PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.10543

eISSN 2348-1900

REVIEW ARTICLE

Yucca plants: A comprehensive review of their biological, nutritional and phytochemical attributes

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Received: 09 July 2025; Accepted: 08 December 2025; Available online: Version 1.0: 12 March 2026

Cite this article: Orozco-Sifuentes MM, Soriano-Melgar LDAA, García-Ortíz JD, Faleye BR, Rodriguéz-Herrera R. Yucca plants: A comprehensive review of their biological, nutritional and phytochemical attributes. Plant Science Today (Early Access). https://doi.org/10.14719/pst.10543

Abstract

The Yucca genus, consisting of nearly 50 species, is among the most prevalent desert plant groups in North America. Yucca plants are perennial, succulent and shrubby, known for their longevity. They possess trunks that can reach heights of up to 10 m, occasionally branching and feature long, linear leaves arranged in a rosette pattern. Since ancient times, they have been used by indigenous cultures in arid regions to obtain fibre, as a building material for huts and livestock fences, as part of traditional medicine and their flowers are consumed as food. Amid ongoing climate change, the issue of water scarcity is becoming increasingly severe for humanity. Yucca plants have sparked great interest due to their ability to adapt to extreme climates. In recent years, there has been a growing focus on exploring the biological, genetic, physicochemical, nutritional, functional and other characteristics of Yucca plants. Our fast-paced lifestyles have led to an increase in processed foods, displacing the natural resources that have traditionally been part of our diet. The phytochemical richness of these valuable resources represents a nutritious and bioactive source that can be utilised by people living in arid regions. This paper reviews the biology, phytochemical composition and potential bioactive properties of Yucca plants, highlighting their value as natural resources addressing the challenges of environmental change. With proper management and the integration of scientific information, these resources can represent sources of marketing and economic income for the inhabitants of the regions where they are distributed, providing the basis for a better understanding of the formation, use and management of these valuable natural resources.

Keywords: chemical compounds; desert plant; functional activity; morphology; nutrient

Introduction

The *Yucca* genus, comprising nearly 50 species and belonging to the Asparagaceae family, is among the most abundant plant groups on the American continent. It is known by the common names of Izote or Palma. Their distribution extends from the Canada-United States border to Central America (1). The *Yucca* species are considered endemic to the American continent and have a great capacity to adapt to extreme climates. According to some historians, the *Yucca* genus evolved between the Eocene and Miocene periods, during a global warming event that caused droughts, leading to the formation of semi-desert areas. Their ancestors are thought to have been tropical trees with fleshy fruits that were commonly dried and consumed (1).

Since ancient times, inhabitants of arid areas of North America have utilised the structures of *Yucca* plants. The stems have been used as building material, the leaves have been used to obtain strong fibres, useful for making basketry, sandals and clothing, while the flowers and fruits have served as food and as part of traditional medicine (2). Currently, this genus has gained importance as a resource in arid zones. With climate change models predicting more frequent extreme environmental events, the study of desert plants has become increasingly vital in addressing these emerging challenges (3). Aspects such as their morphology, physiology, reproduction, type of pollinators, as well as those involved in their nutritional and phytochemical composition, are of vital relevance to understand the benefits of these valuable natural resources and to have a better plant management (4, 5). Multiple studies have been aimed at exploring the potential benefits of *Yucca* plants, which are a source of steroidal saponins and other compounds, such as polyphenols, terpenes, carotenoids and flavonoids, among others, have been detected in their leaves, flowers and fruits (6–8). Among the bioactive activities that have been most successfully explored are its antioxidant, anti-inflammatory, antimicrobial, anticancer, neuroprotective and hepatoprotective, among others (9–12).

Yucca plants are wild plants and some species are listed under special protection regulations by the Norma Official Mexicana NOM-059-SEMARNAT-2010 (Secretary of Environment and Natural Resources) and CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora). To determine the profitability of their commercialisation, a targeted study is necessary for each species. In Mexico, only one species has been domesticated for cultivation and industrialisation, *Yucca* *schidigera* Roezl ex Ortgies, a species whose products are traded in Europe, Asia and Latin America. The genus is numerous and the most recent research provides interesting data on its uses and potential nutritional and health benefits for humans. Each contribution is key to ensuring its proper use and future applications. This paper reviews the biological, nutritional and phytochemical characteristics of *Yucca* plants, which serve as a valuable resource in arid regions. The integration of relevant bibliographic information about *Yucca* plants paves the way for better management and understanding of resources in arid zones. The seasonal production of their edible parts (flowers and fruits) represents not only a nutritional and functional source but also the possibility of generating income for inhabitants of arid regions. These actions contribute, to some extent, to an improvement in quality of life, the maintenance of their cultural and traditional uses and the care of natural resources. The relevance of *Yucca* plants in arid and semi-arid ecosystems should be extensively studied and highlighted, as they represent valuable phytogenetic resources in a future where arid climates are expected to predominate.

Biological aspects of the *Yucca* genus

Morphological and anatomical adaptations to arid environments

Morphological and anatomical adaptations in the Yucca genus are essential for its survival in arid and semi-arid ecosystems. Yucca species have evolved to generate diverse structures that optimise the use of limited resources, such as water and the space in which they are developing (Fig. 1). One example is *Yucca brevifolia* Schott ex Trel., which has leaves with modifications in shape and size associated with its microhabitat. Species show variations in leaf thickness and vein density in response to moisture gradients in the Mojave Desert-traits that contribute to mechanical strength and water retention (13). At the reproductive level, fruit and seed structures show relevant morphological adjustments. In *Yucca thompsoniana* Trel., a high proportion of full seeds ~60 % and significant morphometric variation between populations have been observed, which may be associated with germination success in arid environments; this is relevant for conservation and propagation programs for these species (14). From an evolutionary perspective, phylogenetic analyses of the genus Yucca indicate an organisation into two main clades, determined by the type of fruit, whether fleshy or dry (4). These morphological differences are associated with dispersal and establishment, elements of great relevance in environments with high spatial heterogeneity and scarce resource availability. *Yucca cernua* E.L. Keith thrives in open savanna climates with clay soils, accentuating the plants' ability to establish themselves in fragmented habitats, associated with the anatomical characteristics of the plants, which allow them to take advantage of particular soil microenvironments (15).

In species such as *Yucca mixtecana*, it is deduced that physical characteristics such as structural resistance, size and shape could be related to protection mechanisms against desiccation or herbivory in arid climate regions (16). While in *Yucca carrii* Clary & T.P. Adams, a recently described species, the architecture of thin leaves with reddish margins stands out, which could represent a morphological adaptation linked to conditions of intense solar radiation and low humidity (17). In *Yucca gloriosa* L., it was observed that its inflorescences are robust and have leathery leaves, which are characteristics repeated in species adapted to arid coastal environments, such as those in the United States. Therefore, it is observed that the morphology and anatomy of *Yucca* are highly integrated with its evolution and adaptive history, reflecting unique structural responses to conditions of aridity, nutrient limitation and environmental and ecological pressure.

Physiological and biochemical responses to abiotic stress

The *Yucca* genus exhibits highly specialised physiological responses to stress conditions, mainly of the abiotic type, particularly focused on the relationship with water availability and precipitation pulses in arid areas. In a field experiment, *Y. brevifolia* showed a significant increase in carbon dioxide (CO_2) assimilation and stomatal opening after rainfall above 10 mm, while rainfall below that level did not generate physiological responses. This suggests that plants have specific threshold water ranges for activating photosynthetic and gas exchange processes, so that these would only respond under certain specific favourable conditions (18). For its part, the long-term phenological response to extreme weather events has also been documented in *Yucca*. Analysis of more than 120 year of phenological data for *Y. brevifolia* demonstrates that mass flowering events (masting) are linked to periods of higher rainfall. Nevertheless, this correlation does not guarantee long-term reproductive success, suggesting a potential disconnect between environmental signals and the plants' adaptive strategies (19).

From a biochemical perspective, *Yucca schidigera* Roezl ex Ortgies produces stilbenes and steroidal saponins with antioxidant, anti-inflammatory and osmoprotective properties,

Fig. 1. Species of *Yucca*. (A) *Yucca treculeana*; (B) *Yucca filifera*; (C) *Yucca carnerosana*.

which play a crucial role in mitigating cellular damage caused by oxidative stress in extreme environments (20). These types of compounds (although studied in veterinary contexts) reflect the adaptive potential of *Yucca*s' secondary metabolism in hostile conditions. *Yucca mixtecana* produces fruits with high nutritional value, particularly rich in protein, indicating both adaptive and functional significance in semi-arid regions (16). From a genomic perspective, the expression of genes related to crassulacean acid metabolism (CAM) in C_3 *Yucca* species indicates that physiological adaptations to water stress may have evolved through regulatory rather than structural modifications (21, 22). The survival of species like *Y.* cernua in degraded clay soils and savannas with limited water availability points to a range of soil-related and physiological adaptations (15). Although these adaptations remain largely underexplored, they play a crucial role in the genus's ecological resilience to various abiotic stressors. All of this evidence indicates that a single trait does not drive *Yucca*s' adaptation to arid environments, but rather a complex interplay of morphological, anatomical, physiological, biochemical and evolutionary factors.

Reproductive biology and plant–pollinator interactions

In the *Yucca* genus, reproduction depends mainly on the close relationship that exists with insects, particularly moths of the Tegeticula genus, which act as almost exclusive pollinators for *Yucca*. This particular link is one of the clearest cases of coevolution between a plant and its associated insect. This relationship has led to changes in the form, chemical compounds and behaviour of both plants and moths, affecting not only how they reproduce, but also how these species differentiate and maintain themselves. That is why the reproductive mechanisms in the *Yucca* genus are deeply determined by the obligate and highly specialised interaction with their pollinating moths (Tegeticula and Parategeticula genera), which has significantly restricted floral biology, dispersal dynamics and genetic diversity. This mutualism has evolved over more than 40 million years, with 54 species of moths currently described, both pollinating and non-pollinating, showing key morphological adaptations such as specialised tissues including the modified ovipositor and tentacles, which are what give the system its specificity (23). However, coevolution has not followed a solely mutualistic trajectory. Some research suggests that larval antagonism, particularly the ability of larvae to feed within the floral ovary, may be the main and determining component in specialisation, rather than the pollinating interaction itself (24).

Tegeticula yuccasella Riley shows some physiological limitations in completing its development in non-native hosts, reflecting a larval rather than floral specialisation. In addition, reproductive isolation has also been investigated and reported, where, through an analysis of hybrid zones, such as that of *Y. brevifolia* and *Yucca jaegeriana* (McKelvey) L.W. Lenz, selection against first-generation hybrids was detected, suggesting that pollinators alone do not explain the separation between species (25). These barriers are distributed throughout the genome and reflect complex isolation mechanisms. In terms of chemical signalling, *Yucca* produces tetranorsesquiterpenoids, which act as specific attractants for its moths. Other compounds, such as filamentol and filamentona, have been identified, confirming the existence of what are now called private chemical channels that intervene between the plant and the pollinator (26). Research has demonstrated that, at the sensory level, species without specialised pheromonal structures, such as *T. yuccasella,* exhibit synergistic communication between sex pheromones and floral volatiles, which are necessary for successful mating in the field (27). Additionally, it has been shown that pollen dispersal in *Yucca valida* Brandegee is local, with a small reproductive neighbourhood and some inbreeding, which generates moderate genetic diversity (27). This type of dynamic has been linked to reproductive efficiency, but also to variable costs of mutualism, as suggested by the larval predation of *Tegeticula mojavella* Pellmyr on *Y. schidigera* fruits, whose effects vary or are modulated geographically (28). Therefore, the *Yucca*-moth system constitutes a unique model of intersection and specialisation, dispersion, ecological conflict and genetic diversity in plants in arid ecosystems.

Nutritive and phytochemical composition of flowers, fruits and leaves of *Yucca* species

Nutritive composition of flowers and fruits

Yucca flowers have been consumed since ancient times. Their flowering season occurs during March and April and can last for more than a month. In countries like Mexico, their local and traditional consumption coincides with the holy week celebrations (29). These structures, in addition to providing colour, flavour and aroma to traditional dishes, provide nutrients, vitamins, minerals, carotenes and bioactive compounds (30). The inflorescence of Yucca is panicle-shaped and may be either erect or pendulous, depending on the species. Its flowers are typically white, though some, such as those of *Yucca treculeana* Carrière, display pinkish hues and various other shades (Fig. 2). Research has demonstrated that *Yucca filifera* Chabaud and *Yucca elephantipes* Regel ex Trel. gave high percentages of humidity (% M) of 88.1 and 87.3 %, of ash (% A) of 9.7 and 9.9 %, of crude protein (% CP) of 25.9 and 23.0 %, of fat or ether extract (% EE) of 2.1 and 1.9 %, of crude fibre (% CF) of 8.5 and 12.7 % and of nitrogen-free extract (% NFE) of 53.8 and 52.5 % highlighting the protein and carbohydrate content (31, 29).

Other studies on *Yucca carnerosana* (Trel.) McKelvey report protein values of 13.0 %, maintaining the high carbohydrate content. Some of its effects on goat feeding in combination with alfalfa are the decrease in glucose levels when consumed in different proportions (32). *Yucca* flowers are typically consumed after cooking, which eliminates some antinutrients (saponins, trypsin inhibitors). However, this process also modifies the chemical composition of the flowers, decreasing their concentration of nutrients and bioactive compounds. Steaming for periods of 3 min is recommended to prevent their reduction (8, 29). *Yucca* flowers, in addition to providing basic nutrients, provide colour, flavour and improve the dishes' appearance. Among the vitamins that have been detected in this flower is ascorbic acid (vitamin C), with values of 273 mg/100 g of petals (33). Other important nutrients reported in *Yucca* flowers are amino acids (aa), which can be essential and non-essential. Essential amino acids are not produced by the human body but are acquired through the diet, while non-essential amino acids are produced by the human body. Among the main functions of amino acids are protein synthesis, participation in immunological processes, growth and mineral absorption, among others. In the edible flowers of *Y. filifera*, the essential amino acids that have been reported are: isoleucine, (Ile), leucine (Leu), valine (Val), phenylalanine (Phe), tyrosine (Try), lysine (Lys),

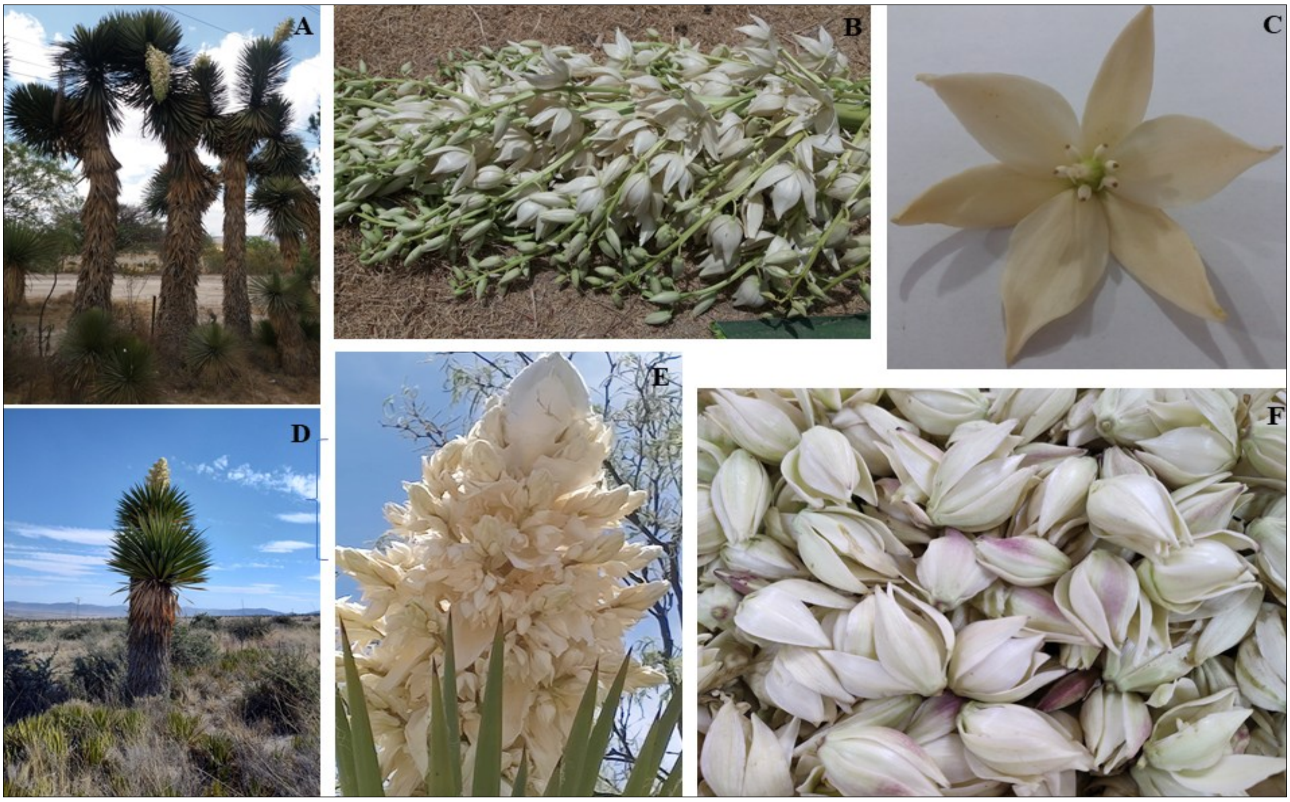

Fig. 2. Morphological features of *Yucca* species. (A) *Yucca filifera*; (B) Inflorescence of *Yucca filifera*; (C) *Yucca* flower; (D) *Yucca carnerosana*; (E) Inflorescence of *Yucca carnerosana*; (F) *Yucca treculeana* flowers.

methionine (Met), cysteine (Cys) and tryptophan (Trp), in the order of 0.85 to 8.65 %. Among the non-essential amino acids, there are glutamic acid (29.7 mg/g dry weight), proline (19.02 mg/g dry weight), aspartic acid (13.09 mg/g dry weight) and leucine (10.89 mg/g dry weight) (29).

In general, edible flowers are a source of minerals such as calcium (Ca), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), phosphorus (P) and zinc (Zn). The minerals that have been found in greatest abundance in edible flowers are Ca and K. In *Yucca* flowers, there are few reports on their mineral content, highlighting their Ca content. In some flowers from desert species, macroelements such as N, P, K, Ca and Mg have been quantified, in the range of 0.12 to 2.70 g/100 g of dry matter, as well as microelements such as Fe, Cu, Zn, Mn and B in the range of 6.20 to 88.60 mg/kg of dry matter (30). Rape fruits of the *Yucca*, known as dates, have been little studied in terms of their nutrients; only a few have been characterised, such as those of *Y. mixteca*. These are characterised by their capsule shape, with a thin, slender epicarp and a soft, yellow mesocarp. Their seeds are matte black and teardrop-shaped. They are distinguished by their high fibre content (51.65 %), while compared to the flowers, they have a low protein (2.29 %) and fat (EE) content (1.70 %). Among the minerals of *Yucca* fruit are: Fe, Na, K, Ca and Mg with 1, 1, 15, 24 and 98 mg/100 g dry matter (16).

Phytochemical composition of its leaves, flowers, fruits and roots

Phytochemical compounds, as the name suggests, are chemical substances derived from various plant tissues. They are generally classified as primary or secondary metabolites. Primary metabolites include nucleic acids, carbohydrates, fatty acids, proteins and other compounds essential for plant growth and development. On the other hand, secondary metabolites are produced after the adaptation of the plant to mitigate multiple factors generating environmental stress, having insecticidal, fungicidal, antibacterial, antioxidant, etc. (7, 34). Among the stress factors in plants, the climatic conditions present during development allow a high variation of phytochemicals, with multiple applications (7, 35). Due to its ability to thrive in diverse arid and semi-arid regions characterised by wide temperature fluctuations and high sunlight exposure, the *Yucca* genus exhibits a broad spectrum of compounds (36, 37). Notable among these are terpenes, alkaloids, carotenoids, polyphenols, isoprenoids, phytosterols, saponins, dietary fibres and various polysaccharides (7, 34). Multiple species of this genus, such as *Y. gloriosa*, *Y. glauca* Nutt., *Y. schidigera*, *Y. aloifolia* L., *Y. desmetiana* Jacobi, *Y. elephantipes*, *Y. macrocarpa* Engelm. and *Y. smalliana* Fernald, are characterised by a phytochemical profile that depends on the type of tissue, generally characterised by the presence of spirostannic and furostannic saponins as major compounds (38, 39) (Fig. 3).

Leaves

It has been reported that the phytochemical characterisation of leaves from multiple *Yucca* species, such as *Y. gloriosa*, *Y. treculeana*, *Y. filamentosa* and *Y. aloifolia,* which have a high variation of saponins (saponifiable and non-saponifiable), with Yuccaloeside C, Yuccaloeside E and Yuccaloeside B being the main ones (40, 41), as well as phytol, gamma-sitosterol, 9,19-cyclolanost-24-en-3-ol and 4-(ethylcyclohexyl)-1-pentylcyclohexene (38). In addition, it has been recorded that *Y. aloifolia, Y. aloifolia* var. *variegata* Rothsch. have spirostan-3-ol-3-O-[β-d-galactopyranosyl-(1→4)-β-d-glucopyranoside, Spirostan-diol- rhamnosyl hexosyl, Hecogenin-rhamnoside, (3β, 5α, 25R)-Spirostan-3-ol-3-O-[β-d-glucopyranosyl-(1→2)-β-d-glucopyranoside], (3β, 5β, 25R)-Spirostan-3-ol-3-O-[β-d-glucopyranosyl-(1→2)-β-d-glucopyranoside], (3β, 5α, 25S)-Spirostan-3-ol-3-O-[β-d-glucopyranosyl-

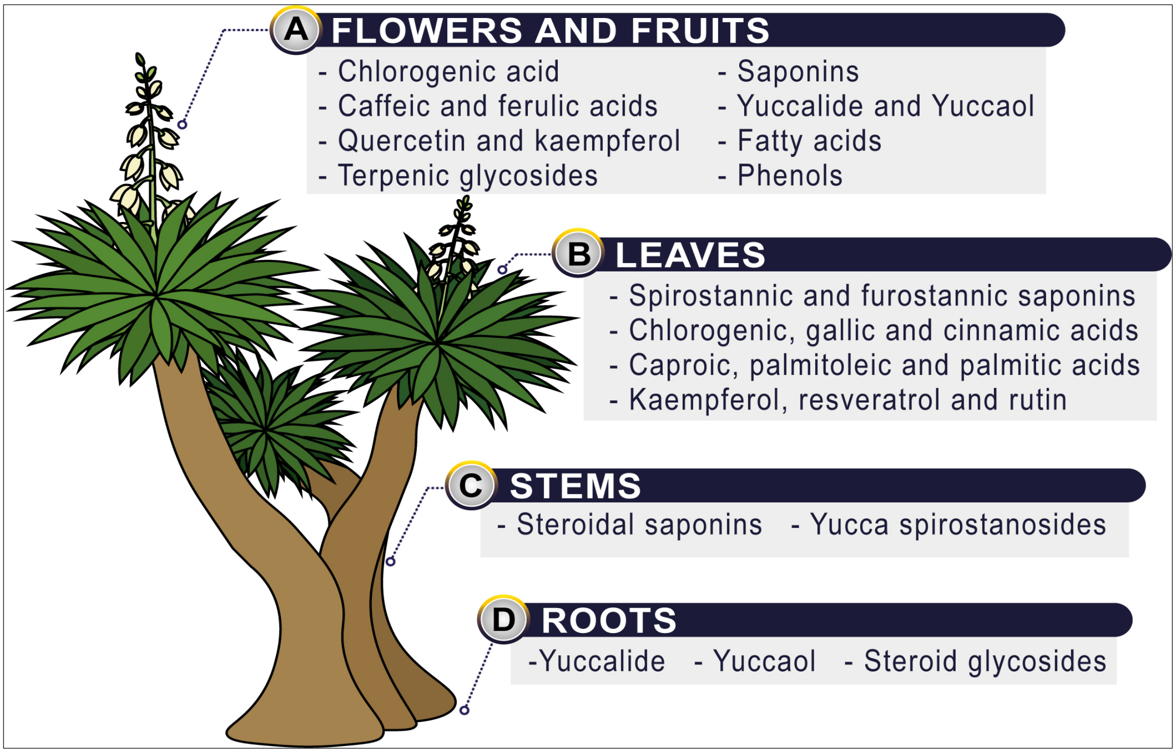

Fig. 3. Compounds present in different tissues of *Yucca* sp. (A) Flowers and fruits; (B) leaves; (C) stems; (D) roots.

(1→2)-β-d-glucopyranoside], (3β, 5β, 25S)-Spirostan-3-ol-3-O-[β -d-glucopyranosyl-(1→2)- β-d-glucopyranoside], 25R-spiostan-diol-dihexoside isomer, 25S-spiostan-diol-dihexoside isomer and spirostanol-dihexoside isomer (38).

Other studies have indicated that *Yucca* leaves show a high variety of phenolic compounds such as kaempferol and resveratrol and compounds such as Chlorogenic acid, Gallic acid, Rutin, Cinnamic acid in species such as *Y. aloifolia*, *Y. aloifolia* var. *variegata* and *Y. filamentosa* as well as, resveratrol, trans-3,3′,5,5′-tetrahydroxy-4′-methoxystilbene, the spirobiflavonoid larixinol, yucaols and yucaone in *Y. schidigera*, these compounds can be related to the composition of the plant, which contains these compounds as a defense against multiple environmental factors (39–45). On the other hand, studies on *Y. aloifolia*, *Y. aloifolia* var. *variegata* and *Y. filamentosa* have indicated that these plants have a high content of fatty acids such as caproic acid, palmitoleic acid and palmitic acid (as major compounds) (38).

Flowers

Hydroalcoholic extracts of the flower in *Y. aloifolia* have showed as major components chlorogenic acid, quercetin, caffeic acid and ferulic acid (16.5 mg/g, 9.5 mg/g, 8.4 mg/g and 7.9 mg/g respectively, all expressed in dry weight), as well as rutin and quercetin (46), on the other hand, the presence of sesquiterpene glycosides and a triterpene glycoside has been documented in *Y. gloriosa* flowers (46, 47). Likewise, studies have mentioned that this type of tissue, in addition to chlorophyll, presents pheophytin, carotenoids and phenolic compounds that are not thermostable at high temperature (8). While in *Y. elephantipes* has been recorded a high variation in compounds such as rutin, vanillic acid, ferulic acid, caffeic acid, chlorogenic acid, kaempferol, protocatechuic acid, quercetin, gallic acid and tetranosesquiterpenoids has been recorded (48, 49).

Just as the leaf tissue is characterised by a high content of saponins, *Yucca* stem or stalk (*Y. schidigera* and *Y. baccata* Torr.) also contain a high content of steroidal saponins, named as Yucca spirostanosides (of multiple molecular weights), schidigera saponins and spirostanol (50–53). Likewise, assays on the bark have indicated the presence of spiroflavo-stilbenoids such as Yuccaols, Yuccalide A, Gloriosaols, spirobiflavonoids such as Yuccalechins, trans-3,3′,5,5′-tetrahydroxy-4′-methoxystilbene and flavonoids such as dihydrokaempferol, naringenin and kaempferol (54).

Fruits and roots

Although limited information is available on the phytochemical composition of *Yucca* fruits and roots, studies have reported that the fruits are rich in phenolic compounds such as rutin, quercetin hexoside, eucomol and gallic acid. They also contain saponins (including furostanol and spirostanol types like furostanol trihexoside), stilbenes such as tetrahydroxymethoxyestilbene and fatty acids like monopalmitin, monostearin, as well as palmitic, oleic and stearic acids (9, 16). On the other hand, it has been mentioned that roots have a high content of Yuccalides (Yuccalide and Yuccaol) in *Y. gloriosa*, as well as a high variation of compounds such as steroid glycosides, 5b-spirostanol glycosides and 5b-furostanol glycoside, found in similar species (55, 56). The knowledge of the phytochemical profile of *Yucca* plants is important to understand their production of metabolites as well as their potential biological, agronomic, food and even pharmaceutical applications (7, 57).

Bioactive properties and health applications of *Yucca*

Bioactive properties of *Yucca* compounds

Biological properties, otherwise known as bioactivities, describe the capacity of a bioactive compound or phytochemical to interact with living cells or organisms, potentially leading to beneficial health effects (58). The *Yucca* genus is known to be rich in natural antioxidants and has demonstrated a range of biological activities, including but not limited to antimicrobial, antioxidant, anti-inflammatory, neuroprotective and anticancer properties, as summarised in Table 1.

Table 1. Biological activities of *Yucca* species

Species	Part of the plant	Extraction method	Study design/ Test method	Target system	Biological activity	Reference
Y. aloifolia	Leaves	95 % ethanol maceration	MTT assay, *in vivo* CCl4-induced hepatotoxicity	Human cancer cell lines (HepG-2, MCF-7), Rat liver	Cytotoxicity against cancer cell lines and hepatoprotective activity	(12)
	Leaves	70 % ethanol maceration	*In vitro* study	*Bacillus subtilis* ATCC19659, *Candida albicans* ATCC2091, *P. aeruginosa* ATCC9027, *Escherichia coli* ATCC8739, *Staphylococcus aureus* ATCC6538	Antimicrobial (no effect)	(38)
	Flowers	Ethanolic extract	*In vitro* enzyme assays and *In vitro* enzyme assays	Enzymes, Gastrointestinal tract microorganisms	Enzyme inhibition, Antimicrobial (MIC), Antioxidant activity (TEAC)	(11)
	Flowers	Hydroalcoholic extract	*In vivo* glucose tolerance test. Cell viability assay	Enzymes, Mice on a hypercaloric/atherogenic diet, DLD-1 cancer cells	Enzyme inhibition, metabolic regulation and cytotoxicity	(46)
	Fruits	Acidified ethanol, acidified 80 % ethanol, acidified 50 % ethanol, acidified distilled water extracts.	Enzyme inhibition. *In vitro* assay and *in vivo* model	*In vitro* assays, Rotenone-induced model in rats	Anti-inflammatory, neuroprotective and antioxidant capacity	(9)
Y. gigantea	Leaves	Methanolic extract	*In vitro* Cytotoxicity	Cytotoxic effect against A431, Hep-2, HSF, MG-63 and A375 cell lines	Cytotoxicity	(10)
			In vitro antimicrobial activity (agar well diffusion and MIC)	Antibacterial (Gram-positive, Gram-negative bacteria) and antifungal (*Candida albicans*).	Antibacterial and antifungal activity	
			In vivo Anti-Inflammatory Activity	Carrageenan-induced acute inflammation	Anti-inflammatory activity	
Y. elephantipes	Root	Methanolic extract	Anti-inflammatory activity (*In vitro* and *in vivo*)	TNF-R2 and NF-KB	Anti-inflammatory activity	(62)
Y. schidigera	Bark	Methanolic extract	Neuroprotective effect (*in vitro* and *in vivo*)	Scopolamine-induced anxiety and memory process deterioration using a Danio rerio model	Neuroprotective effect	(54)
Y. baccata	Stem	Butanolic extracts	*In vitro* antioxidant activity and antimicrobial activity	DPPH, ABTS and FRAP assays	Antioxidant activity	(59)
				MIC and MBC	Antimicrobial activity	

CCl_4: Carbon tetrachloride; HepG-2: Human hepatocellular carcinoma cell line; MIC: Minimum inhibitory concentration; TEAC: Trolox equivalent antioxidant capacity; DLD-1: Human colorectal adenocarcinoma cell line; HSF: Human skin fibroblast; A375: Human malignant melanoma cell line; TNF-R2: Tumor necrosis Factor Receptor 2; NF-κB: Nuclear factor kappa-B; DPPH: 2,2-Diphenyl-1-picrylhydrazyl; ABTS: 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); FRAP: Ferric reducing antioxidant power; MBC: Minimum bactericidal concentration.

Antioxidant activity

Antioxidants are substances that slow down or prevent oxidation by neutralising free radicals. They achieve this by capturing reactive species and transforming them into non-radical or more stable forms (58). The antioxidant activity of *Yucca* species cannot be overemphasised. The antioxidant potential of the butanolic extract of *Y. baccata*, chitosan only and *Y. baccata*-chitosan combination was conducted, employing ABTS (2,2-azino-bis-3-ethylbenzothiazoline-6-sulphonic acid), DPPH (2,2-diphenyl-1-picrylhydrazyl) and FRAP (Ferric Reducing Antioxidant Power) assays (59). It was discovered that the butanolic extract of *Y. baccata* yielded the highest antioxidant activity in ABTS and FRAP assays, while the combination of *Y. baccata* with chitosan offered the highest activity with the DPPH assay. This indicated that the addition of chitosan to *Y. baccata* increased its antioxidant capacity. While *Y. aloifolia* fruit extract showed antioxidant properties by reducing oxidative stress markers and increasing antioxidant markers in the rat model (9). Gallic acid, kaempferol, flavonol, quercetin and its glycosides were reported to have contributed to this property (60, 61). In addition, the antioxidant activity of ethanolic extracts from *Y. aloifolia* flowers was determined using the TEAC (Trolox equivalent antioxidant capacity) assay, which was linked to the presence of compounds such as kaempferol and quercetin in the extract (11).

Anti-inflammatory effects

The anti-inflammatory property of some *Yucca* species has been reported in the literature. The anti-inflammatory effects of *Y. gigantea* Lem. methanol leaf extract against carrageenan-induced acute inflammation (10). The extract exhibited significant anti-inflammatory effects by reducing paw oedema, PGE-2, TNF-α, NO production and serum IL-6 and IL-1β levels while also decreasing COX-2 immunostaining. It further replenished GSH levels and improved histopathological outcomes. This effect was attributed to flavonoids such as apigenin, kaempferol, luteolin and quercetin that were identified in the extract through LC-ESI-MS. The anti-inflammatory effects (*in vitro*) of *Y. aloifolia* fruit extract through inhibition of TNF-R2 and NF-KB, with IC50 values of 4 ± 0.06 ng/mL and 3.87 ± 0.07 pg/mL, respectively, were documented (9). Moreover, the anti-inflammatory effect (*in vitro* and *in vivo*) of the methanolic extract from *Y. elephantipes* where shown in an oxidative burst assay and carrageenan-induced paw oedema in rats (62).

Antimicrobial properties

The antimicrobial activity of *Y. aloifolia* extracts has yielded mixed results. While some studies reported no detectable antimicrobial effects, others observed moderate activity from the ethanolic extract of *Y. aloifolia* inflorescence, particularly against *Staphylococcus aureus* Rosenbach and *Candida albicans* (C.P. Robin) Berkhout (11, 38). In the study, the minimum inhibitory concentration (MIC) of the extract was tested against bacterial species associated with the gastrointestinal tract, which include: *Escherichia coli* (Migula) Castellani & Chalmers, *Staphylococcus aureus* Rosenbach, *Enterococcus faecalis* (Andrewes & Horder) Schleifer & Kilpper-Bälz, *Salmonella typhi* (Schroeter) Warren & Scott and *Candida albicans* (C.P. Robin) Berkhout. This discrepancy could be due to differences in extraction methods, plant parts used, or the specific microorganisms tested. However, the antimicrobial activities of other *Yucca* species have been documented. Methanolic leaf extracts of *Y. gigantea* have been studied and shown to possess vigorous antibacterial activity against both Gram-positive bacteria (*S. epidermidis* and *S. aureus)* and Gram-negative bacteria *Pseudomonas aeruginosa* (Schroeter) Migula, *Klebsiella pneumoniae* (Schroeter) Trevisan, *Proteus mirabilis* Hauser, *Escherichia coli* (Migula) Castellani & Chalmers, *Salmonella typhimurium* (Loeffler) Castellani & Chalmers), as well as antifungal activity against *Candida albicans* (C.P. Robin) Berkhout. This bioactivity has been attributed to the presence of compounds such as apigenin, kaempferol, luteolin and quercetin (10). Moreover, the antibacterial activity of *Y. baccata*, chitosan and *Y. baccata*-chitosan against *S. typhimurium*, *E. coli*, *S. aureus* and *L. monocytogenes* Pirie was studied using MIC and MBC. It was reported that *Y. baccata* exhibited the lowest MICs and MBCs against all tested bacteria, while *Y. baccata*-chitosan demonstrated stronger antimicrobial activity than chitosan alone (59).

Anticancer activity

Several studies investigated the cytotoxic effects of *Yucca* extracts on cancer cell lines. Among these investigations is the report of the cytotoxic effect of *Yucca filamentosa* L., *Y. aloifolia*, *Y. elephantipes* and *Y. aloifolia variegata* against four human cancer cell lines (colon cancer Caco-2, liver cancer HEPG-2, lung cancer A549 and breast cancer MCF-7). From this research, it was gathered that the ethanolic extracts of leaves from *Y. aloifolia* var. *variegata* had the highest cytotoxic effect against liver cancer HepG-2 and breast cancer MCF-7. Out of the 18 flavonoids and 19 phenolic acids identified in the fractions of *Y. aloifolia* var. *variegata* by HPLC, 2 flavonoids, namely: hesperidin and kaemp-3-(2-p-coumaroyl) glucose and phenolic acids: gallic acid and protocatechuic acid were the compounds attributed to this bioactive property (12).

In addition, a reduction in the viability of DLD-1 cells with an IC50 of 117.9 µg/mL has been specifically reported using the hydroalcoholic extract of *Y. aloifolia* (46). The study also showed the prevention of polyamine accumulation via anti-ornithine decarboxylase activity. Importantly, the constituents of this extract exhibited minimal toxicity in probiotics and 3T3 fibroblasts, reinforcing their safety for human consumption. This biological activity of *Y. aloifolia* extract was attributed to the presence of ferulic acid, chlorogenic acid, caffeic acid, quercetin and their glycosides (rutin and quercitrin). In another study, the cytotoxic effect of the methanolic extract from *Y. gigantea* leaves against A431, Hep-2, HSF, MG-63 and A375 cell lines was studied (10). The extract showed strong cytotoxic activity, particularly against human melanoma (A375) and osteosarcoma (MG-63) cell lines. Saponins, flavonoids and various organic and phenolic compounds were found in the extracts with the aid of Liquid chromatography coupled to electrospray ionization mass spectrometry (LC-ESI-MS). However, flavonoids such as apigenin, kaempferol, luteolin and quercetin were said to be responsible for this activity.

Neuroprotective effects

The neuroprotective property of *Yucca* species is another bioactivity that has been documented by some studies. For instance, evidence of the neuroprotective potential of *Y. aloifolia* fruit extract has been reported in an *in vivo* model (9). The Wnt/β-catenin/AMPK pathway was investigated as a potential mechanism involved in the pathogenesis and a possible target of anthocyanins. From this study, Western blot analysis revealed that rotenone significantly reduced protein expression in rats, while YA-C treatment partially restored these protein levels. The study combined *in vitro* mechanistic insights with *in vivo* validation and it was reported that *Y. aloifolia* showed promising neuroprotective potential and highlighted the Wnt/β-catenin/ AMPK pathway as a potential therapeutic target for Parkinsons' disease (PD). Gallic acid, flavonol quercetin and its glycosides were reported to have contributed to this property, as well as choline and homoisoflavonoid eucomol (60–63).

Moreover, from another study, the effect of both single spiro-flavostilbenoids (Yuccaol B and gloriosaol A) and phenolic fractions derived from *Y. schidigera* bark on scopolamine-induced anxiety and memory process deterioration using a *Danio rerio* model was evaluated. It was reported that *Y. schidigera* has *in vitro* potent anti-inflammatory, antioxidant and moderate cholinesterase inhibitory activities. The neuroprotective effects of the extract were reported to be due to its phenolic compounds, including spiro-flavostilbenoids, resveratrol derivatives and flavonoids like naringenin. These compounds act through antioxidant, anti-inflammatory and cholinergic mechanisms, offering potential therapeutic benefits for neurodegenerative diseases like Alzheimers' (AD) and Parkinson's (PD). Further studies were recommended to confirm their ability to cross the blood-brain barrier (BBB) and exert direct effects in the brain (54).

Hepatoprotective activity

Hepatoprotective activity describes the capacity of certain substances to safeguard the liver from damage or aid in its recovery. The liver performs essential functions of metabolism, storage, detoxification, secretion and digestion, which makes it highly susceptible to harm from toxins, medications and oxidative stress (64). Plant extracts abundant in antioxidants show great potential in promoting liver health and protection. Plant-derived compounds with liver-protective properties include phenolics, flavonoids, alkaloids and saponins (65). The increasing interest in natural liver-supporting agents has driven extensive research into plant-based compounds for liver health and protection (66). The hepatoprotective effects of the ethanolic extracts from *Y. filamentosa*, *Y. aloifolia*, *Y. elephantipes* and *Y. aloifolia* var. *variegata* leaves against CCl4-induced hepatotoxicity in rats have been reported (12). While the four extracts demonstrated good capacity to protect the liver cells from CCl4 injury, *Y. aloifolia* var. *variegata* was said to be the most potent of them all. The authors attributed this biological activity to 2 flavonoids (hesperidin and kaemp-3-(2-p-coumaroyl) glucose) and phenolic acids (gallic acid and protocatechuic acid) as identified using HPLC.

Enzyme inhibition properties

Enzyme inhibition refers to the process by which a molecule, termed an inhibitor, reduces or ceases the activity of an enzyme, thereby preventing it from catalysing a biochemical reaction. Recent studies on enzyme inhibition emphasise its significance in controlling biological functions and advancing therapeutic solutions (67). The application of enzyme inhibition strategies is essential in the treatment of conditions such as cancer, neurological disorders and infectious diseases (68). Natural products continue to be a valuable source of enzyme inhibitors, with diverse screening approaches utilised to discover promising candidates from plant-based compounds (69).

Several studies reported notable enzyme inhibition properties of some *Yucca* extracts, demonstrating inhibition of pancreatic lipase, alpha-glucosidase and ornithine decarboxylase (ODC) with the application of the ethanolic extract from *Y. aloifolia*. It was recommended that additional chromatographic techniques would aid in identifying the bioactive compounds with anti-ODC properties (11). In addition, research has also reported potent inhibition of lipase, ornithine decarboxylase and alpha-glucosidase with the application of hydroalcoholic extract from *Y. aloifolia* (49). The consistency in enzyme inhibition across these studies suggests potential applications in metabolic disorders and cancer prevention, given the roles of these enzymes in lipid metabolism, glucose regulation and polyamine synthesis.

Metabolic regulation

Metabolic regulation encompasses complex mechanisms that govern biochemical reactions within cells to maintain homeostasis, meet energy demands and adapt to environmental changes. It ensures the efficient functioning of metabolic pathways by modulating the production, utilisation and storage of nutrients according to the bodys' requirements. Furthermore, it plays a pivotal role in shaping immune cell responses through epigenetic changes, affecting their activation and memory formation (70). A study provided evidence of the metabolic regulatory effects of *Y. aloifolia* flower extract (*in vivo*), recording an improvement in glucose and lipid profiles in mice subjected to a hypercaloric/ atherogenic diet. This finding, combined with the observed enzyme inhibition properties, suggests potential applications in metabolic disorders such as diabetes and obesity (46).

Health applications of *Yucca*

Nutraceuticals and dietary supplements

Commercial *Yucca* extracts are FDA-approved as Generally Recognised as Safe (GRAS). They are important food supplements, flavour enhancers and are widely used as surfactant additives in the production of beverages (71, 72). Moreover, *Yucca* products are valued for their foaming properties, making them useful in soft drinks like root beer and food production (73). They are also used as dietary supplements (74). However, more clinical trials in humans are needed to fully validate these health claims and to determine the optimal dosage.

Joint and bone health

Yucca species have been reported to be helpful in the management of osteoarthritis and rheumatoid arthritis. It is important in the pharmaceutical industry due to its medicinal properties (75). It also provides para-pharmaceutical aids and has gained a strong reputation in traditional medicine (71). Its extracts have been used to relieve joint pain, bleeding and inflammation of the urethra and prostate. Its crushed roots were applied as a poultice for wound healing and were also used to treat rheumatism. *Yuccas* were also used topically for wound healing (38, 76). They are also used for treating (77). Additionally, infusions made from its leaves and roots were mentioned to help with asthma and headaches.

Gastrointestinal health

Yucca schidigera extract (YSE) has shown multiple benefits across different livestock species. It supports poultry production by promoting intestinal health and inhibiting harmful bacteria, protozoa and nematodes that can hinder growth and efficiency (78). Furthermore, studies on broiler chickens raised in tropical conditions have shown that YSE improves growth performance, nutrient absorption and gut health. Additional research has also emphasised its role in enhancing antioxidant defences, strengthening immune function and optimising nutrient utilisation (78, 79). Likewise, in weaned piglets, improved feed conversion, lower hindgut ammonia production, improved nutrient digestibility and lower blood urea levels have been observed after YSE supplementation (80).

Skin health and cosmetic applications

The important health application of the *Yucca* species is for skin health and cosmetic applications. It serves anti-ageing and skin-soothing properties. The plant is also known for its skin-softening and sleep-inducing. In addition, brewed *Yucca* leaves were traditionally used to treat common conditions such as psoriasis, dandruff, hair loss and skin sores. They are also used topically for sunburns (38). *Yucca* saponins were used by native Americans for various purposes, including as a natural soap. *Yucca schidigera* extract and *Yucca* powder (made from dried, finely ground logs) are widely used in the cosmetic industry (73). They are used as moisturising agents and surfactant additives in cosmetics due to their foaming properties (72).

Agricultural and veterinary applications

In livestock feed, some *Yucca* species have been reported to improve germination and vigour in plants. For example, the bio-stimulant effect of two *Y. schidigera* extracts on plant growth at different developmental stages under diverse abiotic stress conditions was examined and it was indicated that these extracts effectively promoted germination (57). It is also important to state that *Yucca* supplementation can influence ovarian functions in sheep, affecting follicle development and hormone production (20). Various extracts and derivatives from these plants are marketed for diverse applications, such as soil enhancers and surfactant additives in animal feed, poultry feed and agricultural products (73). Additionally, *Y. schidigera* extract is a natural feed supplement containing steroidal saponins and polyphenols, known for its beneficial effects on animal productivity and environmental health. It is commonly utilised to manage odour and ammonia emissions in intensive livestock systems such as poultry, swine and aquaculture by binding ammonia-nitrogen and limiting its buildup. In ruminants, it helps to reduce methane emissions by suppressing methanogenic archaea and protozoa linked to methane production. Research highlights *Y. schidigera* extracts' ability to enhance livestock performance while minimising environmental impact, making it a valuable component in sustainable animal and agricultural production (78–80).

Discussion

It is well known that desert areas exist all over the world. These fascinating ecosystems can be found on every continent. Experts state that climatic conditions are changing. The increase in the global mean surface temperature (GMT) extends from the land to the oceans, altering atmospheric circulation patterns. High land surface temperatures are indicators of decreased soil moisture, exacerbating drought conditions. The frequency of these conditions is causing the expansion of arid zones worldwide (81). Numerous studies have warned about the future prevalence of these conditions; to meet this challenge, the study of desert plants is essential. *Yucca* plants are extraordinary models for study, as they not only provide food, fibre and building material, but their genetic variability can also yield relevant data on their specialised physiology in response to water stress. These plants, by adapting to extreme environments, can colonise different sites around the world and their potential functional benefits can be truly utilised by the inhabitants of these ecosystems. Although the genus is endemic to North America, Mexico and parts of Central America, there are specimens that have adapted to European climates, such as in Spain, where a large number of specimens have been exported for ornamental purposes and are part of botanical gardens (82).

Its adaptability is attributed to its morphological characteristics; various studies agree that the variation in the size and shape of its plant structures, such as leaves, flowers and fruits, has been acquired from evolutionary processes in response to the availability of moisture in arid zones (18). Regarding the nutritional quality of their flowers, only a few species have been studied. They are distinguished by their high content of carbohydrates, protein and fibre, as well as minerals and essential amino acids (33). Their fruits are distinguished by their fibre content; however, there are few studies focused on their nutritional content. The phytochemical content of *Yucca* leaves (*Y. aloifolia*, *Y. gloriosa*, *Y. glauca*, *Y. schidigera*, *Y. macrocarpa*, *Y. elephantipes* and *Y. smalliana*) has been extensively studied, with reports agreeing that they are a source of steroidal saponins, spirostannic acid, furostannic acid, stilbenes and flavonoids (38, 41). The antioxidant, antimicrobial, cytotoxic, hepatoprotective, metabolism-regulating, hypoglycemic, neuroprotective and anti-inflammatory properties of these plants present substantial potential for use in diverse sectors such as food, pharmaceuticals, cosmetics, materials and agriculture. Studies focusing on their bioactive properties have been demonstrated in *in vitro* and *in vivo* tests on healthy and cancerous cell lines (10).

Although most species are wild, only *Y. schidigera* has been domesticated and has reached commercial production levels. This species is distributed from Nevada in the USA to Baja California in Mexico, where it is cultivated. In Mexico, there are plantations of up to 500 ha produced by the company Agroin® Baja Agro Internacional. Its products are marketed in Europe, Asia and Latin America and demand is continuously growing due to their organic and environmentally friendly nature. Its products are used as a food supplement, aiding in nutrient absorption and reducing cholesterol levels; as a feed additive for farm animals and in aquaculture systems, helping to reduce ammonia emissions (NH3) and as flavourings and foaming agents in the soft drink industry, due to their saponin content and surfactant and emulsifying properties (37). Its fibres are used in the textile and paper manufacturing industries. There are still a large number of *Yucca* species to be explored and their bioactive properties are scientifically supported. Knowledge of these valuable resources represents a potential source for harnessing compounds of interest not only for human well-being, but they have also proven to be excellent restorers of soil and water environmental conditions. And since their structures are highly usable for obtaining high-value products, it favours one of the most relevant aspects of sustainable production, namely the circular economy, which today has as its main objective reducing the generation of agro-industrial waste, reducing pressure on ecosystems and protecting the environment through the optimisation of its processes (83).

Conclusion

Undeniably, plants native to arid regions have been vital to the survival of local populations for thousands of years. Their structure, phytochemistry and diversity represent a broad field of study for researchers around the world. Of the nearly fifty existing species, only a few have been thoroughly studied, such as *Y. schidigera*, *Y. aloifolia* and *Y. elephantipes* and only one is cultivated on an industrial scale; the rest are still under study. Their ancestral uses have survived to this day and their bioactive properties are increasingly being studied. To understand them and unravel their processes, it is necessary to establish domestication systems, especially for the most promising ones, taking into account their slow growth rates and large size. Studying and understanding these plants should lead us toward more mindful stewardship and sustainable use, especially as we confront growing challenges like water scarcity driven by climate change. With their remarkable ability to thrive in extreme environments, these exceptional species may prove to be some of our most valuable allies.

Acknowledgements

The first author thanks the Secretary of Sciences, Humanities, Technology and Innovation (SECIHTI), Mexico for the support through a postdoctoral fellowship EPM-2021(1) to carry out this research.

Authors' contributions

MMOS participated in the design, coordination, photography and writing of the manuscript. LAASM participated in the writing and organisation of the manuscript. JDGO participated in the writing and created figures. BRF compiled data, developed part of the manuscript and created tables. RRH participated in the writing, design and oversaw the English grammar of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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