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Research Article

A survey of ethno-botanical food resources in Pakistan's Thal desert

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Abstract
This study investigates the nutritional potential of ten native medicinal plant species from the Thal Desert, Pakistan, as sustainable food resources for arid regions. The selected species, including *Ziziphus nummularia*, *Cenchrus ciliaris*, *Salvadora oleoides*, *Vachellia nilotica*, *Calotropis procera*, *Cordia myxa*, *Capparis decidua*, *Tamarix aphylla*, *Prosopis juliflora*, and *Chenopodium album,* were analyzed for key nutritional components. Significant interspecies variation was found: *Salvadora oleoides* possessed the highest crude fat (11.25%) and carbohydrate (73.4%) content, while *Ziziphus nummularia* exhibited the highest ash (26.5%) and protein (20.33%) levels. *Cenchrus ciliaris* showed the maximum fiber content (33.01%). Heatmap dendrogram analyses revealed distinct clustering, reflecting species-specific adaptive strategies to the desert environment. The findings underscore the considerable nutritional diversity of these ethno-botanicals, highlighting their potential to combat malnutrition and enhance food security. This research provides a scientific basis for integrating these plants into local diets, functional foods, and conservation strategies, promoting their role in sustainable desert ecosystems.
Keywords: Arid-zone, Biodiversity, Ethnobotany, Nutraceuticals, Rangelands, Sustainable

Introduction

Securing global food security is challenged by climate change and population growth, necessitating sustainable agricultural solutions. While the Green Revolution boosted yields through high-input practices, it incurred environmental costs and promoted nutrient-poor diets reliant on a few staples (John & Babu, 2021) such as wheat and rice. Diversifying food systems with underutilized, resilient crops offers a strategic path forward. Integrating these locally adapted species is crucial for developing climate-resilient agriculture and achieving related Sustainable Development Goals (Raza et al., 2023).

Desert ecosystems impose extreme abiotic stressors, including temperature fluctuations, water scarcity, high salinity, and infertile soil, which have driven the evolution of resilient flora that survive by accumulating specialized metabolites to resist these challenges (Asati et al., 2021; Madouh & Al-Sabbagh, 2021). These compounds subsequently contribute significant nutritional and nutraceutical value to the edible species. Wild edible plants (WEPs), which have been integral to human diets for millennia (Food, 2010), represent a vast reservoir of nutritional diversity with the potential to bolster global food security. Of the approximately 30,000 edible species worldwide, many are nutritionally rich (John & Babu, 2021) and can be found across various botanical forms from herbs and shrubs to trees (Carvalho & Barata, 2016). These species offer a critical opportunity to develop food systems that are more nourishing, sustainable, and resilient to abiotic stresses (Powell et al., 2015). Their consumption remains vital, particularly in isolated or economically disadvantaged communities (Omamo, 2016; Wunder et al., 2014) and during periods of crop failure (Pinela et al., 2017), underscoring their continued relevance. WEPs constitute a critical resource for enhancing global nutrition and food security (Ford et al., 2011; Toledo & Burlingame, 2006), yet their potential is hindered by fragmented data on their edibility and composition (Deokule & Aberoumand, 2009; Food, 2010; Ogle, 2001; Powell et al., 2015). Systematic investigation and the compilation of comprehensive nutritional databases are essential foundational steps. Beyond macronutrients, WEPs are valuable sources of pharmacologically active compounds such as phenols, flavonoids, alkaloids, and saponins that exhibit antioxidant and anti-inflammatory activities (Job et al., 2022; A. Narayanankutty, 2021; Yu et al., 2021; Zhang et al., 2015), with bioactivity linked to the prevention of chronic diseases (A. Narayanankutty, 2019; V. Narayanankutty et al., 2019). The concurrent presence of essential vitamins and trace elements (AlFadhly et al., 2022; Kennedy, 2016; Padayatty & Levine, 2016; Scheiermann et al., 2022; Wooten et al., 2022) further underscores their dual nutraceutical and medicinal significance.

The arid and semi-arid regions of the Indian subcontinent host several such resilient, nitrogen-fixing legumes (e.g., *Prosopis cineraria*, *Acacia senegal*, and *Cyamopsis tetragonoloba*) and non-legumes like millets, *Capparis decidua*, and *Ziziphus mauritiana*. However, many of these nutritionally rich species are now underutilized and risk becoming threatened (Witcombe et al., 1978), underscoring the imperative to conserve this valuable biodiversity for sustainable food systems. Millets are climate-resilient, C4 plants suited to semi-arid regions, offering a sustainable alternative to water-intensive cereals; their importance is highlighted by the UN's declaration of 2023 as the International Year of Millets (Joshi et al., 2023). Other notable underutilized species, rich in bioactive compounds, include *Ziziphus nummularia* (anti-obesity, anticancer); *Salvadora oleoides* (antiseptic, anti-tumor); *Aegle marmelos* (analgesic, hypoglycemic); *Carissa carandas* (anti-anemic, antioxidant) (Karunanayaka et al., 2022); *Feronia limonia* (antidiabetic); *Annona squamosa* (antioxidant, antimalarial); and *Buchanania lanzan* (treats asthma, ulcers) (Meena et al., 2022); alongside multi-use species like *Opuntia ficus-indica*, *Grewia subinaequalis*, and the oil-yielding *Eruca sativa* (Mahawar & Shekhawat, 2019). Ethnobotanical studies in Thal desert confirm that species such as *Ziziphus nummularia*, *Salvadora oleoides*, *Capparis decidua*, and *Tamarix aphylla* are deeply embedded in the local culture, historically providing essential food, medicine, and forage (Ali et al., 2023; Kolde, 2019).

This study delineates the potential of native flora from the Thal Desert as pivotal resources for enhancing future food and nutrition security. We evaluate their dual function in bolstering agricultural productivity in marginal environments and serving as direct sources of essential nutrients. Furthermore, the article identifies critical research gaps about semi-arid and arid edible species and proposes potential solutions, highlighting the application of modern biotechnological and agronomic approaches to harness their potential as sustainable functional foods.

Material and methods

Experimental Site

This study was conducted in the Thal Desert of Punjab, Pakistan (31°10′N, 71°30′E). The region extends approximately 190 miles in length and 70 miles in width, bounded by the Salt Range Piedmont and the floodplains of the Indus, Jhelum, and Chenab Rivers. The climate is arid, characterized by high annual temperatures (25–30 °C), with summer maxima exceeding 45 °C. Precipitation is low (100–200 mm/year) and predominantly occurs during the monsoon season (July–September). The landscape consists of dunes with sparse, drought-adapted thorny vegetation and ephemeral herbs.

Selection of Species

The study focused on ten native medicinal species (*Ziziphus nummularia*, *Cenchrus ciliaris*, *Salvadora oleoides*, *Vachellia nilotica*, *Calotropis procera*, *Cordia myxa*, *Capparis decidua*, *Tamarix aphylla*, *Prosopis juliflora*, and *Chenopodium album*) selected for their ethnobotanical relevance and prevalence in the study area (Ali et al., 2023).

Collection of Samples

For each of the ten target species, a single individual was harvested from each of three geographically distinct localities within the Thal Desert, yielding 30 samples in total (n = 3 per species). The localities such as Mankera (Site 1), Chamb (Site 2), and Choubara (Site 3) are separated by sufficient distance to ensure spatial independence. Consequently, the three samples per species constitute a spatially explicit replicate series designed to capture among-site (β-spatial) variance, rather than temporal or within-site microhabitat heterogeneity. Healthy and mature parts of the plants (leaves, stems, and fruit) were collected using clean pruning shears. Each sample was placed in pre-labelled polyethylene bags and transported to the laboratory in ice boxes to minimize degradation or moisture loss.

Processing of Samples

In the laboratory, samples were washed thoroughly with tap water followed by distilled water to remove adhering dust, soil particles, and contaminants. The clean samples were air-dried under shade at ambient room temperature (25–30 °C) for 5–7 days until initial moisture was removed. Subsequently, the samples were oven-dried at 60 ± 2 °C for 48 hours to achieve constant weight, ensuring uniform moisture content across all samples for reliable proximate analysis. After drying, the samples were ground into a fine powder using a stainless-steel Wiley mill and passed through a 40-mesh sieve. The powdered samples were stored in airtight, labeled zip-lock polyethylene bags and kept in a desiccator to prevent moisture absorption until analysis.

Nutritional Analysis

The proximate composition (moisture, crude protein, crude fat, total ash, and crude fibre) of the samples was determined in triplicate according to the standard methods of the Association of Official Analytical Chemists (AC, 1990). Moisture content was determined by drying 2.0 g of each fresh sample in a crucible at 105 °C in a forced-air oven until a constant weight was achieved. The resulting dry matter was used for all subsequent analyses. Crude protein was estimated by the Kjeldahl method. A conversion factor of 6.25 was used to calculate the crude protein content (% total nitrogen × 6.25) from the determined nitrogen content in a 2.0 g sample. Crude fat content was determined by exhaustively extracting a 5.0 g sample using a Soxhlet apparatus with petroleum ether (boiling point range 40-60°C) as the solvent. Total ash content was quantified by incinerating a 10.0 g sample in a muffle furnace at 550 °C for 5 hours. Crude fibre was obtained by sequentially digesting a 2.0 g sample with 1.25% H_2SO_4 and 1.25% NaOH solutions, followed by incineration of the residue in a muffle furnace at 550°C for 5 hours.

Statistical Analysis

The experimental data were subjected to one-way analysis of variance (ANOVA) to determine the significance of differences among the medicinal plant species for each nutritional trait, following the procedures described by (Steel & Torrie, 1960). Post-hoc comparisons of means were carried out using Tukey's Honest Significant Difference (HSD) test to identify statistically significant differences between species means (Tukey, 1949). To visualize trait variability among plant species, a heatmap was generated using the *pheatmap* package (version 1.0.12) in R software (Kolde, 2019; Team, 2020). This multivariate visualization facilitated clustering of species based on their nutritional profiles.

Results and Discussion

Analysis of variance (ANOVA) indicated highly significant differences ($p < 0.005$) among the plant species for all analyzed nutritional traits: moisture content, crude fat, crude protein, ash content, crude fiber, and carbohydrate content (Table 1). The significant interspecific variation observed in the nutritional profiles of the Thal Desert plants reveals a wide spectrum of nutritional potential. This is consistent with studies on other desert flora, where such divergence is explained by species-specific metabolic adaptations to arid environments (Akhtar et al., 2023; Ali et al., 2023). The influence of local ecological conditions on plant composition, as reported by Afzal et al. (2021) and Umair et al. (2017), further supports this finding. The observed nutritional diversity offers a compelling scientific rationale for the ethnobotanical promotion of these adapted species as traditional medicinal foods. This approach has significant potential to improve nutrition and health in arid regions and underscores the importance of further research into their sustainable dietary and therapeutic applications (Amna Aslam et al., 2016).

Table 1. Mean Squares values from Analysis of variance (ANOVA) for nutritional traits among different medicinal plants from the Thal Desert

Sources of variation	DF	MC	CF	CP	AC	CFb	CHO
Plant Species	9	2631.46*	29.2424*	51.4341*	34.9131*	390.903*	1412.18*
Error	20	1.61	0.5393	0.5863	0.172	1.419	3.09
Total	29						

Sources of variation (SOV), Moisture Content (MC), Crude Fat (CF), Crude Protein (CP), Ash Contents (AC), Crude Fiber (CFb), Carbohydrate (CHO), *= significant value because *p* value is less than 0.005

The moisture content of a food material represents the mass fraction of water present, a key determinant of its physical, chemical, and microbiological stability. Beyond its role in the food matrix, dietary moisture serves as a crucial contributor to human hydration. It is estimated that water from food constitutes about one-fifth of an individual's total daily water intake (Yaqoob et al., 2024). Following ingestion, this water is efficiently absorbed by the gastrointestinal tract, supporting systemic hydration and cellular functions. Moisture content varied significantly ($p < 0.05$) among the species, with values ranging from 7.63% to 83.40% (Table 2). Post-hoc analysis using Tukey's HSD test identified four homogenous subsets (a–d). The highest moisture content was observed in *Chenopodium album* (83.40 ± 0.92%) and *Cordia myxa* (75.11 ± 1.43%), both grouped in subset 'a'. Species such as *Salvadora oleoides* (70.44 ± 1.15%) and *Cenchrus ciliaris* (67.33 ± 1.70%) formed intermediate groupings. The lowest moisture contents were recorded in *Vachellia nilotica* (7.63 ± 0.93%), *Prosopis juliflora* (7.77 ± 0.90%), and *Ziziphus nummularia* (11.91 ± 1.19%), each assigned to separate statistical subsets indicating distinct low moisture levels.

Table 2. Mean values of nutritional analysis of selected medicinal plants from the Thal Desert for nutritional traits

Plant name	Moisture Content	Crude Fat	Crude Protein	Ash Content	Crude Fiber	Carbohydrate
Ziziphus nummularia	11.91±1.19 c	1.67±0.13 d	20.33±1.28 a	26.5±1.21 a	6.29±0.51 c	23.93±1.26 d
Cenchrus ciliaris	67.33±1.7 ab	3.03±0.23 c	5.75±0.86 d	7.21±0.58 c	33.01±0.89 a	44.7±2.58 b
Salvadora oleoides	70.44±1.15 a	11.25±1.8 a	15.8±1.21 a	7.64±0.21 c	10.83±0.99 b	73.4±2.23 a
Vachellia nilotica	7.63±0.69c	1.48±0.04 d	5.83±0.75 d	12.47±0.81 ab	11.84±0.99 b	29.69±1.31 c
Calotropis procera	62.46±0.84 ab	4.5±0.05 ab	11.37±0.4 b	5.37±0.24 d	1.46±0.06 d	15.42±0.5 d
Cordia myxa L.	75.11±1.43 a	2.22±0.05 c	6.27±0.1 c	7.51±0.1 c	23.15±2.26 ab	54.39±1.99 a
Capparis decidua	65.44±0.69 ab	6.15±0.1 a	13.01±0.96 ab	14.25±0.13ab	6.12±0.07 c	62.69±0.53 a
Tamarix aphylla	52.94±0.76 b	2.03±0.04 c	14.35±0.13 ab	6.3±0.08 d	29.4±0.92 a	27.58±0.84 c
Prosopis julifora	7.77±0.09 c	4.72±0.13ab	7.43±0.11 c	4.46±0.09 d	21.71±0.67 ab	53.31±0.68 a
Chenopodium album	83.4±0.92 a	0.76±0.03d	11.73±0.12 b	7.72±0.09 c	2.13±0.11 d	7.1±0.21 d

Mean values of nutritional traits in selected traditional medicinal plants from the Thal Desert. Tukey's HSD test was used for post-hoc comparison at the 0.05 significance level. Different letters (a, b, c, d) within each column indicate statistically significant differences among species; identical letters denote non-significant differences.

The pronounced variation in moisture content has direct implications for the post-harvest management of these medicinal resources. Species with high moisture content, such as *C. album* and *C. myxa*, are highly perishable and necessitate rapid processing or specialized storage to prevent spoilage. In contrast, species with low moisture content, including *V. nilotica* and *P. juliflora*, exhibit inherent shelf stability, facilitating longer storage durations. This pattern is consistent with previous findings that associate high moisture with leafy and succulent tissues and lower moisture with woody, dry fruit, or seed-based species (Anwar et al., 2024; Farooq et al., 2019). A comparative analysis reveals that the moisture content ranges reported here are consistent with literature values for wild flora from other Mediterranean and arid climates, including the United Arab Emirates (Shahid et al., 2023) and Spain (Guerrero & Torija Isasa, 1997). This similarity suggests convergent adaptations in water content among wild plants inhabiting regions with comparable environmental pressures.

Dietary lipids are a crucial component of human nutrition, serving as a concentrated energy source and facilitating the absorption of fat-soluble vitamins (e.g., carotene and vitamin A) (Holleman & Conti, 2020). Furthermore, they supply essential fatty acids, such as linoleic and linolenic acid, which the body cannot synthesize de novo. These compounds are vital for regulating inflammation, blood coagulation, and neurological development. However, lipid intake must be moderated; a dietary profile where 1–2% of caloric energy is derived from fat is considered appropriate, as excessive consumption is an established risk factor for cardiovascular diseases (Kris-Etherton et al., 1988). Significant interspecific variation ($p < 0.05$) was observed in crude fat content, with values spanning from 0.76% to 11.25% (Table 2). Post-hoc analysis using Tukey's HSD test categorized the species into four distinct homogenous subsets (a–d). *Salvadora oleoides* demonstrated the highest crude fat content (11.25 ± 1.87%), followed by *Capparis decidua* (6.15 ± 0.10%), both forming the top statistical group (a). Intermediate values were recorded for *Prosopis juliflora* (4.76 ± 0.13%) and *Calotropis procera* (4.50 ± 0.05%), while the lowest values were found in *Ziziphus nummularia* (1.67 ± 0.13%), *Vachellia nilotica* (1.48%), and *Chenopodium album* (0.76 ± 0.03%), the latter forming the lowest subset (d). The pronounced variation in crude fat content highlights differential nutritional and therapeutic potential among the species. The high lipid content in *S. oleoides* and *C. decidua* identifies them as promising sources of dietary energy and lipid-soluble bioactive compounds, potentially underpinning their traditional medicinal uses. In contrast, the minimal fat content in *C. album* is consistent with its profile as a low-lipid leafy vegetable (Azhar et al., 2022; Ozturk et al., 2018) and wild flora from the United Arab Emirates (Shahid et al., 2023). The overall spectrum of lipid reserves observed aligns with well-documented species-specific adaptations in arid zone plants, reflecting divergent metabolic strategies and resource allocation (Hameed et al., 2011; Iqbal et al., 2014).

Historically, dietary protein guidelines have been defined by the minimum daily requirement to sustain nitrogen balance, ensuring sufficient high-quality protein to avert a catabolic state. This remains a major public health focus, especially for mitigating sarcopenia risk in aging populations (Paddon-Jones et al., 2008). However, the level of protein required to prevent deficiency is not synonymous with the level that supports optimal physiological function. Consequently, there is increasing scientific support for the concept that dietary protein intakes exceeding the traditional minimum can play a therapeutic role in complex disorders such as obesity, metabolic syndrome, type 2 diabetes (T2D), and atherosclerotic cardiovascular disease. Significant interspecific variation ($p < 0.05$) was observed in crude protein content, with values ranging from 5.75% to 20.33% (Table 2). Post-hoc analysis with Tukey's HSD test categorized the species into four distinct homogenous subsets (a–d). *Ziziphus nummularia* contained the highest protein content (20.33 ± 1.28%), forming the top statistical subset (a). *Salvadora oleoides* (15.80 ± 1.21%) was also distinguished by a high value. Intermediate levels were recorded for *Tamarix aphylla* (14.35 ± 0.13%) and *Capparis decidua* (13.01 ± 0.96%), while the lowest contents were found in *Cenchrus ciliaris* (5.75 ± 0.86%), *Cordia myxa* (6.27 ± 0.10%), and *Prosopis juliflora* (7.43%). The pronounced disparities in protein content highlight the differential potential of these species to address nutritional challenges. The high protein levels in *Z. nummularia* and *S. oleoides* position them as promising candidates for dietary interventions to combat protein-energy malnutrition in arid regions. This finding aligns with and substantiates the traditional use of such plants, confirming that certain desert shrubs are valuable sources of plant-based protein and can contribute significantly to food security in resource-limited environments (Haq et al., 2022; Majeed et al., 2023; Shahid et al., 2023). According to established nutritional guidelines, a good protein source is defined as a diet in which protein constitutes approximately 12% of the total caloric intake (Kris-Etherton et al., 1988)

Ash represents the total inorganic residue remaining after complete combustion of plant biomass and, consequently, constitutes a comprehensive index of mineral, micro, and macronutrient load. This fraction is composed of oxides and ionic salts, primarily phosphates, sulfates, and chlorides, along with physiologically essential cations (Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}, Mn^{2+}, Fe^{3+} , and associated halides) that are indispensable for cellular homeostasis and metabolic function (Sassi et al., 2018). Ash content, a proxy for total mineral composition, was quantified to estimate the micronutrient density of the studied taxa and thus appraise their dietary relevance. Values varied significantly among species (4.46–26.5 % DW; Table 2). One-way ANOVA confirmed inter-specific differences ($p < 0.05$), and Tukey's HSD test resolved four homogeneous subsets (a–d). *Ziziphus nummularia* registered the highest ash yield (26.50 ± 1.21 %) and occupied the top statistical group (a), followed by *Capparis decidua* (14.25 ± 0.13 %) and *Vachellia nilotica* (12.47 ± 0.81 %). Intermediate levels were recorded for *Chenopodium album* (7.72 ± 0.09 %), *Cordia myxa* (7.51 ± 0.10 %), *Salvadora oleoides* (7.21 ± 0.21 %), and *Cenchrus ciliaris* (7.21 ± 0.58 %). The lowest mineral residues were observed in *Tamarix aphylla* (6.30 %), *Calotropis procera* (5.37 ± 0.13 %), and *Prosopis juliflora* (4.46 ± 0.09 %), the latter forming the lowest subset (d). The substantial variation in ash content indicates a wide disparity in the mineral density of the studied species. The exceptionally high value in *Z. nummularia* highlights its potential as a rich source of essential minerals such as calcium, potassium, and magnesium, making it a promising candidate for dietary supplementation in arid regions. In contrast, the low mineral content observed in *P. juliflora* and *C. procera* is consistent with reports for other species that accumulate lower levels of inorganic material in their tissues (Aslam et al., 2023; Rehman & Adnan, 2018; Sadia et al., 2021). These wild plants contain ash that is comparable to that of several of the arid plants from the United Arab Emirates (Shahid et al., 2023) as well as wild vegetables that are frequently consumed in Bangladesh, India, and Africa (Iheanacho & Udebuani, 2009; Sheela et al., 2004; Vermani et al., 2010).

The crude fiber content, a critical component for digestive health, varied significantly ($p < 0.05$) across the studied species, ranging from 1.46% to 33.01% (Table 2). According to Tukey's HSD test, the species were classified into four distinct homogenous subsets (a–d). *Cenchrus ciliaris* (33.01 ± 0.89%) and *Tamarix aphylla* (29.40 ± 0.92%) comprised the highest statistical group (a), indicating their potential as excellent sources of dietary fiber. Intermediate values were observed in *Cordia myxa* (23.15 ± 2.26 %) and *Prosopis juliflora* (21.71 ± 0.67 %). Lower fiber contents were recorded for *Salvadora oleoides* (11.84 ± 0.99%), *Vachellia nilotica* (10.83 ± 0.99 %), *Capparis decidua* (6.12 ± 0.07 %), and *Ziziphus nummularia* (6.21%). The lowest fiber content was found in *Chenopodium album* (2.13 ± 0.11%) and *Calotropis procera* (1.46 ± 0.06

%), which constituted the lowest statistical group (d). The pronounced variation in fiber content aligns with the morphological characteristics of the species; for instance, the tender leaves of *C. album* are consistent with its low fiber and high digestibility. These findings corroborate previous studies linking high fiber in arid plants to fodder value and health applications (Aslam et al., 2023; Sadia et al., 2021; Shar, 2022).

Carbohydrate content, a primary determinant of caloric value and glycemic response, was evaluated to assess the energy-providing potential of the species. The analysis revealed significant interspecific variation ($p < 0.05$), with values ranging from 7.10 to 73.40 % (Table 2). *Salvadora oleoides* exhibited the highest carbohydrate content (73.40 ± 2.23 %), forming the top statistical group (a) alongside *Capparis decidua* (62.69 ± 0.53 %), *Cordia myxa* (58.23 ± 1.15 %), and *Prosopis juliflora* (54.89 ± 0.91 %). Intermediate values were recorded for *Cenchrus ciliaris* (44.70 ± 2.58 %), *Vachellia nilotica* (29.69 ± 1.31 %), and *Tamarix aphylla* (27.58 ± 0.84 %). Lower contents were observed in *Ziziphus nummularia* (23.93 %) and *Calotropis procera* (18.45 ± 0.67 %), while *Chenopodium album* (7.10 ± 0.21 %) constituted the distinct lowest group (d). The high carbohydrate content in species such as *S. oleoides* and *C. decidua* underscores their potential as energy-dense resources, consistent with their traditional dietary uses. The low value in *C. album* may be attributed to its high moisture content and succulent nature. Our findings align with previous studies linking carbohydrate composition in arid plants to energy sustenance and glycemic management (Aziz et al., 2023; Shar, 2022; Siddique et al., 2021). The values reported here are comparable to those described for wild edible plants in Bangladesh (Sheela et al., 2004), Northeast India (Iheanacho & Udebuani, 2009; Vermani et al., 2010), Pakistan (Aziz et al., 2023), and the United Arab Emirates (Shahid et al., 2023), but are generally higher than those reported for leafy vegetables in other parts of India and Pakistan (Khan et al., 2013; Seal & Chaudhuri, 2016).

Hierarchical agglomerative clustering was applied to the centred and scaled macronutrient matrix (moisture, crude fat, crude protein, ash, crude fibre, and total carbohydrate) of the ten species. The resulting heat-map dendrogram (Fig. 1) resolved four principal nutritional phenotypes, reflecting distinct ecological strategies of Thal Desert flora. Cluster-I comprised *Cordia myxa* (6) and *Cenchrus ciliaris* (2), united by elevated moisture (≥ 65 %) and fibre (≥ 23 %). This water–fibre syndrome is consistent with sclerophyllous xerophytes that maintain cell turgor under chronic water deficit (Maitry et al., 2025). Cluster-II was represented solely by *Salvadora oleoides* (3), distinguished by the highest crude-fat (18.4 %) and carbohydrate (55.7 %) reserves. The energy-dense profile corroborates ethnographic records of its drupes being consumed as a high-caloric supplement during famine periods (Anwar et al., 2024; Zaman et al., 2025). Cluster-III paired *Tamarix aphylla* (4) and *Prosopis juliflora* (7). Both species combined moderate protein (12–14 %) with high ash (9–11 %), indicative of halophytic adaptations that facilitate osmotic adjustment in saline substrates. Cluster-IV contained the remaining four species, yet internal branch lengths > 80 % dissimilarity justified treating them as singletons: *Ziziphus nummularia* (1) exhibited peak protein (19.8 %) and ash (11.2 %); *Calotropis procera* (5) displayed low fibre (1.5 %) coupled with high moisture (78 %), consistent with succulent water-storage tissue; *Capparis decidua* (8) and *Vachellia nilotica* (9) occupied intermediate positions. *Chenopodium album* (10) affiliated loosely with Cluster-IV, driven by elevated carbohydrate (63 %), supporting its role as a readily metabolisable energy source (Rehman & Adnan, 2018). The segregation of nutritional syndromes aligns with known stress response axes, water retention, osmoprotectant accumulation, and structural reinforcement thereby providing a quantitative basis for selecting climate-resilient candidates for functional food development (Ali et al., 2023).

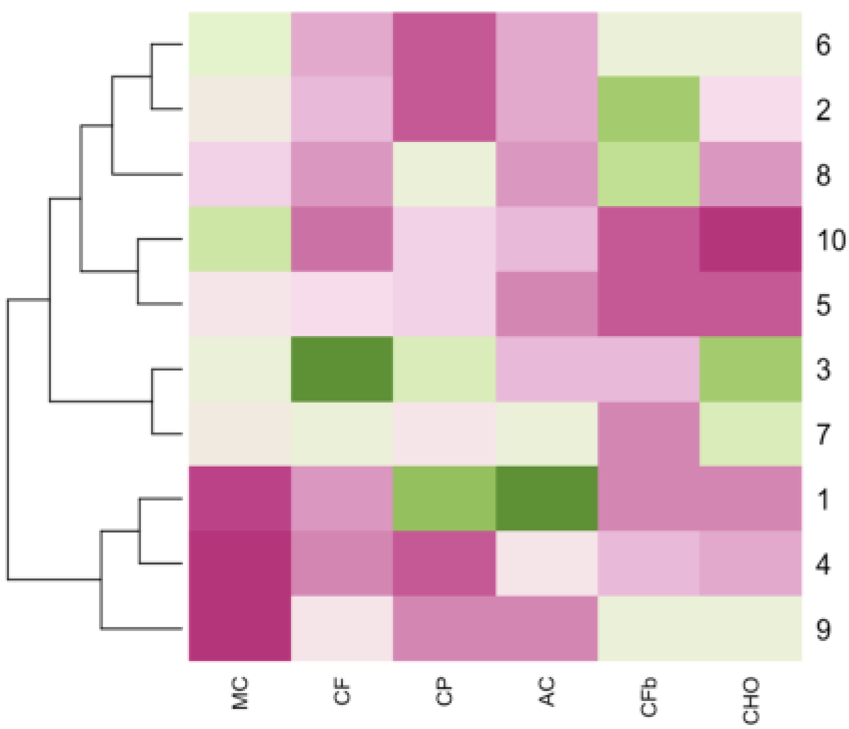

Figure 1. Heatmap dendrogram showing the clustering of ten traditional medicinal plant species from the Thal Desert, Punjab, based on key nutritional traits: Moisture Content (MC), Crude Fat (CF), Crude Protein (CP), Ash Content (AC), Crude Fiber (CFb), and Carbohydrate (CHO). The plant species analyzed include:

1 = *Ziziphus nummularia*, 2 = *Cenchrus ciliaris*, 3 = *Salvadora oleoides*, 4 = *Vachellia nilotica*, 5 = *Calotropis procera*, 6 = *Cordia myxa L.*, 7 = *Capparis decidua*, 8 = *Tamarix aphylla*, 9 = *Prosopis juliflora*, and 10 = *Chenopodium album*. The numbering corresponds to Figures 1–10.

Conclusion

This study provides a systematic nutritional profiling of ten medicinal plants from the Thal Desert, revealing significant interspecific variation in their proximate composition. The multivariate analysis identified distinct species clusters, reflecting diverse ecological adaptations to arid conditions, from the high-fiber, drought-tolerant strategy of *Cenchrus ciliaris* and *Tamarix aphylla* to the energy-dense profile of *Salvadora oleoides*. These findings scientifically validate their traditional uses and highlight their substantial potential as sources of dietary fiber, protein, and energy. To translate this potential into tangible benefits, specific application pathways are proposed. High-fiber species are ideal for developing functional foods to address obesity and diabetes, while energy-rich species can be directly incorporated or processed into local diets as nutritional supplements. However, the promotion of these valuable resources must be coupled with strong conservation strategies. We emphasize the critical need for sustainable harvesting practices and the initiation of cultivation programs for high-demand species to prevent overexploitation and ensure long-term availability. Finally, this work lays a foundational groundwork that should be expanded upon. Future research must progress beyond proximate analysis to include phytochemical screening, toxicological assessments, and studies on the impact of processing on nutrient bioavailability. The final step is to validate this potential through field trials assessing cultivation viability and public acceptance. Through an integrated approach that connects laboratory findings with sustainable conservation and community needs, these plants can be transformed into practical, climate-resilient solutions for food security in arid regions and elsewhere.

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