Mexican tea	*Dysphania ambrosioides (*L.) Mosyakin & Clemants	2	0.04	0.04
Basil / Sweet basil	*Ocimum basilicum* L.	5	0.1	0.1
Anise	*Pimpinella* anisum L.	1	0.02	0.02
Tar	Not identified	3	0.06	0.06
Parsley	*Petroselinum crispum* (Mill.) Fuss	1	0.02	0.02
Woolly cumin	*Matricaria chamomilla* L. or *Anthemis* spp.	4	0.08	0.08
Heather	*Erica* spp.	1	0.02	0.02
Nettle	*Urtica dioica* L.	1	0.02	0.02
Sage	*Salvia officinalis* L.	3	0.06	0.06
Oak moss	*Evernia prunastri* (L.) Ach.	2	0.04	0.04
Garden cress	*Lepidium sativum* L.	1	0.02	0.02
Flax seed	*Not identified*	1	0.02	0.02
Zygophyllum	Tetraena gaetula (Emb. & Maire) Beier & Thulin	1	0.02	0.02
Stone breaker	Not identified	1	0.02	0.02
Harmal	*Peganum harmala* L.	1	0.02	0.02
Cowherb	*Gypsophila vaccaria* (Mill.) Rchb.	1	0.02	0.02
Garlic	*Allium sativum* L.	2	0.04	0.04
Apple mint	*Mentha suaveolens* Ehrh.	1	0.02	0.02
Wild basil	Not identified	4	0.08	0.08
Inula	*Dittrichia viscosa* (L.) Greuter	1	0.02	0.02
Ash	Not identified	4	0.08	0.08
Alfalfa	*Medicago sativa* L.	1	0.02	0.02
Tea	*Camellia sinensis* (L.) Kuntze	2	0.04	0.04
Clove	Syzygium aromaticum (L.) Merr. & L.M.Perry	4	0.08	0.08
Night-blooming jasmine	*Cestrum nocturnum* L.	1	0.02	0.02

Apricot leaves	*Prunus armeniaca* L.	1	0.02	0.02
Corrigiola telephiifolia	*Corrigiola telephiifolia* Pourr.	1	0.02	0.02
Ginger	*Zingiber officinale* Roscoe	2	0.04	0.04
Black pepper	*Piper nigrum* L.	1	0.02	0.02

The correspondence analysis (Figure 6) further highlighted spatial variation in medicinal plant utilization. Midelt was mainly associated with species such as *Allium cepa*, *Cactus* spp., *Foeniculum vulgare*, *Hibiscus sabdariffa*, and *Cinnamomum zeylanicum*. Errachidia was characterized by the use of *Lippia citriodora*, *Eucalyptus* spp., *Glycyrrhiza glabra*, *Salvia officinalis*, *Zingiber officinale*, *Citrullus colocynthis*, *Petroselinum crispum*, *Ocimum basilicum*, *Rosmarinus officinalis*, *Lepidium sativum*, and *Mentha pulegium*. Tinejdad and Zagora were associated with *Chenopodium ambrosioides*, *Pimpinella anisum*, *Lawsonia inermis*, *Zygophyllum gaetulum*, *Marrubium vulgare*, *Piper nigrum*, *Peganum harmala*, *Lavandula multifida*, *Pinus sylvestris*, *Cestrum nocturnum*, *Camellia* spp. (Theaceae), and oak moss. Tinghir was characterized by *Crocus sativus*, *Laurus nobilis*, *Rosa* spp., *Apis mellifera* products, *Origanum compactum*, heather, chamomile, and *Juniperus thurifera* var. *africana*. Conversely, Rissani, Goulmima, and Arfoud were associated with a distinct group of traditional remedies, including sulfur, acetic acid, *Anthemis stiparum*, *Dittrichia viscosa*, *Lawsonia inermis*, and *Olea europaea*, reflecting clear geographic differences in ethnomedicinal practices across the region.

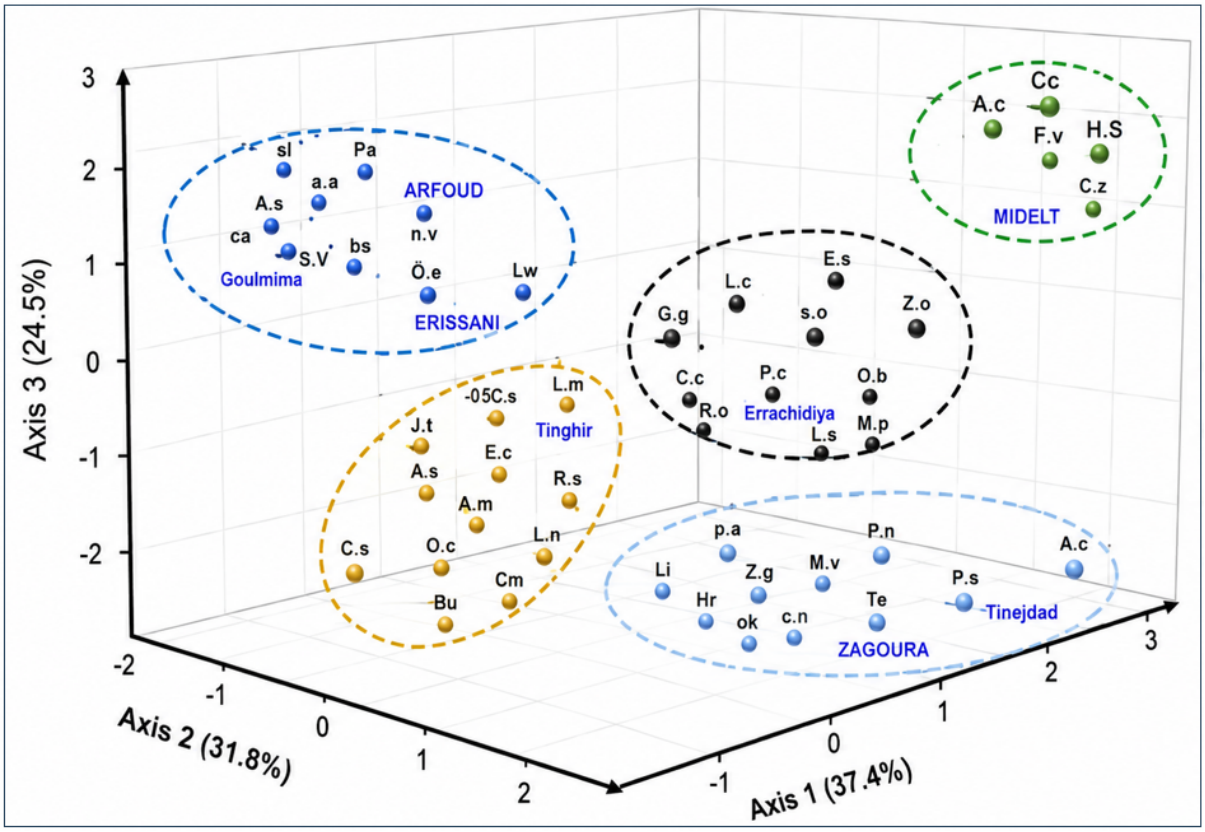

Figure 6. 2D plot of correspondence analysis showing the associations between provinces and recorded medicinal plants (C.s: *Crocus sativus*; L.i: *Lawsonia inermis*; O.c: *Origanum compactum*; L.m: *Lavandula multifida*; L.n: *Laurus nobilis*; S.r: *Salvia Rosmarinus*; F.v: *Foeniculum vulgare*; H.s: *Hibiscus sabdariffa*; A.c: *Allium cepa*; C.z: *Cinnamomum zeylanicum*; O.e: *Olea europaea*; M.p: *Mentha pulegium*; M.v: *Marrubium vulgare*; C.s: *Ceratonia siliqua*; A.s: *Anthemis stiparum*; A.c: *Aloysia citrodora*; D.a: *Dysphania ambrosioides*; O.b: *Ocimum basilicum*; P.a: *Pimpinella anisum*; J.t: *Juniperus thurifera*; C.c: *Citrullus colocynthis*; P.c: *Petroselinum crispum*; S.o: *Salvia officinalis*; L.s: *Lepidium sativum*; Z.g: *Zygophyllum gaetulum*; P.h: *Peganum harmala*; V.h: *Vaccaria hispanica*; A.s: *Allium sativum*; D.v: *Dittrichia viscosa*; G.g: *Glycyrrhiza glabra*; S.a: *Syzygium aromaticum*; C.n: *Cestrum nocturnum*; P.a: *Prunus armeniaca*; Z.o: *Zingiber officinale*; P.n: *Piper nigrum*)

The diversity of medicinal plants documented across the Drâa-Tafilalet region reflects a heterogeneous ethnobotanical landscape in which plant selection is likely shaped by ecological availability, cultural transmission, market access, and local healthcare conditions. The pronounced geographical differentiation in plant use suggests that ethnomedicinal knowledge is not spatially homogeneous, but instead responds to differences in vegetation structure, oasis environments, agricultural

practices, and accessibility to medicinal resources. The concentration of citations in some localities may therefore reflect both greater availability of culturally valued species and stronger continuity of traditional knowledge, whereas limited documentation elsewhere may indicate urbanization, reduced plant accessibility, changing therapeutic preferences, or weaker intergenerational transmission. Such spatial variation is particularly relevant in an arid region where environmental fragmentation and increasing pressure on natural resources can influence the persistence of medicinal flora and associated knowledge.

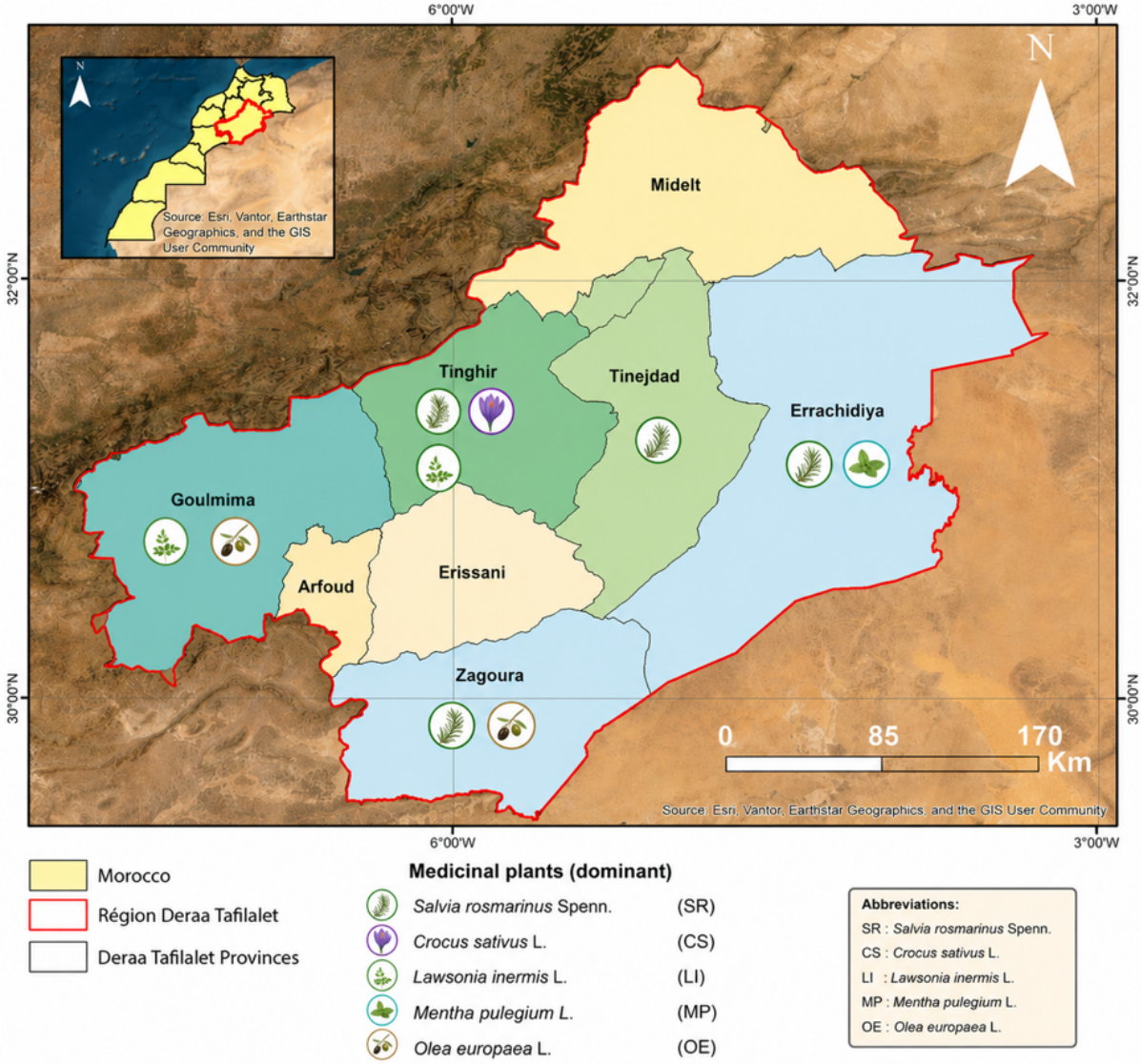

Figure 7. Mapping of dominant medicinal plants in sampled provinces in Morocco

The recurrence of species such as *Lawsonia inermis*, *Salvia rosmarinus*, *Origanum compactum*, *Lavandula multifida*, and *Mentha pulegium* across the region is consistent with Moroccan ethnobotanical studies showing the importance of these taxa in traditional management of cutaneous leishmaniasis (Zeouk *et al.* 2020; El-Mouhdi *et al.* 2023). Similar patterns have been reported in Algeria, where ethnobotanical surveys have documented substantial medicinal-plant knowledge associated with leishmaniasis management (Amari *et al.* 2021, Bouzabata *et al.* 2024, 2025). Experimental studies reporting antileishmanial activity for several commonly used Moroccan taxa further suggest that traditional selection may partly reflect pharmacological properties, although ethnobotanical frequency should not be interpreted as evidence of clinical efficacy (Bouyahya *et al.* 2017, 2018; Balahbib *et al.* 2020).

The broader spatial coverage of this study extends previous localized investigations by revealing geographical differentiation within southeastern Morocco. From a conservation perspective, these patterns emphasize the need for locality-specific management of medicinal plants, particularly where intensive harvesting coincides with habitat degradation. Preserving

ethnobotanical knowledge alongside plant resources could simultaneously support biodiversity conservation, cultural heritage, and locally accessible healthcare, while providing a rational basis for prioritizing species for pharmacological validation and sustainable utilization.

Machine Learning-Based Classification

The PCA-K-means clustering analysis (Figure 8A) separated the medicinal plants into distinct groups according to their citation characteristics (FC, RFC, and UV). PC1 explained nearly all of the total variance, indicating that citation frequency was the principal factor driving species differentiation. Highly cited species formed a clearly isolated cluster, whereas moderately and rarely cited plants were grouped separately. The limited contribution of PC2 reflects the strong linear relationship among the three ethnobotanical indices, confirming that species importance was primarily determined by citation frequency.

The clustering distinguished three clearly separated groups according to ethnobotanical importance. High-priority species comprised *Salvia rosmarinus*, *Lawsonia inermis*, and *Origanum compactum*, reflecting their dominant traditional use. A second cluster included moderately cited medicinal plants, whereas the largest cluster consisted of rarely mentioned species. This pattern indicates that local medicinal knowledge is concentrated around a limited number of culturally important taxa, while numerous plants are only occasionally reported.

Silhouette analysis demonstrated that partitioning the medicinal plants into two clusters provided the best clustering performance (silhouette score = 0.820) (Figure 8B). The progressive decline in silhouette values for K ≥ 3 suggests increased overlap and reduced cluster compactness. These findings indicate that the medicinal plants are naturally divided into two citation-based groups, corresponding to highly cited and less frequently cited taxa.

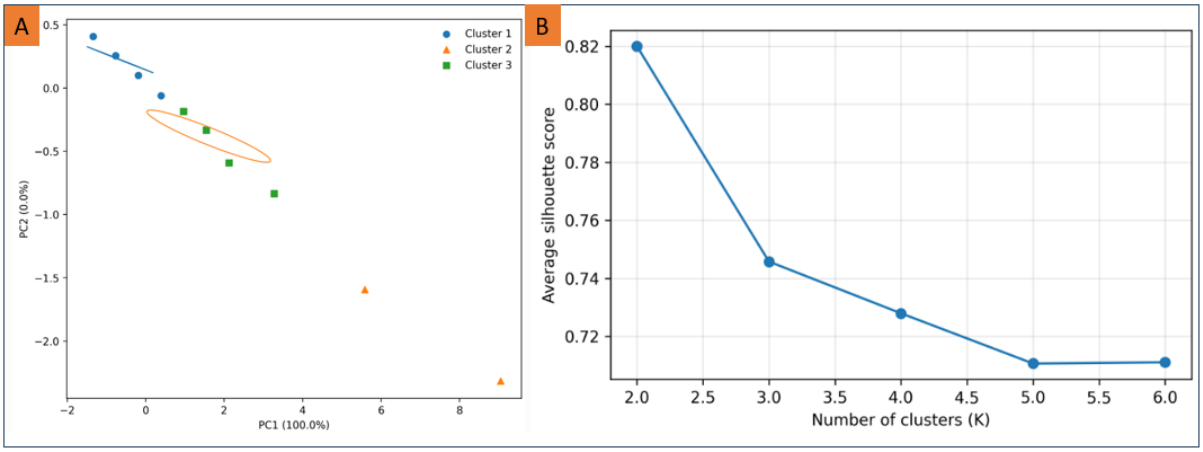

Figure 8. PCA-K-means clustering analysis (A) and Silhouette analysis (B) of medicinal plants according to their citation characteristics (FC, RFC, and UV)

The PCA-K-means clustering results demonstrate that medicinal plant knowledge in the study area is strongly concentrated around a small number of culturally important species. The clear separation of *Salvia rosmarinus*, *Lawsonia inermis*, and *Origanum compactum* reflects their widespread recognition and frequent therapeutic use, consistent with ethnobotanical studies showing that a limited number of species often dominate traditional pharmacopoeias due to their proven efficacy, availability, and long-standing cultural acceptance. The limited contribution of PC2 indicates that FC, RFC, and UV convey largely overlapping information, highlighting citation frequency as the primary determinant of ethnobotanical importance. Likewise, the high silhouette score (0.820) confirms the robustness of the clustering and suggests a natural distinction between highly valued and infrequently cited taxa. Similar machine learning approaches have successfully identified priority medicinal plants and revealed patterns of traditional knowledge in ethnobotanical datasets. These findings provide a quantitative basis for prioritizing culturally significant species for conservation, phytochemical investigation, and sustainable utilization.

Use practices

Plant Parts Used

Figure 9A illustrates the distribution of the different parts of medicinal plants used by participants in the Draa-Tafilalet region. The results indicate that leaves were the most frequently used plant part for treating leishmaniasis and other diseases,

accounting for 40% of all reported uses. Other plant parts ranked second, accounting for 25% of reported uses. In comparison, fruits were used by 20% of the respondents. Flowers and seeds were the least frequently utilized plant parts, accounting for 12% and 3% of the reported uses, respectively.

Use modes

Figure 9B presents the different modes of use of medicinal plants reported by participants in the Draa-Tafilalet region. The recorded preparation methods include decoction, infusion, powder, bkhour (fumigation/incense), and other modes of use. The results show that decoction was the most frequently used method, accounting for 46% of the reported preparations. This was followed by the use of medicinal plants in powdered form, representing 27%. Infusion accounted for 13% of the reported uses, while other preparation methods represented 10%. The least common mode of use was bkhour (fumigation), which accounted for 4% of the reported preparations.

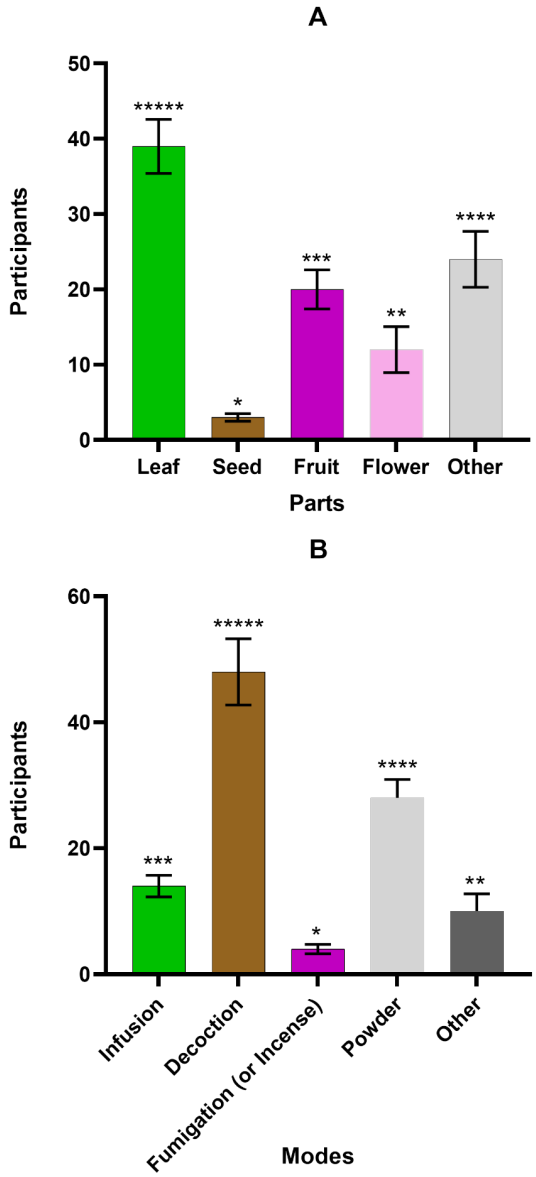

Figure 9:.Used parts (A) and use modes (B) of recorded medicinal plants

The hierarchical clustering heatmap revealed marked geographical variation in the ethnomedicinal practices of the Draa-Tafilalet region (Figure 10). Er-Rachidia and Tinghir formed a closely related cluster, characterized by high numbers of reported medicinal plants, frequent use of leaves, and predominance of decoction and powder preparations. Goulmima and Tinejdad constituted a second cluster with intermediate ethnobotanical diversity, whereas Midelt showed moderate similarity to these

localities. In contrast, Rissani, Arfoud, Ouarzazate, and Zagora clustered together due to their low frequencies of reported medicinal plants and preparation methods, reflecting comparatively limited ethnomedicinal knowledge and utilization.

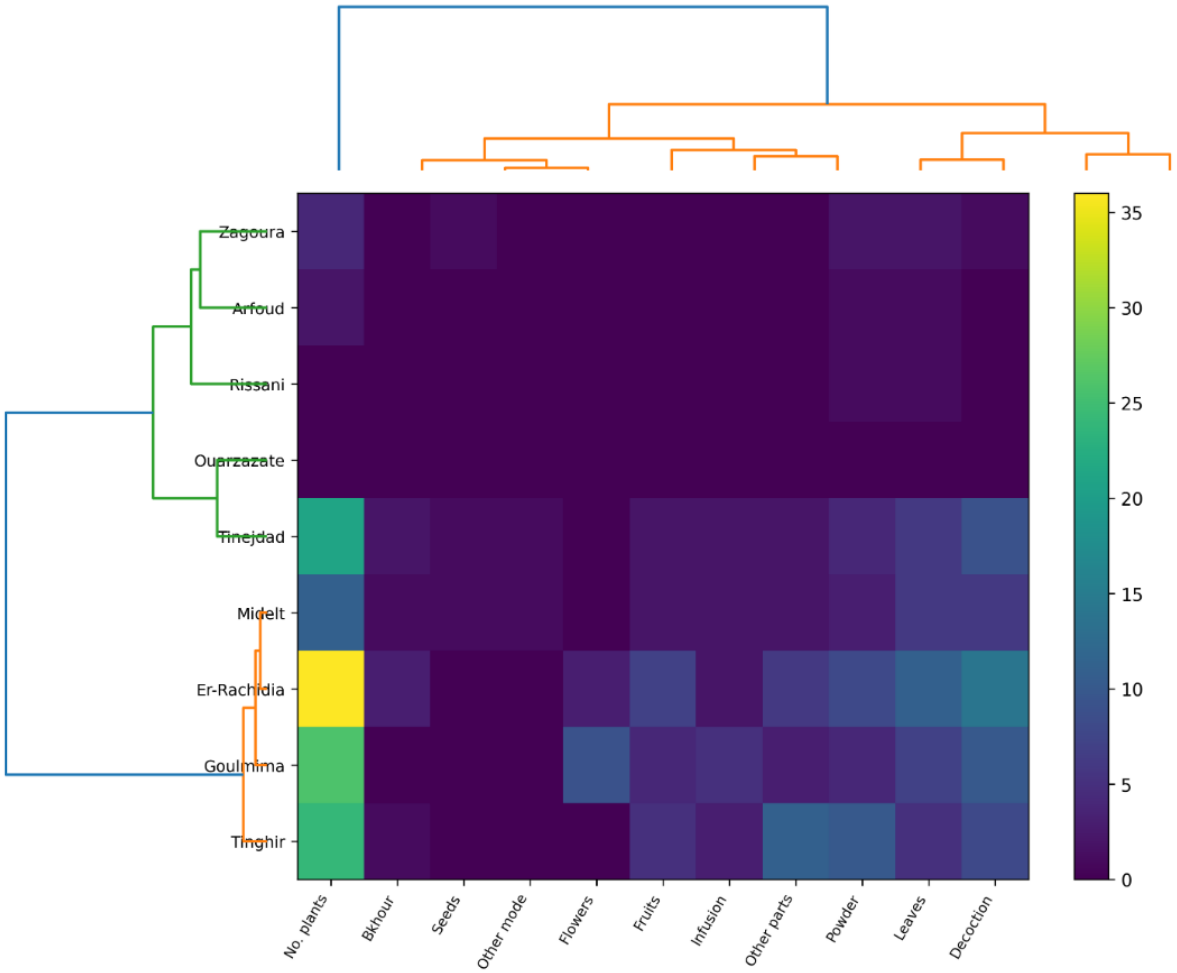

Figure 10. Hierarchical clustering heatmap revealed marked geographical variation in the ethnomedicinal practices of the Draa-Tafilalet region

The preferential use of leaves across Drâa-Tafilalet is consistent with broader Moroccan ethnobotanical patterns (Bouyahya *et al.* 2017; Haouari *et al.* 2018; Kachmar *et al.* 2021; Merrouni *et al.* 2021; Chaachouay *et al.* 2022; El-Mernissi *et al.* 2023). This pattern likely reflects the ecological accessibility and continuous regeneration of foliage, particularly within the region's oasis agroecosystems, where irrigated cultivation and perennial vegetation provide readily available medicinal resources. However, spatial differences in plant-part selection may also reflect local flora, harvesting traditions, and intergenerational transmission of ethnomedical knowledge. The use of leaves, fruits, flowers, and seeds is pharmacologically plausible because these organs contain diverse secondary metabolites, including phenolics, flavonoids, terpenoids, alkaloids, and essential oils with reported antileishmanial properties. For instance, compounds associated with *Origanum compactum*, *Salvia rosmarinus*, and *Lavandula* spp. have demonstrated inhibitory activity against *Leishmania* in experimental studies (Balahbib *et al.* 2020). Nevertheless, traditional frequency of use should not be interpreted as direct evidence of clinical efficacy.

Preparation practices similarly reflect the interaction between local knowledge and practical accessibility. The predominance of decoction, particularly in communities where household preparation remains important, may represent an empirically established strategy for obtaining water-soluble constituents from locally available plant material. Powder preparation may additionally facilitate direct application to cutaneous lesions, whereas infusion can provide a simpler alternative for thermolabile compounds (Elachouri *et al.* 2021; Chaachouay *et al.* 2022). Geographical variation in these practices may therefore arise from differences in plant availability, cultural preferences, and healthcare accessibility. By integrating spatial analysis with multivariate and machine-learning approaches, the present regional assessment provides a basis for identifying locality-specific ethnomedicinal practices and prioritizing plant organs and preparations for targeted phytochemical and pharmacological validation.

Conclusion

This study aimed to document the traditional use of medicinal plants for the management of leishmaniasis in the Drâa-Tafilalet region of southeastern Morocco and to assess the influence of sociodemographic and geographic factors on ethnomedicinal knowledge and practices. A total of 61 medicinal plant species were documented, with *Rosmarinus officinalis*, *Lawsonia inermis*, and *Origanum compactum* emerging as the most frequently cited species. Leaves were the most used plant part, while decoction was the predominant preparation method. Substantial spatial variation in plant selection and medicinal-use patterns was observed among the surveyed provinces, indicating considerable geographic heterogeneity in ethnomedicinal practices. Despite the relatively high educational attainment of many participants, a considerable proportion demonstrated limited knowledge of medicinal plants, suggesting a potential decline in the transmission and preservation of traditional ethnomedicinal knowledge.

This study provides a comprehensive regional assessment of medicinal plant use, encompassing both rural and urban communities in an area that remains comparatively understudied ethnobotanically within Morocco. The integration of Geographic Information System (GIS)-based spatial analysis, correspondence analysis, and machine-learning approaches provided complementary insights into the spatial distribution of medicinal plant use and the relationships between sociodemographic characteristics and plant selection. The findings establish an important baseline for biodiversity conservation, ethnopharmacological investigation, and the development of evidence-informed public health strategies. However, the study relied primarily on questionnaire-based ethnobotanical data and did not include phytochemical, pharmacological, or clinical validation. Future research should therefore combine phytochemical characterization, pharmacological and clinical evaluation, and molecular identification of bioactive compounds, while extending ethnobotanical surveys to other understudied regions of Morocco. Such efforts could contribute to the scientific validation and sustainable development of safe, affordable, and potentially effective plant-based interventions for leishmaniasis.

Declarations

Ethics approval and consent to participate: Before conducting interviews, prior informed consent was obtained from all participants. No further ethics approval was required.

Consent for publication: Not applicable

Availability of data and materials: The datasets used and/or analysed during the current study are study are included within the article.

Competing interests: Not applicable

Funding: Not applicable

Author contributions: C.B. and L.E.G. designed the paper and conceived the idea. C.B. was responsible for writing and L.E.G. was responsible for editing the manuscript. All authors discussed and revised the manuscript.

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