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Post-harvest handling, value-addition and nutritional profiling in the traditional crop-plants of *Thar* Desert

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The indigenous crop plants of *Thar* Desert are integral to traditional rain-fed cropping systems, providing food, fodder, and medicinal resources to local inhabitants under extreme edaphoclimatic conditions. This study focuses on documentation, developing post-harvest handling protocols and value addition through on-farm drying of selected indigenous crop species, including trees, shrubs, and annuals such as khejri (*Prosopis cineraria*), ker (*Capparis decidua*), lasoda (*Cordia myxa*), kheemp (*Leptadenia pyrotechnica*), phog (*Calligonum polygonoides*), jharber (*Ziziphus nummularia*), bordi (*Ziziphus rotundifolia*), kumat (*Senegalia senegal*) and native vegetables like guarphali (*Cyamopsis tetragonoloba*) kachri (*Cucumis melo* var. *callosus*), kaakdia (*Cucumis melo var. momordica*), tinda (*Benincasa fistulosus*) and paan-methi (*Trigonella corniculata*). Standardized harvesting stage, blanching, and sun-drying protocols were developed to improve product quality and shelf life, addressing challenges of non-uniformity and inferior quality. Proximate, biochemical, and mineral analyses of dried products of selected eight plant species revealed that products like *sangri* (dried pods of khejri), *guarphali*, and kumat seeds are rich in proteins, fats, antioxidants, and essential minerals, with notable bioactive compounds such as phenols and flavonoids, especially in *phogla* (unopened flower bud of phog) and *sangri*. The study highlights the potential of these native plants as nutraceuticals and functional foods, emphasizing their nutritional diversity, adaptability to harsh climates, and depicted prospects for sustainable utilization. Promotion of these traditional crop-plants can enhance nutritional security, support local livelihoods, and contribute to the conservation of arid-region biodiversity.

Keywords: India, Indigenous crop-plants, Mineral profiling, On-farm drying, Post-harvest handling, Proximate analysis, *Thar* Desert

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The Indian *Thar* Desert landscape is mainly consisted of sand-dunes, sandy-plain farm-lands and low, barren hills spread over 32 million hectares and accounting to about 10% geographical area of the country spans primarily in the Rajasthan, Gujarat, Haryana and Punjab states[1]. The desert eco-system experiences scanty and erratic rainfall, temperature extremes (-5° to 50°C), low humidity, high evapo-transpiration and wind velocity. In addition, the soils are poor in water holding capacity, highly susceptible to wind erosion and deficit in organic carbon[2]. Despite of harsh climatic and challenging living conditions, the *Thar* Desert supports a rich diversity of flora and fauna of about 682 species[3].

The native arid flora with agri-horti-silvi-pastoral significance including trees, shrubs, grasses, creepers and seasonal crop-plants thrives well, highly adaptive and productive under desert environment. The key native trees with horticultural potential include khejri (*Prosopis cineraria*), pilu (*Salvadora oleoides*), bordi (*Ziziphus rotundifolia*), gunda or lasoda (*Cordia myxa*), gundi (*Cordia gharaf*), kumat (*Senegalia senegal*), rohida (*Tecomella undulata*) and also the perennial shrub-plants such as ker (*Capparis decidua*), jharber (*Ziziphus nummularia*), phog (*Calligonum polygonoides*) and kheemp (*Leptadenia pyrotechnica*). Among seasonal crops, pre-dominantly the monsoon supported arid vegetables such as guarphali (*Cyamopsis tetragonoloba*), kachri, mat-kaachr or kachri melon (*Cucumis melo* var. *callosus*), kaakdia or snap melon (*Cucumis melo var. momordica*), mateera, a drought hardy watermelon (*Citrullus lanatus*), tinda or round melon (*Benincasa fistulosus*) and paan-methi (*Trigonella corniculata*)[4,5]. These native crops offer a diverse range of fruits and vegetables to the local

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inhabitants throughout the year, even during extreme heat waves and harsh winters.

The arid zone crop-plants experiencing recurrent abiotic stresses owing to inhospitable climatic conditions promote accumulation of the nutritionally and therapeutically significant bio-active compounds such as polyphenols, tannins, flavonoids, antioxidants, saponins, alkaloids and many-more[6]. Traditionally, the fruit and vegetable crop-plants grown without the uses of harmful chemical inputs making them ideal commodities for promotion as natural products. The availability of fresh produce of the majority of native fruits and vegetables at desirable maturity is for very short period and staggered. However, the shelf-life of these produce can be extended through preservation and value- addition techniques. Among various preservation methods, the sun-drying is simple and cost-efficient strategy in the *Thar* Desert due to abundant solar radiation and low humidity throughout the year. While local communities traditionally preserving the crop-plants produces through sun-drying, the resulting products often suffer from non-uniformity, poor appearances and inferior in quality. Standardized harvesting stages, pre-processing/blanching, on-farm drying and nutritional/biochemical profiling of *Thar* Desert native fruits and vegetables is limited. The present study addresses this gap and aimed to standardize the harvesting, post-harvest handling, blanching and sun-drying processes for the prioritised native crop-plants. Additionally, uses of traditional crop-plants and their products were documented and also analysis of proximate composition, bio-active compounds and mineral profiling was conducted to assess the nutritional and functional properties of the preserved food products.

Materials and Methods

Documentation of traditional crop-plant produces of *Thar* Desert

The seven districts namely Bikaner, Barmer, Churu, Jaisalmer, Jodhpur, Nagaur and Pali of Rajasthan state which primarily representing the desert eco-system were selected for documenting fruits and vegetable produce derived from native crop-plants. The existing traditional methods of value-addition, mode of consumption and to identify reasons for inferior quality of the produce were the prioritized aspects of documentation. The information was collected from rural women, growers, consumers, sellers and gram-panchayat representatives through open-ended questionnaire and personal interviews. Based on economic importance and consumption pattern of traditional produce some crop-plants (khejri, ker, lasoda, phog, kheemp, kachri, kaakdia, tinda, guarphali, paan-methi, jharber, bordi, kumat) were selected to standardize harvesting stage, post-harvest handling, pre-processing and drying protocols.

Harvesting stages and pre-processing

Marketable fresh produce of seasonal crops (kachri, kaakdia, tinda, guarphali, paan-methi) and perennial trees-shrubs (khejri, ker, lasoda, kumat, phog, jharber, bordi and kheemp) grown in the vegetable research blocks of ICAR-CIAH, Bikaner were used as experimental material. To identify ideal harvesting stages suitable for green produce drying, tagging was done at fruit-setting stage subsequently fruit or vegetable harvested at three days intervals during the period of attaining horticultural maturity. The fresh produce harvested at different maturity stages were subjected to sorting, grading, washing and need-based blanching. Sun-drying was carried out in the locally fabricated multi-storey vertical protected structure as designed at ICAR-CIAH, Bikaner and shade drying was carried out in perforated steel trays kept in well-ventilated room with running ceiling and exhaust fans. Dried product was rehydrated and assessed based on sensory parameters to know the ideal harvesting stages.

Blanching

Khejri, kheemp, guarphali pods, kumat seeds and lasoda fruits required blanching prior to drying. The blanching time was standardized according to the method suggested[7] with minor modification. The fresh produce blanched at 90°C for different time periods and then dried separately according to blanching time in perforated stainless-steel trays. Dry product recovery (%) was calculated using formula (Dried produce weight/ Fresh produce weight) ×100. Ideal blanching time for a particular crop-produce was determined based on drying and rehydration ratio, colour and sensory parameters.

Biochemical profiling

Estimation of phenolics, flavonoids and total antioxidant activities were carried out in aqueous 70% methanolic extracts of dry product.

Total phenols and flavonoids

The total phenols content was determined with the Folin- Ciocalteu reagent and expressed as mg gallic acid equivalents (GAE/g DW). Total flavonoids content was assessed by the aluminium chloride colorimetric assay[8] using catechol as the positive reference standard, expressed as mg catechol equivalent (Ct.E/g DW).

Total antioxidant activity (TAA) Assay

The total antioxidant activity (TAA) was determined *in vitro* by cupric ion reducing capacity (CUPRAC) assay[9] using ascorbic acid as reference compound expressed as mg AAE.g^{-1} DW.

Proximate analysis

The proximate analysis of dried produce was determined as procedure outlined by the Association of Official Analytical Chemists[10] for assessing moisture, crude protein, total fat, crude fibre and ash content. Protein, fat and fibre content were analysed by protein estimation system (KES20LE-Kelplus), Soxhlet fat extraction (SOCSPLUS-SCS08-R), fibre estimation system (Fibraplus-FES08-AS), respectively. Ash content was estimated by muffle furnace (MFLT-12(DX)-MAC). The total carbohydrate content (%) was calculated by difference method[10] by subtracting the sum (g/100 g dry matter) of crude protein, total fat, ash and fibre content from 100 g.

Mineral analysis

Mineral analysis was conducted following the method outlined by Raghuramulu *et al*. with minor adjustments[11]. One-gram powdered sample was placed in a 100 mL volumetric flask and subjected to digestion using a triacid mixture of HNO_3, H_2SO_4, and $HClO_4$ in a 9:4:1 ratio. The digested samples were then heated on a hot plate until the volume was reduced to approximately 3 to 5 mL. Digestion completion was confirmed when the liquid became colourless. After allowing the samples to cool, 20 mL of distilled water was added to each flask. Aliquots of this solution were utilized for the determination of K, Ca, Fe, Mn, Zn, Na and Cu. The mineral content was estimated using an Atomic Absorption Spectrophotometer (Shimadzu AA-7000) with AAS standard solution (Thermo fisher Scientific) in 5% HNO_3 was used as a reference.

Statistical analysis

The statistical analysis of data was conducted using analysis of variance (ANOVA) in R software (version 4.3.1). Post-hoc comparisons were carried out using Duncan's Multiple Range Test (DMRT) with the *agricolae* package in R (version 4.3.1).

Results and Discussion

Documentation of traditional crop-plant products and their utilization in the *Thar* Desert

A total of 15 native crop-plant species with notable food values in the *Thar* Desert have been targeted where they are relished and utilized by the local inhabitants to support both nutritional and economic security (Table 1). Perennial trees and shrub-plants such as khejri, ker, pilu, jharber, bordi, kumat, phog and kheemp are commonly found both in the natural habitats and protected areas of farm-lands. Among annuals, arid zone cucurbits such as kachri, kaakdia, mateera and tinda along with vegetable use legume *i.e*., cluster bean (guarphali) pre-dominantly cultivated under rainfed conditions during the monsoon season. The paan-methi, a unique leafy vegetable commercially grown for leaf-drying during the winter season[12].

The tender pods of khejri (Fig. 1a), popularly known as *sangri* are harvested during the peak summer months (April-May) and used for vegetable culinary and pickles or dehydrated and it is a key ingredient in the traditional royal vegetable "*Panchkutta"* delicacy[13]. This vegetable dish includes dried forms of *sangri*, ker, lasoda, kachri fruits and kumat seeds. Ker (Fig. 1b) bears fruits twice a year (April–May and September–October) and its tender fruits used for vegetable culinary or pickled and dehydrated, and for similar uses lasoda fruits (Fig. 1c) are harvested during April–May. Kumat (Fig. 1d) plants produces pods that are full of mature green seeds and used in "*Panchkutta"* culinary. Phog (Fig. 1e) is a multi-function perennial shrub blooming in March and its un-opened flower buds (*phogla*) are traditionally harvested and used fresh or dried as a flavoring agent in *rayta*– a curd-based vegetable culinary. Pilu is an evergreen tree, produces small and juicy fruits (yellow, red or purple colour) during May–June month. Pilu fruits are highly relished during the extreme summer, and the surplus is sun-dried and stored as "*kokad"* for diverse uses. Jharber (Fig. 1f) bears small, red and ripe fruits during October–December and it is consumed both fresh and dried. Dried fruits of jharber are powdered to prepare a traditional product "*borkutta*"[14].

Similarly, bordi trees yield mature fruits during March–April that are consumed fresh and dried for off-season uses[11].

Guarphali (Fig 2a), a highly drought-tolerant legume, cultivated for its tender pods and seeds. The dried tender pods known as *Ramphali*, are stored and used year-round. Paan-methi (Fig. 2b) is a winter season crop, well known for its dried leaves. Dried paan-methi is a high-value product and widely marketed for use in flavoring and garnishing curries and it is in demand by spices manufacturing industry for preparation of ready-to-use curry powders[15]. Kachri (Fig. 2c) is an important indigenous vegetable considered as a "rescue crop" of the *Thar* Desert.

Table 1 — Traditional fruits and vegetables and their products consumed in the *Thar* desert.

S. No.	Scientific name	Common name	Family	Edible part	Traditional product name	Life cycle	Plant form	Fresh produce availability	Mode of consumption
1	*Prosopis cineraria* (L.) Druce	Khejri	Fabaceae	Tender green pods (sangri) and mature pods (khokha)	*Sangri* and *Khokha*	Perennial	Tree	Sangri in April-May and khokha in May-June	Vegetable and pickle; and an ingredient of *Panchkutta* vegetable
2	*Capparis decidua* (Forssk.) Edgew	Ker	Capparaceae	Tender immature fruits	*Ker, Keria*	Perennial	Shrub or dwarf tree	April-May, September-October	Vegetable and pickle
3	*Cordia myxa* L.	Lasoda, Lasora, Gunda	Boraginaceae	Green immature & mature fruits	*Gunda*	Perennial	Tree	April-May,	Vegetable and pickle
4	*Senegalia senegal* (L.) Britton	Kumat	Fabaceae	Mature pods & seeds	*Kumtia* (seeds)	Perennial	Tree	November	Vegetable and pickle
5	*Calligonum polygonoides* L.	Phog	Polygonaceae	Unopened flower buds	*Phogla*	Perennial	Shrub	March	Flavoring agent in *rayta*
6	*Cucumis melo* var. *callosus* (Rottler) Cogn.	Kachri	Cucurbitaceae	Mature fruits	*Kachar, kachri*	Annual	Vine	September-October & April-June	Vegetable, pickle, powder for spice-base
7	*Cucumis melo* L. var. *momordica (Roxb.)*	Kaakdia	Cucurbitaceae	Mature & ripen fruits	*Kachra, kaakdia* & *khelera*	Annual	Vine	October-November & April-June	Vegetable, salad & dried *khelra* for vegetable
8	*Cyamopsis tetragonoloba* (L.) Taub.	Guarphali	Fabaceae	Tender pods	*Guarphali, Ramphali*	Annual	Herb	August-October & April-June	Vegetable & dried as *Ramphali* for culinary
9	*Benincasa fistulosus* (Stocks)	Tinda	Cucurbitaceae	Tender & mature fruits	*Tendsi* & *Phophalia*	Annual	Vine	September-October	Vegetable
10	*Trigonella corniculata* L.	Paan-methi	Fabaceae	Fresh and dried leaves	*Paan-methi*	Annual	Herb	December-January	Vegetable and flavoring agent
11	*Leptadenia pyrotechnica* (Forssk.) Decne.	Kheemp	Apocynaceae	Tender pods	*Kheepoli*	Perennial	Shrub	March-April & September-October	Vegetable and pickle
12	*Ziziphus nummularia* (Burm.f.) Wight & Arn.	Jharber	Rhamnaceae	Fresh fruits	*Boria, channber*	Perennial	Shrub	October-November	Fresh fruits and dried fruit for year-round uses and powder for *borkutta*
13	*Ziziphus rotundifolia* Lam.	Bordi	Rhamnaceae	Fresh fruits	*Bordi*	Perennial	Tree	March-April	Fresh fruits and dried fruit for year-round uses
14	*Ziziphus mauritiana* Lam.	Ber	Rhamnaceae	Fresh fruits	*Bor*	Perennial	Tree	January-March	Fresh fruits and dried fruit for year-round uses
15	*Salvadora oleoides* Decne.	Meetha jal	Salvadoraceae	Fresh fruits	*Kokad*	Perennial	Tree	May-June	Consumed as fresh fruit and dried for off-season use

Its mature fruits are extensively utilized in vegetable cooking, chutneys, pickles and salad making. Kachri fruits also dehydrated on large-scale and powder is utilized industrially for preparing ready-to-use sweet-acidic curry mixes[12]. Kaakdia or phoot-kakdi (Fig. 2d) is an underutilized cucurbit have considerable diversity and its mature ripen fruits are consumed fresh as dessert-salad, vegetable cooking and slices also dried and called "*khelera"* which are utilized for off-season vegetable after rehydration. Kaakdia fruit juice has cooling effect and its protein-rich seeds are used in sweets and confections. Kheemp (Fig. 2e) is short perennial, xerophytic and leafless shrub which bears green pods during March–April and September-

Fig. 1 — (a) Khejri tree, fresh *sangri*, dried *sangri*; (b) Ker plant, fresh fruits, dried fruits; (c) Lasoda tree, fresh fruits, dried fruits; (d) Kumat tree, fresh pods, dried seeds; (e) Phog plant, fresh flower buds, dried flower buds (*phogla*); (f) Jharber plant, fresh fruits, dried fruits

October. Tender pods known as "*kheepoli*" consumed fresh as vegetable culinary and also sun-dried for off-season uses[16]. Tinda or round melon (Fig. 2f) is a notable arid cucurbit and grown under mixed cropping during kharif season. The native landraces produce bigger sized fruits compared to the commercial varieties, and mostly harvested during October month for dehydration. Tender fruits are of medium quality and consumed fresh for vegetable cooking while fully mature fruits after removal of seeds are sun-dried into a preserve form known as "*Phophalia"*.

Fig. 2 — (a) Guarphali plant, fresh pods, dried pods; (b) Paan-methi plant, fresh leaf, dried leaf; (c) Kachri plant, fresh fruits, dried slices; (d) Kaakdia plant, fresh fruits, dried slices (*khelra*); (e) Kheemp plant, fresh pods, dried pods (*kheepoli*); (f) Tinda plant, fresh fruits, dried slices (*Phophalia*)

Standardization of harvesting stages, blanching and on-farm drying

The stages of harvest significantly influence the post-harvest shelf-life, drying yield, quality of dried product and market acceptability. Optimal harvesting stages have been standardized for traditional fruits and vegetables to enhance the efficiency and quality of on-farm drying methods. For drying purposes, fruits and pods of ker, kheemp, khejri and guarphali should be harvested at the tender green stages and approximately 12-15, 8-12, 10-18 and 12-20 days after fruit or pod set, respectively (Table 2). Harvesting of ker fruits beyond 15 days resulted into seed hardening and increased acridity, and rendering them unsuitable for pickling or drying. Similarly, khejri pods (*sangri*) harvested after 18 days from setting or pod development hardened the seed and lignified pod walls which deteriorate textural quality and drying suitability. Lasoda fruits are best harvested at the fully developed mature green stage when the latex around the stone becomes diluted and begins to exude naturally from the stalk end upon removal of the basal cap. Ripen lasoda fruits with increased sugar content and loss of firmness is not suitable for culinary or pickling applications.

The cucurbitaceous vegetables such as kachri, kaakdia and tinda should be harvested at full maturity to ensure high quality dried products. Immature fruits have high moisture content and resulting in lower drying recovery and bitterness. For tinda, the pericarp is utilized for drying and therefore, fruit harvesting at full maturity allows easier separation of seeds. Fruits of jharber and bordi should be harvested at ripen and turning to red colour stage when it easily detaches

Table 2 — Standardization of harvesting stage, pre-processing and drying of fresh produce

Produce	Harvesting stage	Pre-processing	Drying method and time	Drying yield (%)
Khejri pods (*sangri*)	Tender green stage (10-18 days after pod setting), before seed hardening and fibre accumulation, needs 3 - 4 harvesting at 3 days interval	Sorting, grading and blanching in boiling water for 5 min and immediately dipping in cold water for 10 min	Sun-drying 36-48 h	25.70±1.34
Ker	Harvesting at tender green stage (12-15 days after fruit setting), before seed hardening, needs 3-4 harvesting at 3 days interval	Sorting, grading and astringency removal by dipping in brine solution for 3-4 days	Sun-drying 48 h	18.04±1.34
Lasoda	Harvesting at mature green stage (18-20 days after fruit set, when latex oozing out while opening of basal cap)	Sorting, grading, blanching in boiling water for 25-28 min and stone removal	Shade drying with proper ventilation for 72 h	16.24±0.49
Kumat seeds	Harvesting at full maturity stage of pod (when pod colour converts from green to light green)	Removal of seeds from pods and quick dip in hot water (30 seconds)	Sun-drying 24-36 h	43.87±1.16
Phog flower buds (*Phogla*)	Harvesting of flower buds prior to just opening (4-5 days after bud initiation)	Sorting and removal of opened flower buds	Shade drying for 24 h with proper ventilation	30.84±0.73
Kachri	Harvesting of fully mature fruits prior to ripening	Washing, peeling and slicing in circular rings	Sun-drying 72-84 h	13.91±0.63
Kaakdia	Harvesting at full maturity stage (A full slip stage when fruit stalk detached easily)	Washing, seed and placenta separation and cutting into 2-3 cm thick slices	Sun-drying 72 h	5.73±0.32
Guarphali	Harvesting at tender green stage (12-18 days after pod setting)	Sorting, grading and blanching in boiling water for 5 min	Sun-drying 72 h	21.14±0.93
Tinda	Harvesting at full maturity stage (when seeds matures)	Washing, cutting into two halves and seed and placenta removal	Sun-drying 72 h	6.14±0.23
Kheemp	Harvesting of pods at tender green stage (8-12 days after pod set)	Sorting, grading, washing and blanching in boiling water for 7 min	Shade-drying for 48 h	16.12±0.77
Paan-methi	First harvest after 55-60 days of sowing, needs 4-5 cuttings in a crop season	Removal of weeds, grasses, leaves and thick stem portion from harvested foliage	Sun-drying for 48-60 h	9.86±1.03
Jharber	Harvesting at fully ripened stage (when fruits turn from yellow to complete red)	Sorting, grading and washing in hot water	Sun drying for 72-84 h	45.58±1.86
Bordi	Harvesting at fully ripened stage (when fruits turn from light green to complete red)	Sorting, grading and washing in hot water	Sun-drying for 48-60 h	49.51±1.98

from branch-lets with gentle shaking. Kumat pods should be harvested at full maturity to ensure the culinary quality and bold seeds.

Standardization of blanching duration

Blanching is critical process and pre-drying heat treatments applied to inactivate the spoilage enzymes, preserve colour and texture, enhance nutrient retention, softens tissues, removes entrapped air and reduces microbial load[17]. Blanching is in particular recommended for tender pods of sangri, guarphali and kheemp and lasoda fruits prior to drying. The blanching duration using boiling water is standardized and it is 30 seconds for kumat, 5 min for sangri and guarphali, 7 min for kheemp and 25-28 min for lasoda (Table 2). The duration of process is influenced by tissue hardness of produce, fruit or pod thickness and the chosen blanching method. Lasoda fruits requires the longest blanching time due to its firm texture and thicker pericarp while kheemp took slightly longer blanching than sangri and guarphali due to its denser tissue structure. The optimization of blanching time is essential to ensure high quality of dried products. Exceeding the recommended duration may lead to undesirable shrinkage, excessive nutrient loss and textural softening. Conversely, under-blanching may adversely affect drying kinetics and product shelf-life[18].

Drying of traditional crop-plant produce

Sun-drying is the most appropriate and cost-efficient method for preserving arid fruits and vegetables in the *Thar* Desert and it is chiefly due to the region's abundant solar radiation and consistently low humidity throughout the year. However, certain crops such as phog flower buds, paan-methi and lasoda require shade drying to retain their desirable colour and over-all quality. The majority of crop produce listed in (Table 2) can be effectively dried using conventional sun-drying methods. The duration required for drying fresh produce varies depending on several factors including the size, thickness, initial moisture content, evaporation gradient and ambient temperature during the drying process[18]. Notable variation in drying time among the different crop-commodities was recorded and it is approximately 36-48 h for sangri, 48 h for ker fruits, 24-36 h for kumat seeds and 48 h for kheemp pods. Crops with higher initial moisture content such as kachri, kaakdia, tinda and guarphali required significantly longer drying duration even during the summer months. This is attributed to the greater amount of water that must be removed to achieve adequate preservation (Table 2). Similarly, longer drying period were recorded for jharber and paan-methi as their harvest period is during cool season, moderate temperature and reduced solar radiation typically in winter months (December–January). In contrast, significantly shorter drying duration were required for phog flower buds (approximately 24 h) and kumat seeds (24-36 h) due to their lower initial moisture content and that facilitates faster moisture loss during dehydration.

Drying yield of arid crop-plant produces

A wide-range of variation has been recorded in the drying yield of edible parts of arid horticultural crop-plants produces (Table 2). The highest dried product recovery was recorded in bordi fruits (49.51±1.98%) followed by jharber fruits (45.58±1.86%) and kumat seeds (43.87±1.16%). Relatively high drying yields were also measured in phog flower buds (30.84±0.73%) followed by khejri pods, (25.70±1.34%), guarphali (21.14±0.93%), ker fruits (18.04±1.34%), lasoda fruits (16.24±0.49%), kheemp pods (16.12±0.77%) and kachri fruits (13.91±0.63%). The dry product yields of paan-methi leaf-lets and tinda fruits were comparatively low 9.86±1.03% and 6.14±0.23%, respectively. The lowest dry product recovery was recorded in kaakdia fruit slices (5.73±0.32%). The higher dry matter yields in bordi and jharber are attributed to the fact that both were dried with the stones intact, which significantly enhanced the final dry weight. In case of kumat, seeds depleted moisture and accumulate dry matter during the development, resulting in higher recovery upon drying. Conversely, the low dry yields in kaakdia and tinda can be attributed to their high moisture content and removal of seeds and placental tissue before drying.

Proximate and bio-chemical analysis of traditional crop-plant produces

The proximate composition of desert crop-plant produces such as *sangri*, ker, lasoda, kumat, phog, kachri, kaakdia and guarphali is presented in (Table 3) highlighting their nutritional profiles in terms of crude proteins, carbohydrates, fats, crude fibres, ash and moisture. Among the produce, kumat stands out with the highest crude protein (36.48%) and fat content (13.57%) indicating its potential as a nutrient dense food source. *Phogla* has the highest crude fibre (33.40%) making it beneficial for digestive health, though it is relatively low in protein (8.50%). Sangri, ker and guarphali are rich in carbohydrates (54.49%,

52.78% and 52.54%, respectively) and maintain moderate protein content (17.07%, 18.70% and 16.09%, respectively) suggesting their utility as energy and protein sources. The proximate data indicates that sangri, ker and guarphali offer a balanced composition with good source of proteins and high carbohydrate levels and thus supporting their traditional uses in local diets for inhabitants of *Thar* Desert. Kachri is a popular traditional vegetable rich in protein (20.10%), fat (11.89%) and fibre (22.85%) and serve as a good energy source with digestive benefits. It is consumed in many-ways such as vegetable, dried slices, pickle, powder, ready to use spice ingredient and as an alternative of raw mango powder for providing acidic flavour to the food[12]. The ash content, representing total mineral content and it is highest in phogla (7.96%) and ker (7.93%) indicating a strong mineral profile. The kaakdia contains highest moisture (93.71%) that is why other than vegetable it is also utilized for salad, sweet-juices and consumed to rehydrated body during summer months[14,19]. These findings emphasize that nutritional diversity of native crop-plants underlining their importance in food security and traditional health systems in the *Thar* Desert.

The bio-chemical profiling of dry products from various arid crop-plants revealed significant variation among the species analysed. *Phogla* contains the highest values for total phenols (132.51 mg GAE/g DW), flavonoids (4.69 mg CatE/g DW) and total anti-oxidants (310.39 mg AAE/g DW). This indicates phogla's potential as a powerful natural anti-oxidant source likely due to its high phenolic and flavonoid content which contributes directly to free radical scavenging capacity and reducing ill effect of heat stroke in hot arid region[20]. Sangri also demonstrated strong anti-oxidant properties with phenolic content (77.97 mg GAE/g DW) and anti-oxidant activity (165.63 mg AAE/g DW) along with high flavonoid levels (4.68 mg CatE/g DW) and statistically comparable to phogla. Due to rich in bio-active compounds, sangri has proven antidiabetic, antihyperlipidemic and immune system booster in several clinical studies[21]. This may be the reason behind integrating sangri since ancient period in traditional food system of *Thar* Desert and being preserved through drying for round the year consumption in various forms such as vegetable, pickle, *Panchkutta* and powder[13]. Ker, kachri, kumat and guarphali generally showed significantly low values across all bio-chemical traits indicating limited anti-oxidant potential compared to phogla and sangri (Table 3). Lasoda, kaakdia and guarphali exhibited moderate levels of flavonoids (2.02 - 2.42 mg CatE/g DW) though their total phenols and antioxidant capacities were relatively lower. The significantly high phenols and antioxidants in sangri and phogla compared to other produce analysed may be due to their survival mechanism under rainfed conditions and also their flowering and fruiting coincided during the extreme summer and prolonged heat period which promotes accumulation of bioactive compounds in plant produce[22].

Mineral content in dried products of arid crop-plants

The mineral composition studies of the selected arid region crop-plant products revealed substantial variations across the species (Table 4). Among the studied products, *phogla* exhibited the highest concentrations of potassium (23,571.33 ppm), zinc

Table 3 — Proximate and bio-chemical analysis of dry products of traditional crop-plants

Product	Crude Proteins (%)	Carbohydrate (%)	Fat (%)	Crude fibres (%)	Ash (%)	Moisture (%)	Total phenols (mg GAE/ g DW)	Total flavonoids (mg CatE/ g DW)	Total antioxidants (mg AAE/ g DW)
Sangri	17.07^{d}	54.49^{a}	4.58^{c}	13.63^{f}	5.03^{e}	75.19^{d}	77.97^{b}	4.68^{a}	165.63^{b}
Ker	18.70^{c}	52.78^{b}	1.46^{d}	6.95^{g}	7.93^{a}	83.70^{b}	9.86^{d}	1.37^{d}	16.53^{e}
Lasoda	14.53^{f}	50.71^{c}	0.78^{e}	19.41^{c}	4.79^{b}	85.22^{b}	16.10^{c}	2.42^{b}	30.49^{c}
Kumat	36.48^{a}	21.73^{f}	13.57^{a}	14.50^{e}	4.48^{f}	55.16^{f}	3.68^{f}	0.56^{e}	13.09^{e}
Phogla	8.50^{h}	32.42^{d}	11.73^{b}	33.40^{a}	7.96^{c}	70.51^{e}	132.51^{a}	4.69^{a}	310.39^{a}
Kachri	20.10^{b}	28.47^{e}	11.89^{b}	22.85^{b}	3.07^{g}	77.60^{c}	9.67^{d}	1.38^{d}	23.81^{d}
Kaakdia	11.69^{g}	50.59^{c}	0.56^{e}	19.12^{c}	3.87^{g}	93.71^{a}	7.95^{de}	2.04^{c}	14.08^{e}
Guarphali	16.09^{e}	52.54^{b}	0.71^{e}	18.57^{d}	6.21^{d}	78.87^{c}	5.99^{e}	2.02^{c}	16.17^{e}
Significance	***	***	***	***	***	***	***	***	***
Pr> F	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

Means followed by different superscript letters within the same column differ significantly based on Duncan's Multiple Range Test (DMRT).
Note: Proximate parameters represented on the dry weight basis while moisture content is calculated based on fresh weight of produce.

Table 4 — Mineral contents in dried products of arid crop-plants

Product	Potassium (ppm)	Zinc (ppm)	Sodium (ppm)	Calcium (ppm)	Manganese (ppm)	Copper (ppm)	Iron (ppm)
Sangri	12596.67^{b}	31.67^{c}	113.28^{g}	1307.25^{d}	23.20^{b}	9.70^{c}	35.62^{c}
Ker	4658.67^{d}	21.68^{f}	14.57^{h}	580.78^{f}	5.81^{e}	7.32^{d}	16.34^{g}
Lasoda	88.69^{g}	17.48^{g}	201.98^{e}	513.16^{g}	4.74^{g}	6.27^{e}	16.01^{h}
Kumat	5182.33^{c}	28.41^{d}	137.10^{f}	1881.10^{a}	9.60^{d}	3.94^{f}	32.05^{e}
Phogla	23571.33a	54.33^{a}	423.90^{a}	1735.71^{b}	77.38^{a}	21.42^{a}	61.50^{a}
Kachri	124.06^{g}	22.94^{e}	220.85^{d}	755.82^{e}	5.60^{f}	4.18^{f}	34.75^{d}
Kaakdia	2051.33^{f}	14.62^{h}	224.70^{c}	1480.03^{c}	4.70^{g}	2.83^{h}	24.41^{f}
Guarphali	2726.67^{e}	46.63^{b}	353.38^{b}	752.04^{e}	17.31^{c}	12.48^{b}	42.71^{b}
Pr> F	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

Means followed by different superscript letters within the same column differ significantly based on Duncan's Multiple Range Test (DMRT).

(54.33 ppm), sodium (423.90 ppm), manganese (77.38 ppm), copper (21.42 ppm) and iron (61.50 ppm), and it significantly exceeding the levels found in other targeted species ($p<0.05$). This indicates potential of *phogla* as a rich source both macro and micronutrients. Sangri also depicted the second highest potassium content (12,596.67 ppm) and moderate levels of other nutrients. Kumat seed is lower in sodium and copper and had the highest calcium content (1,881.10 ppm) making it potentially valuable for the dietary calcium supplementation. In contrast, lasoda and kaakdia consistently reported the lowest nutrient concentrations in particular to the zinc, copper and manganese. However, kaakdia had relatively higher sodium (224.70 ppm) and calcium (1,480.03 ppm). Guarphali often considered nutritionally rich also contains high levels of zinc (46.63 ppm), sodium (353.38 ppm) and iron (42.71 ppm) and thus supporting its valuation for traditional medicinal and dietary uses. The observed nutritional variability among the species highlights the adaptive mechanisms of desert crop-plants to extremes of climate and influence of their growing conditions on the nutrient accumulation. Similar results on variations in the mineral contents were also observed among species of leafy vegetables from north-east India and indigenous food plants of Himalayas[23,24]. The present findings underline the nutritional diversity among the arid zone produce of the *Thar* desert with implications for the promotion in particular to *phogla*, *sangri* and guarphali richness in multiple minerals especially in potassium, zinc and iron in nutrition-sensitive agriculture and food security initiatives under resource constraints environment.

Conclusions

This study concludes that adopting standardized protocols for optimal harvesting, post-harvest handling, pre-processing, blanching, and hygienic drying can significantly enhance the quality and marketability of both fresh and preserved products. Fresh products such as *sangri*, kumat, ker, lasoda, guarphali, and kheemp demonstrated high dry product recovery, making them highly suitable for processing and commercial promotion. Additionally, kumat, *phogla*, *sangri*, and guarphali exhibited high concentrations of proteins, fats, fibers, antioxidants, and essential minerals. In particular, *phogla* and *sangri* were rich in minerals and bioactive compounds, indicating strong potential for use in nutraceuticals and health supplements in future. The promotion and commercialization of these native crops can provide nutritionally valuable food products while enhancing the economic resilience of local communities.

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Author Contributions

PSG: conceptualization, documentation, methodology, proximate and mineral analysis, writing original draft, DKS: provide resources, guiding, manuscript editing, HR: Provide fresh produce, assist in conducting experiment, KLK: help in documentation, experiment, statistical analysis, MKB: biochemical analysis, D.K. Sarolia: Manuscript editing, resources.

Conflict of Interest

The authors declare that they have no conflict of interest.

Ethics Approval

Not applicable

Prior Informed Consent

All the respondents provided prior informed consent.

Use of Artificial Intelligence (AI)

The authors declare that AI-assisted tools were used solely for language editing, including improving grammar, clarity, and overall readability of the manuscript. AI tools were not used to generate figures or develop the scientific content. All data analysis, interpretation of results, and conclusions were independently developed, reviewed, and validated by the authors. The authors assume full responsibility for the accuracy, originality, authenticity, and scientific integrity of the work presented in this manuscript.

Data Availability

All the data are exclusively retained by the corresponding author and will be available upon reasonable request.

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