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CLEANER PRODUCTION AND SUSTAINABLE PROCESSES FOR ENVIRONMENTAL REMEDIATION

Arid/semi-arid flora as a treasure trove of bioactives and bioenergy: the case for underutilized desert legumes towards environmental sustainability

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Abstract
As the spectre of climate change gains in strength with each passing moment, many of our mundane food crops like rice face the heat, leading to uncertain yields and unforeseen disease outbreaks. Subsequently, mankind is forced to look for alternative food choices that should primarily come from indigenous plants that are less demanding in terms of usage of water and application of chemical-based fertilizers/pesticides. There are plants growing in the wild in the arid and semi-arid zones of Rajasthan, India, that can come to the rescue, with an added potential for development into valuable functional foods—i.e., not only as source of carbohydrates, proteins, and micro-nutrients but also that of health benefiting nutraceuticals (like antioxidant flavonoids) and relevant enzymes. The other parts (non-edible) of these plants have often also been traditionally validated via diverse ethnomedicinal practices; these could also be useful bioenergy sources. Keeping in mind the broader aim of looking at future functional foods that are also required to be environmentally sustainable, the current report: (a) reviews the extant literature on underutilized legumes from arid/semi-arid zones, (b) discusses current status with respect to biological activities present therein, and (c) suggests pertinent research questions and solution paths in the domains of bioactives, bioenergy, and sustainable environment.

Keywords Underutilized plant · Desert legume · Functional food · Nutraceutical · Antioxidant · Bioenergy · Environmental sustainability

Introduction

All over the world, a variety of plants are consumed as grains, vegetables, and fruits, but only a few have been utilized as commercial cash crops. So there remain to be explored various neglected, underutilized or orphan plant species that possess the potential to add diversity to the human diet, and also increase food production levels, and thus, enable more sustainable and resilient agro- and horti-food systems (Baldermann et al. 2016). These underutilized plants could not only enrich our food palette with appropriate nutrients (such as proteins and vitamins to name a few) and nutraceuticals (such as health-promoting terpenoids and flavonoids) but also enhance the capacity of the future generations to feed themselves in an environmentally sustainable manner. Reports also exist to show that some of these plants contain higher levels of nutrients such as vitamin C and pro-vitamin A compared to the more widely available commercial species (Kour et al. 2018).

A major challenge in future would be to feed a growing world population (expected to reach 9.6 billion people by 2050) while maintaining sustainable environmental conditions (Foley et al. 2011). In the past, it was easier to practice sustainable agriculture as the human populations as well as dependence on chemicals (e.g., fertilizers and pesticides) were low. The four major crops that received the focus of agricultural domestication were wheat, rice, corn, and potatoes. Further intensification of food production (through

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irrigation-supported plantation of disease-resistant, high-yielding grain varieties) heralded by the Green Revolution helped meet the nutrition demands of people to a large extent. However, the overuse of antimicrobial agents, toxic chemicals, and pesticides has resulted in declining biodiversity and human health. Also, the changing climate has started affecting the crop production in main producing areas, ultimately leading to price rise (Porter et al. 2014). Long-term natural sustainability priorities include water-shortage and land-erosion prevention measures, ecological restoration and balanced land usage (innovative crop cultivation, avoiding overgrazing), and socioeconomic awareness aimed for sustainable resource exploitation (Chlachula 2021).

It is a fact that despite initiatives such as the Green Revolution in the field of food and agriculture, millions still go hungry in different areas of the world. This has prompted the United Nations (UN) to have zero hunger as one of the Sustainable Development Goals (SDGs) via eradication of hunger and malnutrition by 2030 (Sustainable Development Goal 2 n.d.). As per the UN data in 2020, 149.2 million children under the age of five suffer from stunting, which is aimed to be reduced by 50% by 2030.

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), a research centre of the Consultative Group on International Agricultural Research (CGIAR), is a non-profit, non-political public international research organization that conducts agricultural research for development in Asia (including India) and Sub-Saharan Africa, in collaboration with a large number of international partners. It has been awarded the 2021 Africa Food Prize for its contributions to the improvement of food security in thirteen sub-Saharan African countries. From 2007 to 2019, ICRISAT led a partnership of collaborators to implement the Tropical Legumes project. In collaboration with the International Center for Tropical Agriculture (CIAT) and the International Institute of Tropical Agriculture (IITA), 266 enhanced-legume varieties and nearly five lakh tonnes of seed for a variety of legume crops were developed. These new varieties have assisted more than 25 million smallholder farmers in becoming more resistant to climate change, pests, and outbreaks of diseases (ICRISAT 2021). Improved varieties of pigeon pea (*Cajanus cajan*) resistant to sterility mosaic disease (SWD) and Fusarium wilt (FW) were also developed (ICRISAT Annual Report 2022).

The Central Arid Zone Research Institute (CAZRI, Jodhpur) was established under Indian Council of Agricultural Research (ICAR), New Delhi, for scientific and sustainable management of resources in arid regions of India. Several projects are being conducted for the genetic improvement of annuals and perennials like cluster bean (*Cyamopsis tetragonoloba*), *Cordia* species, sorghum etc., through hybridization and mutagenesis, functional food development from local plant sources, biodiversity conservation, land and water resource management, non-conventional energy systems, and integrated pest management (CAZRI 2022).

The current review discusses the scope of underutilized plants of Indian (semi) arid regions to cater to the needs of (a) healthy nutrition and (b) green energy. Challenges and opportunities for the legume scientists are also highlighted.

To eat or not to eat: targeting the triple burden of malnutrition

Scientists today accept that there are three facets to malnutrition: undernutrition (associated with underweight and child stunting) that coexists with overnutrition (associated with overweight and diet-related non-communicable diseases like obesity) (Victora and Rivera 2014) and micronutrient deficiency. This is referred to as the triple burden of malnutrition, and is seen today in both the urban and rural populations. Nguyen et al. (2021) pointed out that urban slum dwellers (whose population is one the rise as people leave villages for better job opportunities in the cities) are the most vulnerable population as far as undernutrition is concerned. As per Nandal and Bhardwaj (2014), undernutrition in the form of protein-energy malnutrition and micronutrient deficiencies not only affect physical appearance and immunity of children but also have long-term repercussions particularly on their mental abilities and productivity.

An ironical fact, worthy of discussion, is also that some sections of society are not consuming healthy foods despite availability. In a research brief published by ICMR-NIN, 'Share of Fruits and Vegetables in Tackling CVDs and NCDs (especially diabetes, heart attack, stroke and cancer) in Indian Context', it was stated that despite the sufficient per capita availability of fruits and vegetables, consumption of these micronutrient rich foods is low in urban and rural areas, and that green leafy vegetables are the least consumed food groups in both rural and urban areas. In another manual published by ICMR-NIN, it was recommended that vegetables including green leafy vegetables and locally available, seasonal fruits should be part of the daily menu for children along with frequent changes in the menu (ICMR-NIN 2011).

On the other side, in low and middle income countries, an increasing trend has been observed towards the purchase and consumption of ultra-processed, packaged foods (Popkin et al. 2020). These foods are often rich in refined sugars, fats, and salts and are relatively inexpensive and often ready-to-eat. They are assumed to be the major causal factors towards development of obesity and other non-communicable disorders. Therefore, the future foods have to be 'smart' in the sense that they should be capable of targeting both types of malnutrition discussed above.

In India, micronutrient deficiency (hidden hunger) continues to be severe. Iron deficiency anaemia (IDA) is believed to impact approximately 60% of anaemic individuals, associated with decreased productivity and fatigue. Important inputs for biological processes, such as iodine and vitamin A, have not yet found their way into the Indian diet. This is of concern because micronutrient deficiency has been associated with increased maternal mortality in adults, decreased cognitive development, and higher newborn mortality (Pingali et al. 2019).

Environmental nutrition: a new philosophy for food scientists

Over the past few decades, the life cycle of food has expanded to include processes such as manufacturing, packaging, long-distance transportation, storage, and waste generation, ultimately leading to high environmental costs of food production. These processes result in degradation of aquatic ecosystems due to nitrogen or phosphorus pollution, rise in the greenhouse gases like nitrous oxide and methane (as agricultural emissions), and photochemical smog—all contributing to climate change (Lynch et al. 2021).

Linking the food system, environment, and public health Sabaté et al. (2016), proposed an environmental nutrition model (ENM). As diet-related health issues (such as obesity and malnourishment) are a major consequence of the food system, it also incorporates societal demands and nutritional adequacy of the food to provide a more comprehensive picture. This model quantifies the inputs (such as water, energy, land, and chemical usage) and outputs (such as GHG emissions and waste) related to the life cycle of a given food item. Such information, conveyed through an appropriate food labelling scheme, should help the consumers to make healthier and environmentally sustainable food choices when faced with multiple options.

Consumers have both vegetarian as well as non-vegetarian food preferences. From an ecological perspective, the production of livestock for human consumption is not very resource-efficient and requires serious contemplation both on the part of consumers and scientists. As per Sabaté et al. (2015), the production of 1 kg of protein from beef requires approximately 18 times more land, 10 times more water, 9 times more fuel, 12 times more fertilizer, and 10 times more pesticide when compared with producing 1 kg of protein from kidney beans (*Phaseolus vulgaris*). However, a similar data is not available for underutilized legumes of India such as *Prosopis cineraria*.

The adoption of underutilized legumes is essential for addressing food security, particularly in this age of climate change. Due to their high nutrient status, capacity to enhance soil nutrients, potential to mitigate the effects of climate change, resilience to negative effects of climate change (such as erosion and disease emergence), potential to control plant diseases, and weed control, underutilized legumes can improve food security. They are very cheap and high in protein, one of the most important nutrients for a healthy life, especially when animal protein sources are discouraged because they are detrimental to human health. Plant-based protein is now being promoted and advised to meet the constantly expanding population's nutritional needs (Ayilara et al. 2022).

Therefore, in light of the above, we feel that food scientists need to work towards generating ENM-specific data for indigenous, underutilized plants, as these might find quicker acceptance among the locally placed consumers owing to traditional patterns of dietary behaviour. Currently, this is a research gap for most of our edible plants, including the underutilized ones.

Underutilized legumes in Indian arid/semi-arid regions: revisiting their traditional uses in food and bioactive potential

Meeting daily protein and energy requirements solely through animal food is often uneconomical and unsustainable, particularly for low-income households, further emphasizing the need to identify alternative plant-based sources for the purpose. Protein deficiency results in stunted growth, low RBC count, low energy, and impaired immunity (Ikhajiagbe et al. 2022). Legumes are the major source of proteins in the diet. A good protein source would contain all the nine essential amino acids, which are actually more prevalent in animal protein. However, consumption of the latter in meat has often been associated with rise in diet-related non-communicable diseases like colorectal cancer, diabetes mellitus, and coronary heart disease (Chung et al. 2021). Since no single legume contains all the nine essential amino acids, it might be wiser to complement the widely consumed legumes with those not-so-widely consumed (such as the underutilized ones) and eat them in a mixture, with a hope that the deficiency would be taken care of in the legume combination. Fulfilling this aim would require the scientists to explore and fully characterize the nutritional as well as the nutraceutical potential of underutilized legumes. As per Arora (2014), 778 underutilized species were reported to exist in the Asia–Pacific region, out of which, 14 were grain legumes/pulses. Considering the land area used for cultivating the above-mentioned plants (in comparison to rice, wheat, maize, and potato), these can be considered as underutilized albeit with potential. The nutraceutical and flavour profiles of orphan legumes can be improved by CRISPR-Cas-based gene editing techniques with higher acceptance by societies and the government (Joshi et al. 2023b).

Prosopis cineraria, *Cyamopsis tetragonoloba*, and *Acacia senegal* are a few of the edible underutilized legumes from Rajasthan, India, (Fig. 1) with the potential to be used as sources of bioactives and bioenergy. *P. cineraria* and *A. senegal* are common ingredients of traditional Rajasthani dish, Panchkuta. It is a classic example of how local people make use of available resources to meet their nutritional requirements and employ various techniques for the conservation and sustainability of these plants (Singh et al. 2023). The authors also reported the cultural knowledge, regional, and seasonal availability of these plants as opportunity to utilize them in an innovative manner. The following paragraphs discuss a few of the traditional uses along with bioactivities reported from these plants:

Prosopis cineraria

Prosopis cineraria (khejdi) is an important legume of the Asian (semi) arid regions, particularly India and United Arab Emirates, and all its parts have some utility for the local human populations. Considered a lifeline of desert agroforestry, its wood provides timber and fuel, the roots harbour nitrogen-fixing bacteria and enrich the surrounding soils, the leaves are fodder for the cattle, while the nutritious pods are edible to humans (Rai et al. 2021). The tree commands religious veneration among the local populace particularly the Bishnoi community of Rajasthan, India, who are known to have sacrificed their lives for its protection. A few of its ethnomedicinal uses have been in cough, dysentery, leukoderma, rheumatism, microbial infections, worms, and scorpion stings (Afifi and Al-rub 2019). The tree bears fruits in the hot seasons of April–June in the form of seed-containing cylindrical green pods, known to be rich sources of antioxidants and nutrients particularly vitamin C, calcium, and iron (Mala 2009). The local communities store these pods by boiling and drying them or pickling for later out-of-season use. The seeds have also been recommended as a potential candidate for targeting protein-calorie malnutrition and development into an economic food for humans. Furthermore, it has been reported that *P. cineraria* pod flour has low glycemic index, which suggests that it could be considered as a healthy alternative to refined wheat flour for incorporation into food items like biscuits (Saraswat et al. 2020).

A few representative studies with respective to bioactives from *P. cineraria* pods are highlighted below. In one study, Ram et al. (2020) reported that crude ethanolic extracts of the pods of *P. cineraria* led to elevation in SOD and catalase activities, as well as reduction in lipid peroxidation in rabbits; the extracts also inhibited HMG-CoA reductase activity, and reduced the pathogenesis of atherosclerosis. They have attributed these effects to the bioactives present in the pod extracts, viz. polyphenols, flavonoids, saponins, etc. Earlier, Liu et al. (2012) had solvent-extracted a few bioactive components from *P. cineraria* pods and verified their roles as potent antioxidant and anti-inflammatory agents by testing for LPO, CoX-1, and COX-2 enzyme inhibitions. These bioactive components obtained by them belonged to the class of triterpenoids, fatty acids, piperidine alkaloids, and polyphenols. It must be noted here that the choice of extraction and purification system significantly affects the

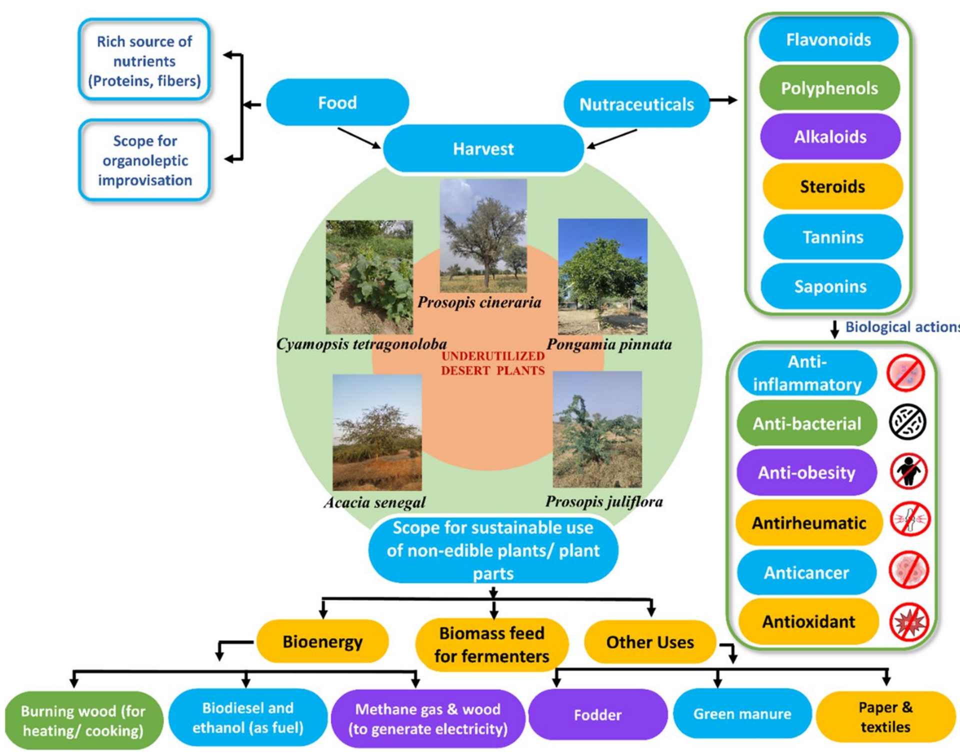

Fig. 1 Underutilized desert legumes as sources of food, nutraceuticals, bioenergy and other applications

kind of metabolites the researchers end with. Recently, our research group used a combination of chromatography procedures and purified flavonoids (vitexin, puerarin, phloridzin, and daidzein) with antioxidant potential from the tree pods (Asati et al. 2022).

Cyamopsis tetragonoloba

The indigenous legume plant *Cyamopsis tetragonoloba* (guar) has also been an important food and fodder source in the arid and semi-arid zones of India, since a long time. It has been reported to be a rich source of protein and phytochemicals such as polyphenolic antioxidants (Asati et al. 2021). Reports also suggest that it has historically been used as green manure (BeMiller 2009). Of the total guar produced in the world, 80% grows in India, out of which 70% is from the desert state of Rajasthan, India. Guar seeds are used for the commercial production of the galactomannan-rich guar gum, utilized in pharmaceuticals, paper, textile, explosive, oil well drilling, cosmetics industry and food thickener, and stabilizer (Mudgil et al. 2014). The seeds are also rich sources of total and soluble dietary fibre—reaching up to 58% and 32% of seed dry weight, respectively (Kays et al. 2006). In one study, Bharath Kumar and Prabhasankar (2016) reported on the hypoglycaemic potential of noodles containing whole guar and guar seed powder.

Badr et al. (2014) reported on the anticancer activity of *Cyamopsis tetragonoloba* seed extract (in crude form) against human prostate carcinoma cell line (PC3), colon carcinoma cell line (HCT116), and intestinal carcinoma cell line (CACO-2). In another study, Wang and Morris (2007) had reported the presence of isoflavonoids such as daidzein and genistein in the seeds of *C. tetragonoloba*; they also emphasized that high kaempferol content of guar seeds may expand its nutraceutical and pharmaceutical utilization. Sharma et al. (2017a) carried out antioxidant activity from crude leaf extracts (containing flavonoids like kaempferol and myricetin, as identified by HPLC analysis) prepared from this plant. They have further highlighted the need for evaluating the bioactive potential of this plant to assess the desirable effect on consumer's health. Raghavendra and Srinivasan (2015) examined the influence of a combination of dietary tender cluster beans (guar) and garlic (Allium sativum) in reducing the cholesterol gallstone formation in mice. In addition of anti-lithogenic effect, dietary cluster beans and garlic in combination had a beneficial antioxidant effect. They have further mentioned that because of their rich dietary fibre, cluster beans may have therapeutic value in the treatment of hypercholesterolaemia. Rawaliya et al. (2022) purified a highly thermostable serine protease from the seeds of *C. tetragonoloba* that can have potential applications in industries and biotechnology. In another study, a trypsin inhibitor was isolated from the seeds of this plant and characterized for its activity and stability by various parameters like temperature, duration of incubation, oxidizing and reducing agents, and microwave heating (Patidar et al. 2020). Cluster bean cultivation technologies like high yielding varieties, rotation and intercropping, sowing method, water and pest management (bacterial blight, powdery mildew, Alternaria leaf spot), and seed production have been improved by CAZRI (2014).

Therefore, *C. tetragonoloba* seems to be a prime candidate for further research with respect to bioactives. Recently, our research group reported on the antioxidant activity enhancer effect of *C. tetragonoloba* seed extract on selected dietary flavonoids/phenolics like epigallocatechin gallate (EGCG) and ellagic acid (Joshi et al. 2023a, b). An important point to note here is that many of the bioactive metabolites such as flavonoids (and isoflavonoids) are stored in the plant cell's vacuole in glycosylated forms, which are acted upon by specific β-glucosidase enzymes to make the more active aglycones available to the plant in times of biotic/abiotic stresses (Asati and Sharma 2019). Elucidating of such metabolic pathways is an important research goal for legume scientists.

Acacia senegal

The seeds of another edible legume of the Indian desert, *Acacia senegal* (known as kumatiya), are added to the traditional dish of 'Panchkuta' (Asati et al. 2021). Another important commercial product obtained from bark of the kumat tree is the gum Arabic. The Acacia gum is used as food additive that is approved by Codex Alimentarius (Al-Assaf et al. 2007). Edible portions from the plant are mainly consumed after cooking—rather than raw, due to an astringent taste. These seeds are rich sources of protein and bioactive compounds. The seeds have been shown to possess antioxidant (Charan et al. 2022) as well as anti-inflammatory and anti-cancer properties (El-Garawani et al. 2021). As per Varshney (2018), the seeds of *A. senegal* contain 39% protein, which is significantly higher than the more popular Bengal gram (19% protein). However, the presence of antinutritional factors in the fruits of the plants discussed above makes them less accepted by the modern consumer, thereby presenting both a challenge as well as an opportunity.

Ram et al. (2014) reported that the administration of seed extracts of *Acacia senegal* in rabbits could reduce the oxidative stress on account of lowering the cardiac lipid peroxidation. The authors also pointed to the fact that in order to develop novel therapeutics (with respect to cardioprotection) from *Acacia senegal* seeds, studies on isolated active principles are needed. Crude methanolic and acetone extracts of the leaves of *Acacia senegal* have been studied mainly with respect to antioxidant activity by Uzunuigbe et al. (2019). A few other isolated studies exist, but mainly with respect to gum Arabic (a commercially useful product which mainly contains polysaccharides) (Aloqbi 2020) rather than flavonoids from the edible seeds of the plant. CAZRI has developed method for enhancing the production of gum Arabic. The technology generated an additional 698.79 lakh rupees in the village, and the supply of gum inducer generated revenue of 30.53 lakh rupees for CAZRI (2021).

Some of the underutilized legumes of (semi) arid regions are lablab beans (*Lablab purpureus*), sesame (*Sesamum indicum*), adzuki bean (*Vigna angularis*), bambara groundnut (*Vigna subterranea*) (Farooq and Siddique 2023), winged bean (*Psophocarpus tetragonolobus*), lima bean (*Phaseolus lunatus*), and jack bean (*Canavalia ensiformis*) (Popoola et al. 2019). Few other examples of underutilized legumes of Rajasthan include moth bean (*Vigna aconitifolia*) and pigeonpea (*Cajanus cajan*).

Environmentally sustainable fuels: the promise of desert legumes as sources of green bioenergy

Bioenergy is considered a smart alternative to non-renewable fuel sources in order to meet future energy demands on account of its greater environmental-friendliness and low pollution levels. Legumes are promising and sturdy candidates to fulfil the demand for this bioenergy as they are drought- and salinity-tolerant, carry out symbiotic nitrogen fixation, are capable of growing on marginal lands (with low nitrogen and phosphorus content in soil), and often accumulate good quality and amount of seed oil (Mitra et al. 2021). In the harsh desert climate of India, two kinds of leguminous plants thrive: (i) those with edible parts and (ii) those that do not produce edible fruits but have been used traditionally as sources of firewood, fodder and ethnomedicine. So, there can be different avenues to explore the bioenergy potential of these underutilized plants.

Rajasthan state government employed different strategies for enhancing energy efficiency and renewable energy—a thorough analysis and forecasting of biomass (from forestry or agro-residues) to create an integrated biomass strategy that addresses production, distribution, and regulation, and other issues for utilizing complete potential of renewable energy, studying the effect of change in climate on energy systems as a measure of increasing energy efficiency, and transmission/distribution loss reduction (Rajasthan State Action Plan on Climate Change 2012).

Legumes have a special function in the production of biomass for bioenergy. They should be carefully considered as crucial elements of future sustainable food, fibre, and energy production systems for human prosperity due to their wide range of potential ecosystem services as well as their capacity to reduce GHG (greenhouse gases) emissions and promote soil carbon sequestration. Alfalfa and other perennial legumes present a promising resource for the future production of second-generation bioethanol, either as a solitary crop or in a mixed cropping pattern with high-yielding non-legume species (Jensen et al. 2012).

A plant like *Cyamopsis tetragonoloba* belongs to the first category, where after the guar pods are harvested for food purpose, the portions that remain (leaves and stem) can be dried and utilized as fuel. This would also satisfy the zero-waste principle—both economically as well as environmentally. Also, the natural antioxidants with multiple hydroxyl groups are considered important additives to biodiesel to improve its shelf life (Amran et al. 2022). Therefore, polyphenolic antioxidants extracted from guar can be used to improve the oxidative stability of biodiesel.

In the non-edible category, one of the most potential legumes is *Pongamia pinnata* (karanja) because of its high biomass and seed oil content (40%) (Calica 2017). A few attractions of its oil are high flash point, high cetane number; lower sulphur and ash content—all being important parameters in eco-friendly fuels. It is both salinity and drought tolerant. Hasnah et al. (2020) reported that extraction methods (mechanical pressing and solvent extraction), machines and genetic factors influence oil (non-edible) production. Biodiesel can be prepared by transesterification of its oil with methanol in the presence of sodium or potassium hydroxide as catalyst (Kazakoff et al. 2011). On degraded land, *Pongamia* is an ideal candidate for sowing as a bioenergy feedstock (Leksono et al. 2021). Protein concentrate for low-quality animal feed supplements (particularly ruminants) can be obtained from the seed cake after oil extraction, as well as second-generation bioethanol, biogas, or thermochemical conversion and biochar production (Jensen et al. 2012). However, as per Biswas et al. (2011), this tree has been lacking in scientifically designed selection and breeding programmes in comparison to established crop species. The top exporters of Pongamia oil in the world are India, Spain, and France. Greece imports 53 Pongamia oil cargoes, followed by the USA with 17, and Japan with 13 (Volza 2023).

Another non-edible legume tree is *Prosopis juliflora* (vilayati kikar), also considered an invasive species a resource competitor for the native *P. cineraria* (Kohli et al. 2012). It is one of the most dangerous invasive plants due to its low nutrient needs, capacity to grow in waterlogged areas, tolerance of high salinity and variable soil conditions, large-scale seed production, ability to form impenetrable thickets, and foliage that is unpalatable to livestock. Its lower moisture and ash content, higher energy-to-volume ratio, and higher fixed carbon content make it a sustainable fuelwood plant (Bandara et al. 2022). In one study, Haile et al. (2018) reported on the potential of *P. juliflora* pods mash to produce bioethanol. This can be an efficient way to tackle the ecological problems created by this invasive species.

In addition to the above, the non-edible plants/plant parts can also have other applications like fodder for cattle (Meena 2019), biodegradable plastics, inks, gums, and in paper and textile industry (Graham and Vance 2003). Besides, owing to their ability to fix atmospheric nitrogen, legumes have consistently been used as green manure to improve the nutrient content of the soil, as well as to prevent soil erosion (Gill et al. 2020).

Attracting the stakeholders: challenges and opportunities for legume scientists

Legumes have been considered important components of sustainable cropping systems, sources of balanced diet and diversified protein, and major contributors to human and soil health (Bramel and Upadhyaya 2018). Although a few of the underutilized plant species (growing in the wild or select cultivars) may be low yielding in terms of biomass production, they have a few major advantages: yield stability, low nutrient and water demand, and adaptation to local pests. On a holistic note, these factors are most crucial as they enable the production of these crops in a cost-effective manner (Thies 2000). Some of the important underutilized vegetables of Rajasthan like cluster bean (guar) are major source of livelihood for the poor tribals and have been reported to play an important role in overcoming malnutrition (Gajanana et al. 2010). Most of the underutilized fruits are rich source of vitamins (ascorbic acid, thiamine, niacin, pyridoxine, and folacin), minerals, fat, protein, and dietary fibre (Hossain et al. 2021). Still, these crops have remained underutilized due to the lack of awareness of their potential. Besides, some of these fruits are not acceptable in the market in fresh form due to their acidic nature and astringent taste. Therefore, focused attention is essential for improving the organoleptic properties of these legumes.

Most of the underutilized legumes bear fruits in a particular season. For instance, the edible pods of *P. cineraria* appear on the tree in April–May, and on post-harvest, they are subjected to boiling/drying as a traditional method of storage. This processing extends the shelf life availability during other periods of the year (Mishra et al. 2016). The legumes often contain anti-nutritional factors (like lectins and tannins) that tend to reduce their marketability (Chibarabada et al. 2017). However, appropriate processing can take care of this aspect. For example, the partly enhanced bioavailability of nutrients e.g., carotenoids, or the development of specific flavours have been reported to lead to an increased acceptability of processed plants/plant parts (Eriksen et al. 2016). Optimization of processing protocols becomes absolutely essential here as traditional methods like thermal processing, and solar drying might lead to loss of nutrient/nutraceutical and antioxidant capacity (Calín-Sánchez et al. 2020). Furthermore, value-added commercial products like jams, jellies, candies, and pickles can be developed from the fruits of underutilized plants, as sufficient technology has been developed for the same (Gupta et al. 2018). Although, *Prosopis sp.* has been used as fuel, fodder, wood resource (for furniture), and charcoal production in the (semi) arid regions of India, its economic utility in the global market is still limited (Giustra et al. 2022).

More recently, our research group has used a combination of chromatography procedures and purified flavonoids with antioxidant and anticancer potential from the pods and seeds of *P. cineraria* and *C. tetragonoloba*, respectively. Many of these flavonoids (and isoflavonoids) are stored in the plant cell's vacuole in glycosylated forms, which are acted upon by specific β-glucosidase enzymes to make the more active aglycone available to the plant in times of stress (Asati and Sharma 2019; Asati et al. 2021). Furthermore, as per Varshney (2018), while the *Acacia senegal* seeds have not been comprehensively analysed for their nutritive value, a comparison of different *Acacia* species to check their benefits for livestock shows that the seeds of gum Arabic are richer in phosphorus, zinc, and selenium than those of the other species. Another analysis shows the seeds have 39% protein. The latest data on nutritive value of India's food shows that whole Bengal gram has just around 19% of protein. France and European Union are among the top exporters and importers of gum Arabic (*A. senegal*), whereas India stands on 12th position in global export of gum Arabic in 2019 (World bank 2019).

Sharma et al. (2017b) have mentioned that *Cyamopsis tetragonoloba* (guar) is a multi-purpose legume crop of industrial importance (mainly as source of guar gum), also used as vegetable for human consumption, particularly in Rajasthan, India, and also used livestock feed and as a green manure crop. The export of guar gum from India (2022–2023) to the top ten countries include, USA followed by Germany, Russia, Norway, Netherland, China, Canada, UK, Australia, and Italy (Agricultural and Processed Food Products Export Development Authority (APEDA), Ministry of Commerce and Industry, Government. of India). Till date, soybean has the most important commercial legume. However, there is a need to identify, develop, and explore other legume sources like guar bean. Crops like guar which are otherwise underutilized (as source of bioactives) can be useful to ensure future food security due to high protein and other constituents. Table 1 shows the traditional uses of underutilized desert legumes and their potential bioactivities.

Table 1 Traditional uses along with phytochemicals and biological activities reported in selected underutilized desert legumes

S. No	Plants	Traditional uses	Reported bioactive phytochemicals	Reported bioactivity	References
1	*Prosopis cineraria*	Leaves—smoke is good for eye infections, paste is applied on blisters, boils, and mouth ulcers in livestock, as cattle feed Seeds—a cheap source of protein Pods—curry and pickle (unripe pods), vegetable (green pods), cookies (flour of mature pods) Bark—non-nutritional purpose (fuel, tanning, firewood), treatment of asthma, bronchitis, muscle tremors, piles	Flavonoids (Prosogerin E, luteolin, rutin, patuletin), Phenolic acid (gallic acid), alkaloids (spicigerin), steroids (sitosterol, stigmasterol, campesterol), linoleic acid, 5,3′,4′trihydroxyflavanone 7-glycoside, tannins, isoflavonoids (puerarin, daidzein), saponins	Antidepressant, antitumor, antioxidant, antidiabetic, antimicrobial, antipyretic, anti-inflammatory, anticonvulsant, hypolipidemic, antiatherosclerotic	(Afifi and Al-rub 2019), (Asati et al. 2022), (Zhong et al. 2022)
2	*Cyamopsis tetragonoloba*	Leaves—treatment of night blindness, asthma, constipation, cough Seeds—source of guar gum, used as laxatives, treatment of arthritis, cattle feed Pods—cure inflammation, sprains, used as a vegetable (green pods)	Phenolic acid (gallic acid, caffeic acid, ellagic acid, chlorogenic acid), flavonoids (quercetin, kaempferol, myricetin), isoflavonoids (daidzein, genistein), coumarin, sterols (stigmasterol, avenasterol, beta-sitosterol, campesterol), gallotannins, saponin (3-epikatonic acid), galactomannan (guran)	Antidiabetic, antiulcer, cytoprotective, hypolipidemic, anticoagulant, antimicrobial, anti-inflammatory, anti-dengue	(Sharma et al. 2011), (Kaushik et al. 2020)
3	*Acacia senegal*	Bark—gum is used on burns and wounds, in cough, sore throat, diarrhoea, urinary tract infections, dysentery, toothaches Seeds—dried seeds used as vegetable Leaves and stem—used as cattle feed Wood—fuel and construction purposes	Alkaloids, flavonoids (fisetinidol, myricetin, taxifolin), saponins, sterols, tannins, triterpenoid (lupenone), gallocatechin	Antibacterial, antidiabetic, antioxidant, anti-inflammatory, antifungal, anti-asthmatic, prophylactic against SARS-CoV-2	(Agrawal 2018), (Charan et al. 2022), (Binyane and Mfengwana 2022)

Table 1 (continued)

S. No	Plants	Traditional uses	Reported bioactive phytochemicals	Reported bioactivity	References
4	*Pongamia pinnata*	Root—used in vaginal and skin diseases, treatment of gonorrhoea, cleaning teeth, gums, and ulcers Stem—sedative, anti-pyretic, piles, skin diseases, stomach pain, wood is used for fuels Leaf—cattle feed, insect-repellent, improves soil fertility, juice is used in cough, cold, gonorrhoea, diarrhoea, itches, laxative used for wounds and inflammations, antiseptic Fruit—used in abdominal tumours, female genital tract problems, ulcers, piles Seed—insecticide, green manure (after extraction of oil), skin ailments, whooping cough, inflammations, fevers, anaemia	Flavonoids (karangin, pongagalabrone, pongapin, pinnatin*, and* kanjone). Flavones and chalcone (Galbone, Pongone, Pongalbol, Pongagallone A, and B). Flavanol glucoside (pongamoside D), alkaloid (paclitaxel, vinblastin, vincristine)	Anti-inflammatory, anti-diarrhoeal, antioxidant, antibacterial, antiparasitic, anthelmintic, antifungal, anti-ulcer, antidiabetic, anti-lipid peroxidative, anti-ulcerogenic	(Sangwan et al. 2010), (Akram et al. 2021), (Shejawal et al. 2014)
5	*Prosopis juliflora*	Leaves—boils, painkiller, eye inflammation, muscular pain Stem/bark—toothache, asthma, boils, cough	Flavonoid (mesquitol, apigenin, luteolin, kaempferol 3-O-methyl ether, isorhamnetin 3-O-glucoside), alkaloid (juliflorine, juliprosine, isojuliprosine, juliprosinene, piperidine), tannins, phenolics (gallic acid), terpenes, steroids	Antibacterial, antifungal, antioxidant, anti-diabetic, anthelmintic, antitumour, antipyretic, antiulcer, anti-inflammatory	(Ukande et al. 2019), (Patil et al. 2016)

Conclusions

The arid and semi-arid regions of India, harbour numerous neglected, edible (*Prosopis cineraria*, *Cyamopsis tetragonoloba* and *Acacia senegal*) and non-edible (*Pongamia pinnata* and *Prosopis juliflora*) legumes that have shown potential to be developed into environmentally sustainable functional foods and biofuels of the future. Some of these underutilized plants could also act as major contributors to ensure food security in the face of drought, famine, floods, and unexpected climate shocks, when our more well-known crops such as rice or wheat might fail. Years of natural selection has led to many of the underutilized plants to develop in a way that they are able to withstand various biotic and abiotic stresses much better than their more well-known counterparts. As a result, they have become increasingly sturdy and require relatively less care in terms of water and chemical-based fertilizers/pesticides for growth and propagation. Such plants would be the right candidates for low input sustainable production systems as well as an appropriate buffer for social and economic shocks resulting from concentrating on only a few crops. These plants would also be potential candidates to target non-communicable diseases such as obesity on account of their containing important classes of natural products belonging to the category of isoflavonoids.

To sum up, we are clearly overdependent on a few selected foods (such as wheat and maize, to name a few) for our regular nutritional and health needs. It is time to supplement these with alternative foods that (a) are healthy and provide nutritional/nutraceutical diversity in the diet, (b) are local and seasonal, thereby reducing the costs of transportation and ultimately enhancing affordability for the poor, (c) are environmentally sustainable to cultivate and process, and (d) are resilient in the face of changing climate patterns. Therefore, we need to look at our underutilized edible plants more closely to reap the desired benefits in food sector. Additionally, the non-edible portions of these plants plus the non-edible plants themselves could be prime candidates for research in the bioenergy sector. Also, the indigenous communities often have good knowledge of the biodiversity and cultivation methods related to these plants and given appropriate incentives (such as earning revenue from providing raw material to food industry) would willingly come forward to conserve and propagate them.

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Author contribution Perinkulam Ravi Deepa and Pankaj Kumar Sharma contributed to the conception and design of this manuscript. Tripti Joshi, Sumit Kumar Mandal, and Vidushi Asati performed literature search. Materials (Figure and Table) were prepared by Tripti Joshi and Sumit Kumar Mandal. The first draft of the manuscript was written by Pankaj Kumar Sharma. The revised version of the manuscript was prepared by Tripti Joshi. All authors read and approved the final manuscript.

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