



REVIEW ARTICLE

Exploring the nutritional composition and health benefits of *Mammillaria*: A review

Bosede Ruth Faleye¹, Grace Omobola Adesina², Azeez Ayodele Alimi¹, Iván A. Niño-Vásquez¹, Opeyemi Esther Adeola³ & Raúl Rodríguez-Herrera^{1*}

¹School of Chemistry, Autonomous University of Coahuila, Saltillo 25280, Coahuila, Mexico

²Department of Agricultural and Food Science, Faculty of Agriculture, University of Mauritius, Réduit, Moka 80837, Mauritius

³Nigerian Navy College of Accounts and Finance, Umuahia 440 001, Abia State, Nigeria

*Email: raul.rodriguez@uadec.edu.mx



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Abstract

The genus *Mammillaria* is one of the largest and ecologically diverse genera in the Cactaceae family, with a broad geographical distribution across the arid and semi-arid regions of the Americas. The species are characterized by tuberculate stems, specialized water-storage tissues and numerous spine arrangements that aid in their survival under extreme drought and temperature fluctuations. Biochemically, *Mammillaria* contain secondary metabolites, such as phenolics, flavonoids, alkaloids and betalain pigments, which contribute greatly to their ecological resilience, antioxidant defense and other biological activities. They are also potential sources of abundant mucilage polysaccharides, structural fiber and minerals. Despite their environmental significance and nutritional and pharmacological potential, there is a lack of a comprehensive synthesis of their composition and functional characteristics and limited research on the chemical properties of most species. Therefore, this review presents an overview of the description, taxonomy, distribution, nutritional composition, medicinal properties, bioactive composition and biological activities of the genus *Mammillaria* reported in the literature from various databases, including Google Scholar, PubMed, Scopus and ResearchGate. In addition, the major limitations, strategic interventions and prospective research directions for maximum production and utilization of the species are discussed. With proper exploration and responsible utilization of the species, *Mammillaria* could offer great economic, technological and nutritional benefits to society.

Keywords

antibacterial; anti-inflammatory; antioxidants; bioactive compounds; nutrients; phytochemicals; polyphenols

Introduction

Mammillaria is one of the largest and morphologically most diverse genera in the cactus family (Cactaceae), with more than 200 recognized species and subspecies (1). The large variability in size, shapes and colors of flowers, combined with the relative ease of culturing and maintenance, makes this genus of significant interest to horticulture (2). Seven common *Mammillaria* species, including *Mammillaria rhodantha* (*M. rhodantha*), *Mammillaria spinosissima* (*M. spinosissima*), *Mammillaria hahniana* (*M. hahniana*), *Mammillaria crucigera* (*M. crucigera*), *Mammillaria candida* (*M. candida*), *Mammillaria albilanata* (*M. albilanata*) and *Mammillaria muehlenpfordtii* (*M. muehlenpfordtii*) widely used in spring flower festival decoration in cactus or desert gardens, have been recognized (3). However, many of the *Mammillaria* species are already threatened due to the variation within them. Species within the genus *Mammillaria*, from small to medium-sized cacti are widely appreciated for their tuberculate stems and their brilliantly coloured flowers. They are typically cultivated as ornamental plants because of their morphological diversity and ease of propagation, making them among the most commercially traded cacti in the international horticultural market. Mexico is the principal producer and centre of diversity of *Mammillaria*

species. At the same time, the international trade in artificially propagated *Mammillaria* is dominated by countries such as Canada and China, with the Netherlands, Japan, Brazil, South Korea, Spain and Canada among the leading exporters of cacti worldwide (4). Besides their ornamental value, recent studies have indicated that *Mammillaria* could be a promising source of food and phytochemicals, with emerging applications in food, health and sustainable development, especially in arid and semi-arid regions, where conventional crops are less adaptable (3, 5).

Cacti contribute to the economic value of the ornamental plant industry through commercial nursery production and international trade in live plants. In Mexico, the total trade value of live plants and floricultural products reached US\$311 million in 2024, highlighting the economic importance of the ornamental plant sector (6). However, unlike agricultural cactus crops such as *Opuntia ficus-indica*, no official global statistics are available on the annual global production or the specific economic value generated by the genus *Mammillaria* in tons, as production and trade are reported within the floriculture industry in terms of nursery production and live-plant commerce rather than biomass yield or market value of specific species (4, 7). The knowledge of the nutritional value of *Mammillaria* is important not only for ecological research but also for studying their possible contributions to human health and food security. Many of the genus *Mammillaria* have been used in native diets and traditional medicine practices, attributable to their bioactive compounds, hydrated tissues and hardness within hostile environments (5, 8). Exploring the nutritional and biochemical profiles of these plants would reveal significant macro- and micronutrient content, antioxidant activities, as well as potentially nutraceutical compounds that may be used locally for subsistence or on an industrial scale for functional foods or pharmaceutical applications.

The ethnobotanical records and preliminary investigations point to the possibility of *Mammillaria* being a source of nutritional compounds like dietary fibre, vitamins, minerals and antioxidants, among others. (3). These compounds are not only important as basic nutritional components but also essential in promoting health and preventing non-communicable diseases, including diabetes, cardiovascular disease and obesity (9, 10). These studies allow exploration and definition of nutritional as well as phytochemical compositions in such plants to open new ways for functional food products and health promoting target products. Furthermore, with the understanding of the ecological and nutritional importance of *Mammillaria*, there is a greater impetus to conserve their natural habitats and genetic resources. Sustainable harvesting and possibly cultivation may also promote biodiversity, as well as generate economic opportunities to support local food production, eco-tourism or the market for healthy foods.

Other studies have also added to the knowledge of the nutritional or biochemical prospects of the genus *Mammillaria*. A study on the fruits of *Mammillaria uncinata* (*M. uncinata*) provided proximate composition data (crude fibre, lipids, ash) and bioactive compounds, which are directly relevant to human nutrition, agronomy and utilization (11). An investigation into the potential agronomic role of *Mammillaria* indicated that some types of treatments can enhance fruit set, flowering, resistance and so on. This study suggests potential for cultivation optimization and strategies for improving yields in this species (12). However, there are important knowledge gaps in these studies. Most work

concentrated on one or several species, one type of tissue (stem or fruit); there are insufficient data for many species within the genus *Mammillaria*, particularly the uncommon ones; edible tissues (fruits, seeds and pulp) as well as non-edible parts. In addition, many papers investigated bioactive compounds (polyphenols, antioxidants), but did not evaluate nutrients, vitamins (such as A, C, E and B complex), minerals (iron, calcium, zinc, etc.) and the trace element profile of *Mammillaria*.

The genus *Mammillaria* is widely understudied in terms of systematic characterization regarding its nutritional value and agricultural potential. Given today's global concern for underutilized plant resources and sustainable food, a comprehensive investigation into the nutritional potential of *Mammillaria* is now both timely and pressing. The main objective of this review is to compile and critically assess the existing literature on the nutritional composition of the genus *Mammillaria*. The scope includes an analysis of macronutrients (such as carbohydrates, proteins and lipids), essential vitamins and minerals, bioactive phytochemicals and their potential health implications. Furthermore, the review aims to highlight research gaps, propose future directions for nutritional and biochemical studies and discuss sustainable uses of *Mammillaria* in food systems.

Materials and Methods

The methodology was based on a systematic and exhaustive review of the scientific literature conducted via a thorough search of all publications (research and review articles) on the species of the genus *Mammillaria*. Electronic databases, including Scopus, Wiley, Web of Science, SpringerLink, ResearchGate, Elsevier, PubMed and Google Scholar, were searched for articles published between January 2000 and September 2025. In addition, a limited number of seminal publications published in 1973, 1981 and 1983 were included because they provide foundational taxonomic and ethnobotanical information that remains relevant to the genus. The literature search was conducted between June and October 2025. The search strategy combined keywords such as taxonomic classification, distribution, ethnobotanical and medicinal uses, nutritional composition, bioactive compounds and biological activities, such as anti-cancer, antioxidant, anti-inflammatory and antimicrobial activities of different species of *Mammillaria*. The scientific names of common and representative species, such as *M. uncinata*, *Mammillaria glassii* (*M. glassii*) and *Mammillaria prolifera* (*M. prolifera*), were also included in the search.

Included studies were peer-reviewed research articles or review papers that reported information on taxonomy, ethnobotany, distribution, nutritional composition, phytochemical profile, bioactive compounds, biological activities or potential applications of *Mammillaria* species. Studies that focused on unrelated cactus genera, conference abstracts, duplicated records and articles not directly relevant to the objectives of this review were excluded.

Additionally, a detailed analysis of the selected studies was performed by extracting and organizing the information obtained into thematic categories to facilitate the presentation and understanding of the results (Fig. 1). Based on the screening and eligibility criteria, 101 publications were included in the final review.

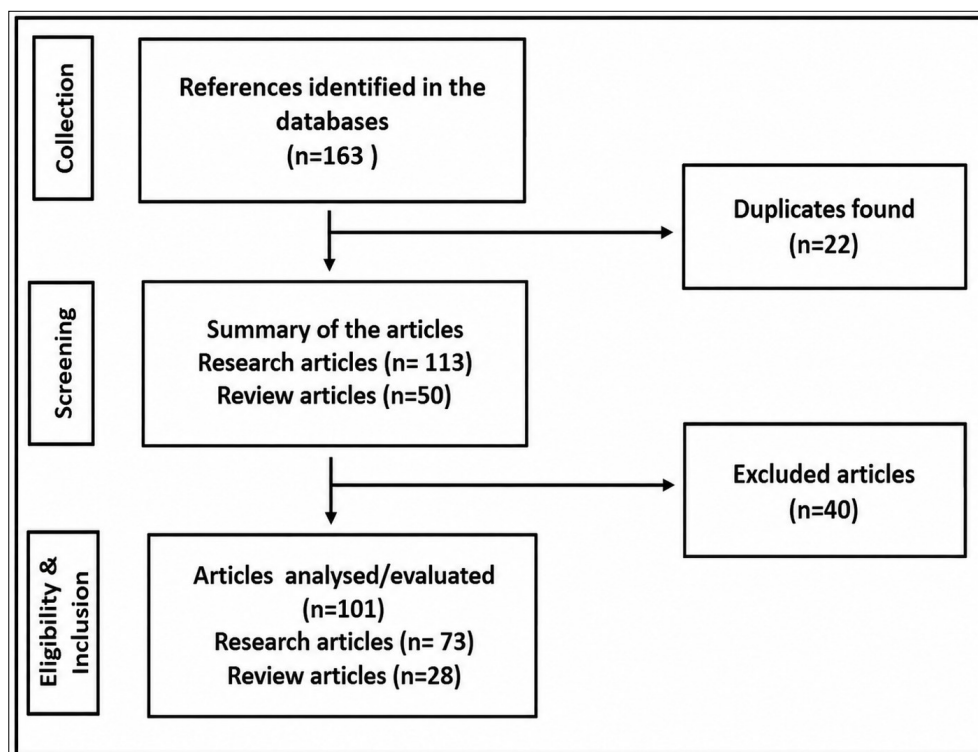


Fig. 1. The methodology for screening the articles for this *Mammillaria* review.

Results and Discussion

Taxonomy and distribution of *Mammillaria*

Taxonomic classification and diversity of *Mammillaria*

The genus *Mammillaria* is taxonomically classified within the tribe Cacteeae, subfamily Cactoideae and family Cactaceae. The diversity of the genus is remarkable, in structure as well as in habitat specialization. The genus has been difficult to classify due to high variability in morphology and interspecific hybridization; however, molecular phylogenies have increased understanding of the genus in recent years (13). The diverse variations among *Mammillaria* can be seen in their ability to inhabit a variety of microhabitats and ecological niches (14). Despite the abundant botanical diversity and adaptive characteristics of *Mammillaria* species catalogued to date, the food or nutraceutical potential of this genus continues to be underrepresented in scientific research and farm practice. *Mammillaria* species are among the underutilized plant resources that have great potential to adapt to the current food and nutrition security, biodiversity conservation and climate-related challenges that humanity faces. This underexploited species offers an opportunity for promising research and sustainable management.

Geographical distribution of *Mammillaria*

Mammillaria species are endemic to the harshest habitats on Earth, such as deserts and rocky environments with little access to water or nutrients (15). Their physiological characteristics qualify them as suitable crops to grow in arid and/or degraded soils with low fertility. Amidst climate change and the rapid expansion of water scarcity, the value of utilizing such resilient species becomes even more important in the development of climate-smart agricultural systems. Geographically, *Mammillaria* species are confined mostly to Mexico, where the genus is a center of diversity, including species such as *Mammillaria bombycina* (*M. bombycina*), *M. uncinata*, *Mammillaria longimamma* (*M. longimamma*), *Mammillaria mamillaris* (*M. mamillaris*), *Mammillaria nana* (*M. nana*), *Mammillaria parkinsonii* (*M. parkinsonii*), *Mammillaria rubrograndis* (*M. rubrograndis*),

Mammillaria tropica (*M. tropica*), *Mammillaria guezowiana* (*M. guezowiana*), *Mammillaria huitzilopochtli* (*M. huitzilopochtli*), *Mammillaria pringlei* (*M. pringlei*) and *Mammillaria plumosa* (*M. plumosa*). (Fig. 2); however, their range extends into the southwestern United States, Central America and even as far south as Colombia (16). Their survival and adaptation to poor nutrient soils and harsh climates also render these wild greens important members of the native ecosystems, as well as good materials for climate-resilient nutrition and agriculture research (17).

Species of *Mammillaria* are widely distributed across 3 regions of Mexico, namely the Puebla-Oaxacan, Jaliscan and Sonoran-Sinaloa regions of Mexico (18). Investigating native plants such as *Mammillaria* can be an alternative and/or a complement to food supply, particularly in rural and indigenous communities of various arid to semi-arid areas where access to traditional crops and market-based food systems may be restricted. Encouraging the in-situ utilization of such species can also support communities to depend on robust, culturally suitable and nutritionally valuable resources.

Macronutrient and micronutrient composition of *Mammillaria* species

Mammillaria species have been studied for their nutritional composition, especially in terms of the bioactive compounds present in them. However, information on their macronutrient and micronutrient contents is limited (Table 1). Proximate composition of the fruit of some *Mammillaria* species, like *M. uncinata* and *Mammillaria elongata* (*M. elongata*), was determined using whole fruit and fruit extract, respectively. The protein value of the whole fruit of *M. uncinata* (0.95 %) was lower than that of the fruit extract of *M. elongata* (6.16 %) (19, 20). Comparatively, *Opuntia ficus-indica*, another member of the Cactaceae family, like *Mammillaria*, was reported to contain low protein (1.39 %) in its Cladode extract and a higher value (5.6 %) in its fruit juice, according to a study on prickly pear (21). Nevertheless, these values are lower than the protein contents of the fruit extracts of other cactus plants, such as



Fig. 2. Various species of *Mammillaria*. (A): *M. Huitzilpochtli*; (B): *M. pringlei*; (C): *M. plumosa*; (D): *Mammillaria backebergiana* (*M. backebergiana*); (E): *Mammillaria magnifica* (*M. magnifica*); (F): *Mammillaria nejapensis* (*M. nejapensis*); (G): *Mammillaria ernestii* var. *albispina* (*M. ernestii* var. *albispina*); (H): *Mammillaria aureilana* (*M. aureilana*); (I): *Mammillaria orcuttii* (*M. orcuttii*); (J): *M. bombycine*; (K): *Mammillaria bocasana* (*M. bocasana*); (L): *M. longimamma*; (M): *M. mammillaris*; (N): *M. nana*; (O): *M. parkinsonii*; (P): *M. rubrograndis*; (Q): *M. tropica*; (R): *M. guelzowiana*; (S): *Mammillaria vetula* subsp. *gracilis* (*M. vetula* subsp. *gracilis*); (T): *M. uncinata*.

Pilosocereus gounellei (*P. gounellei*) (12.35 %) and *Cereus Jamacaru* (13.01 %) (22). The fat content of the whole fruit of the *M. uncinata* species was 1.79 % (19). This is higher than that found in the *Cladode* extract (0.11 %) and fruit juice (0.22 %) of prickly pear (21).

Contrarily, higher fat contents of 7.79 % and 5.22 % were reported for *P. gounellei* and *Cereus Jamacaru*, respectively (22). Regarding the carbohydrate content of *Mammillaria* species, a high amount of reducing sugar, such as glucose, was reported for the fruit extract of *M. elongata*, though the value was not indicated (20). Similarly, fruits of *P. gounellei* and *C. Jamacaru* have also been reported with high sugar content. The variation in the macronutrient profiles of *Mammillaria* is a result of the individualistic nature of each species' chemical composition (22). In the same way, different profiles of macronutrients in plant species of non-conventional food plants consumed in the Brazilian Atlantic Forest have been reported (23). Moreover, the treatment of *Mammillaria* with various algae has been recognized to have notable effects on the sugar and vitamin contents of their fruits. For instance, there was an increase in the sugar content of *M. glassii* and *M. prolifera* fruits after treating their plants with some selected algae, *Hypnea comuta* (Rhodophyta), *Ulva ohnoi* (Chlorophyta) and *Sargassum muticum* (Phaeophyceae). The sugar content of both species ranged from 3.70–4.85 g after the

treatments. Vitamin A content ranged from 6.14–7.36 mg, with an increasing trend observed in the fruit of *M. glassii* in contrast to *M. prolifera* fruit. Vitamins C and E of the 2 species also increased after the algae treatments, ranging from 7.36–8.95 mg and 0.02–0.064 mg, respectively. The effect of the algae treatment could be attributed to the bioactive compounds in the algae employed (12). Another study similarly demonstrated cactus pear plants with enhanced nutritional and nutraceutical value after inoculation with a strain of *Arthrobacter* sp. (24).

Despite the increasing scientific interest in *Mammillaria* species, a major limitation in the available literature is the lack of comprehensive information on their mineral composition. While a few studies have reported the mineral profiles of some species within the Cactaceae family, no studies have characterized the mineral composition of *Mammillaria* species. This knowledge gap limits the accurate assessment of their nutritional value and potential applications in food and nutraceutical development. Therefore, future research should prioritize comprehensive characterization of the macro- and micronutrient compositions of *Mammillaria* species, including their amino acid, fatty acid, carbohydrate, vitamin and mineral profiles in both stems and fruits.

Table 1. Macronutrient and micronutrient composition of some *Mammillaria* species

Species	Nutrient	Values
<i>M. uncinata</i> (whole fruit)	Protein	0.95–6.16 %
<i>M. elongata</i> (fruit extract)		
<i>M. uncinata</i> (whole fruit)	Lipid	1.79 %
<i>M. glassii</i> , <i>M. prolifera</i> (algae-treated fruits)	Carbohydrates (Sugar)	3.70–4.85 mg
<i>M. glassii</i> , <i>M. prolifera</i> (algae-treated fruits)	Vitamin A	6.14–7.36 mg
<i>M. glassii</i> , <i>M. prolifera</i> (algae-treated fruits)	Vitamin C	7.36–8.95 mg
<i>M. glassii</i> , <i>M. prolifera</i> (algae-treated fruits)	Vitamin E	0.02–0.064 mg

Health benefits and applications of *Mammillaria*

Some species of *Mammillaria* have been found useful in traditional medicine practices and their potential applications in modern medicine are being studied. *Mammillaria pilcayensis* (*M. pilcayensis*), commonly known as the bottlebrush cactus, has a history of being used for the treatment of rheumatism, stomach ailments and fever. Its antimicrobial and anti-inflammatory properties make it effective in treating infections and reducing inflammation. Additionally, it is reported to contain pain-relieving compounds that make it effective for managing various types of somatic pain, including menstrual cramps and headaches. *Mammillaria pilcayensis* also enhances the overall digestion process by boosting the production of digestive enzymes. Moreover, its potential use in treating diabetes and cancer has been suggested by some researchers (25).

Similarly, *Mammillaria heyderi* (*M. heyderi*) was reported as a traditional medicine with a magical power to clear vision as well as a cure for headaches and earaches, especially when roasted. This species is not only used as medicine, but its edible red fruits also serve as a food source (26). Overall, few reports only have the traditional uses of *Mammillaria* sp.; its application in contemporary medicine and culinary practices should be further investigated and well-established.

Bioactive compounds

Phytochemicals: Polyphenols, flavonoids and other bioactive compounds in *Mammillaria*

Phytochemicals, often referred to as secondary metabolites, are bioactive compounds that are naturally present in plants. Although they do not provide any nutrients, they are highly beneficial to humans, as they are healthful and help prevent certain diseases. They are non-nutritive components of plants that offer health benefits and disease-prevention properties. They are categorized into two main types, namely, primary or secondary metabolites (27). Primary metabolites play a direct role in plant growth and development. They are also involved in processes such as photosynthesis, respiration, protein synthesis and hormone synthesis. Examples include proteins, sugars, amino acids, purines, chlorophyll, pyrimidines of nucleic acids and vitamins (28–30).

Secondary metabolites, on the other hand, do not have a direct role in plant growth and development. Rather, they are significant in mediating the interactions between the plant and its physical environment, especially under adverse conditions and stress. They serve as a defence mechanism against diseases and plant predators (31). Different types of secondary metabolites are synthesized in plants, which are meant to aid their survival and protection (11). Phenols, flavonoids, terpenes, steroids, alkaloids,

lignans, curcumins and saponins are examples of secondary metabolites (32, 33). Worthy of note are the commercial applications of secondary metabolites as drugs, insecticides, flavouring agents and dyes.

Polyphenols are phenolic compounds containing many hydroxyl groups in their structure. They are compounds that delay aging and protect the body against oxidative stress and its associated diseases, such as coronary heart disease, inflammation, neurodegenerative diseases, diabetes, hypertension, obesity, asthma and cancers (34). Polyphenolic extracts are well known for their beneficial effects on human health, due to their antioxidant, anticancer, cardio-protective, neuro-protective, anti-inflammatory and antimicrobial properties (34, 35). Polyphenols are important compounds in relation to biological activities since they undergo a series of mechanisms such as apoptosis, antioxidant mechanisms, antiproliferation, anti-inflammatory activity, induction of detoxification enzymes and stimulation of cell cycle arrest, among others (36–40).

Currently, research on natural products has focused on the discovery of new and healthy resources from polyphenols. Known sources of polyphenols include fruits, vegetables, cereals and beverages, with recent studies revealing other sources such as tree barks, plant stems and fungi (41, 42). During the profiling of the methanolic stem extracts of *M. rhodantha*, *M. hahniana*, *M. candida*, *M. crucigera*, *M. albilanata*, *M. spinosissima* and *M. muehlenpfordtii* using high-performance liquid chromatography with a DAD detector (HPLC-DAD), the following phenolic acids were found: gentisic acid, chlorogenic acid, caffeic acid, protocatechuic acid, sinapic acid and p-hydroxybenzoic acid. The *Mammillaria* species had varying concentrations of the phenolic acids: gentisic acid was dominant in *M. spinosissima* and *M. rhodantha*; chlorogenic acid was dominant in *M. muehlenpfordtii*, *M. crucigera*, *M. candida* and *M. rhodantha*; and caffeic acid was dominant in *M. rhodantha*, *M. crucigera* and *M. spinosissima*. In summary, *M. rhodantha* and *M. spinosissima* were the richest sources of phenolic acids out of the 7 species studied (43).

The phytochemical profile of *Mammillaria herrerae* (*M. herrerae*) Werdermann callus and shoot cultures was determined using UHPLC-MS/MS (44) and it was reported that the shoots had more compounds (36) than the callus (29) (Table 2); likewise, the total phenolic and flavonoid contents were higher in the shoot than in the callus. Sterols, tannins, flavonoids, saponins and alkaloids were also found in the phytochemical analysis of *M. spinosissima*, *Mammillaria polythele* (*M. polythele*) *Mammillaria supertexta* (*M. supertexta*) *Mammillaria springlei* (*M. springlei*) and *M. hahnianain* extracts (Table 2) (45).

In another investigation, phytochemical analysis of the

ethanolic extract of *Mammillaria geminispina* (*M. geminispina*) revealed the presence of tannins, flavonoids, cardiogenic glycosides and sesquiterpene lactones. In contrast, GC-MS analysis of the same extract revealed the presence of myristic and chlorogenic acids (46). Myristic acid has been previously identified in other species of cactus, such as *O. ficus indica* seeds (47), *Hylocereus polyrhizus* and *P. gounellei* (seed oil) (48) and *Opuntia dillenii* (*O. dillenii*) (49).

Muncinata is said to be a potential source of phytochemicals following the phytochemical profile of its stem and root using four types of extraction solvents (hexane, ethyl acetate, 80 % ethanol and water) (20). Abundant alkaloids were present in its ethanolic and aqueous stem extracts. From the four extraction methods, flavonoids, sterols (triterpenes), alkaloids and saponins were found in the stem extracts, while sterols and saponins were found in the root extracts (Table 2). Tannins were also detected through histochemical tests. These substances were found in other cactus plants and more importantly, they have been reported to have some biological activities (50). For example, flavonoids, which are a group of polyphenolic compounds, have been frequently reported for their antioxidant activity (51, 52). The secondary metabolites contained in *M. uncinata* fruits were determined using four different polarity solvents (n-hexane, ethyl acetate, 80 % ethanol and water) and identified as alkaloids, sterols, saponins, coumarins, flavonoids and free amino acids (19).

Antioxidants: Role of antioxidants in health promotion and disease prevention

Antioxidants play a vital role in promoting good health and preventing diseases by neutralizing harmful free radicals, which are unstable molecules that can damage cells, DNA and tissues in the body (54). This action helps reduce oxidative stress, which causes chronic conditions such as cardiovascular diseases, neurodegenerative disorders, diabetes and cancer (55). Besides directly neutralizing free radicals, dietary antioxidants can also boost the body's own defense systems. They do this by activating the Nrf2 pathway, which increases the production of the body's natural antioxidant enzymes. Epidemiological and laboratory studies link higher intake of antioxidant-rich foods like fruits, vegetables and whole grains to lower incidence of chronic diseases, improved cellular resilience and healthier aging trajectories (56).

Biological activities of the genus *Mammillaria*

The biological activities reported in *Mammillaria* species include anticancer, anti-inflammatory, antibacterial, antioxidant and enzyme inhibitory activities, with the details presented in Table 3.

Anticancer activities of *Mammillaria* species

The cytotoxic effect of *Mammillaria geminispina* (*M. geminispina*) was reported, where its ethanolic extract inhibited the viability of the C6 mouse glioma cell line at concentrations of 100, 150 and 200 µg/mL. In the same study, cytotoxicity (47 %) was shown against a non-cancerous cell line of human keratinocytes (HaCaT) and more toxicity (24.54 %) with cells treated with lipopolysaccharide at 100 µg/mL. Also, ethanol extracts of *M. geminispina* had cytotoxic activity for C6 cells at higher concentrations (46). This effect was attributed to the presence of sesquiterpene lactones and chlorogenic acid in *M. geminispina*'s extract (57, 58). The anti-cancer potential of *Mammillaria* species was attributed to the protective effects of polyphenols present in this species, thus inhibiting the growth and spread of tumour cells (34).

According to an investigation on the antiproliferative and cytotoxic effects of stem extracts of 7 *Mammillaria* species (*M. rhodantha*, *M. hahniana*, *M. candida*, *M. crucigera*, *M. albilanata*, *M. spinosissima* and *M. muehlenpfordtii*) on MCF-7, HeLa, Jurkat and HT-29 cells, it was discovered that the highest anti-cancer activities were against HeLa, MCF-7 and Jurkat cells, with the best antiproliferative activities found in the treatments with extracts of *M. rhodantha*, *M. spinosissima* and *M. muehlenpfordtii* on HeLa and MCF-7 cells, while the extracts of *M. rhodantha* and *M. spinosissima* had the best anticancer results against HT-29. Also, *M. rhodantha* and *M. spinosissima* presented the best effects against Jurkat cells. It was also noted that with the apoptotic assay, *M. rhodantha*, *M. spinosissima* and *M. muehlenpfordtii* had accumulation of necrotic cells in both early and late apoptotic (59). The anticancer effect of *M. rhodantha*, *M. spinosissima* and *M. muehlenpfordtii* was attributed to the presence of gentisic, chlorogenic, protocatechuic, caffeic, sinapic and p-hydroxybenzoic acids in their methanolic extracts as identified with HPLC-DAD. Previous research has demonstrated the anti-cancer activities of these compounds. Gentisic acid is known as a quinonoid phenolic acid that plays a paramount role in cancer prevention and treatment. It was previously used to control HCT-116 cancer cells and reduce brain tumours by activating brain chemotherapeutics. The anticancer activity of chlorogenic acid has been reported (58). It achieves this by activating the chemotherapeutics of the brain, which reduces brain tumours (60). The other polyphenols found in these species, such as Protocatechuic acid, sinapic acid and p-hydroxybenzoic acid, are also important antioxidants and anticancer compounds (61). Also, caffeic acid was effective against human cervical cancer (62).

Antibacterial activities of *Mammillaria* species

Polyphenols play a crucial role in inhibiting bacteria and controlling the spread of bacterial infections in humans and plants (59). More importantly, they use mechanisms such as deprivation of essential minerals, increasing cell membrane permeability, influencing the metabolism of bacteria, inhibiting microbial enzymes and cytoplasmic membrane destabilization to demonstrate strong antimicrobial activities (both antibacterial and antifungal) on disease-causing (pathogenic) bacteria (44).

The antibacterial activities of some *Mammillaria* sp. were confirmed with a positive effect on *Bacillus cereus*, *Listeria monocytogenes* (*L. monocytogenes*), *Escherichia coli* (*E. coli*), *Micrococcus flavus*, *Staphylococcus aureus* and *Pseudomonas aeruginosa*. It was also noted that the methanolic stem extracts of *M. rhodantha*, *M. spinosissima*, *M. crucigera* and *M. muehlenpfordtii* were the most effective against most of the bacteria (44). It was evident that the antibacterial activities of these species were attributed to polyphenols, including chlorogenic acid, caffeic acid and protocatechuic acid and excluding gentisic acid, since it showed no activity against bacteria (63, 64).

Again, the antibacterial activity of *M. geminispina* against ten bacterial strains (*L. monocytogenes*, *E. coli*, clinical *Klebsiella pneumoniae*, *Acinetobacter baumannii*, clinical *A. baumannii*, *P. aeruginosa* and clinical *P. aeruginosa*, *S. aureus*, clinical *S. aureus*, Methicillin-resistant *S. aureus* and antifungal activity against 2 fungal strains (*Candida albicans* and *Cryptococcus neoformans*) were investigated. It was discovered that *M. geminispina* exhibited antimicrobial activity on all the microbial strains with a minimum inhibitory concentration ranging from 200–2000 µg/mL. The highest antimicrobial activity of *M. geminispina* was recorded on

Table 2. Bioactive compounds identified in *Mammillaria* species

<i>Mammillaria</i> species	Part of the plant used	Method of extraction	Extraction solvent	Compounds	Reference
<i>M. rhodantha</i>	Stem	Sonication	Methanol	Phenolic acids: gentisic acid, chlorogenic acid, caffeic acid, protocatechuic acid, sinapic acid and p-hydroxybenzoic acid	(41)
<i>M. muehlenpfordtii</i>	Stem	Sonication	Methanol	Chlorogenic acid	(41)
<i>M. hahniana</i>	Stem	Sonication	Methanol	Chlorogenic acid	(41)
<i>M. albilanata</i>	Stem	Sonication	Methanol	Chlorogenic acid	(41)
<i>M. candida</i>	Stem	Sonication	Methanol	chlorogenic acid	(41)
<i>M. spinosissima</i>	Stem	Sonication	Methanol	Gentisic acid, caffeic acid	(41)
<i>M. crucigera</i>	Stem	Sonication	Methanol	chlorogenic acid, caffeic acid	(41)
<i>M. geminispinga</i>	Stem	Maceration with agitation	Ethanol (3 days)	Tannins, myristic acid and chlorogenic acid	(46)
<i>M. uncinata</i>	Stem	Sequential extraction using reflux	Hexane	Flavonoids	(11)
<i>M. uncinata</i>	Root	Sequential extraction using reflux	Hexane	Sterols	(11)
<i>M. uncinata</i>	Stem	Sequential extraction using reflux	Ethyl acetate	Sterols and flavonoids	(11)
<i>M. uncinata</i>	Root	Sequential extraction using reflux	Ethyl acetate	Sterols	(32)
<i>M. uncinata</i>	Stem	Sequential extraction using reflux	Ethanol (80 %)	Alkaloids, sterols, flavonoids and saponins	(11)
<i>M. uncinata</i>	Root	Sequential extraction using reflux	Ethanol (80 %)	Sterols	(11)
<i>M. uncinata</i>	Stem	Sequential extraction using reflux	Water	Alkaloids, flavonoids and saponins	(11)
<i>M. uncinata</i>	Root	Sequential extraction using reflux	Water	Saponins	(11)
<i>M. hahniana</i>	Plant	Maceration	Ethanol (70 %)	Sterols, flavonoids, tannin, saponin, alkaloids	(45)
<i>M. springlei</i>	Plant	Maceration	Ethanol (70 %)	Sterols, tannin, saponin, flavonoids	(45)
<i>M. polythele</i>	Plant	Maceration	Ethanol (70 %)	Tannins, saponins, flavonoids and alkaloids	(45)
<i>M. spinosisima</i>	Plant	Maceration	Ethanol (70 %)	Saponins, tannins, sterols, flavonoids	(45)
<i>M. supertexta</i>	Plant	Maceration	Ethanol (70 %)	Flavonoids, sterols, saponins and tannins	(45)
<i>M. uncinata</i>	Fruit	Reflux (30 mins)	n-Hexane	Alkaloids, sterols	(19)
<i>M. uncinata</i>	Fruit	Reflux (30 mins)	Ethylacetate	Sterols, coumarins	(19)
<i>M. uncinata</i>	Fruit	Reflux (30 mins)	80% Ethanol	Free amino acids, coumarins, saponins, flavonoids, sterols and alkaloids	(19)
<i>M. uncinata</i>	Fruit	Reflux (30 mins)	Water	Flavonoids, free amino acids, saponins, coumarins and saponins	(19)
<i>M. uncinata</i>	Fruit	Homogenization and centrifugation	Methanol	Betacyanins and betaxanthins, phenolic compounds and flavonoids	(19)
<i>M. candida</i>	Callus	HPLC-DAD analysis of the Cellular suspension	Murashige and Skoog (MS) medium	Phenolics: quinic acid, digalloyl rahmnoside	(53)
				Flavonoids: epicatechin gallate, epigallocatechin-methyl gallate, methyl-(epi) galocatechin derivative, acetyl silychristin, luteolin 3'-methyl ether.	
				Betalains: decarboxi-dehydro-neobetanin, bidecarboxy-dehydro-neobetanin,	
				Organic acid and ester: aconitic acid, malic acid methyl ester	

Table 3. Biological activities of active compounds extracted from *Mammillaria* species.

<i>Mammillaria</i> species	Type of plant extract	Method of analysis	Mode of study	References
<i>M. rhodantha</i>	Stem extract	HPLC-DAD	-Antiproliferative and cytotoxic effects on MCF-7, HeLa, HT-29 and Jurkat cells. Apoptotic assay - DPPH, β -carotene bleaching and FRAP assays). Micro-dilution assay with MIC and MBC study against <i>B. cereus</i> , <i>L. monocytogenes</i> , <i>E. coli</i> , <i>M. flavus</i> , <i>S. aureus</i> and <i>P. aeruginosa</i>	(41)
<i>M. muehlenpfordtii</i>	Stem extract	HPLC-DAD	Antiproliferative and cytotoxic effects on MCF-7 and HeLa cancer lines. -Antioxidant activity (DPPH, β -carotene bleaching and FRAP assays). Antibacterial activity: Micro-dilution assay with MIC and MBC study against <i>B. cereus</i> , <i>L. monocytogenes</i> , <i>E. coli</i> , <i>M. flavus</i> , <i>S. aureus</i> and <i>P. aeruginosa</i>	(41)
<i>M. hahniana</i>	Stem extract	HPLC-DAD	-Antioxidant activity (DPPH, β -carotene bleaching and FRAP assays).	(41)
<i>M. albilanata</i>	Stem extract	HPLC-DAD	-Antioxidant activity (DPPH, β -carotene bleaching and FRAP assays).	(41)
<i>M. candida</i>	Stem extract	HPLC-DAD	-Antioxidant activity (DPPH, β -carotene bleaching and FRAP assays).	(41)
<i>M. spinosissima</i>	Stem extract	HPLC-DAD	Antiproliferative and cytotoxic effects on MCF-7, HeLa, HT-29 and Jurkat cancer cell lines. Antibacterial activity: Micro-dilution assay with MIC and MBC study against <i>B. cereus</i> , <i>L. monocytogenes</i> , <i>E. coli</i> , <i>M. flavus</i> , <i>S. aureus</i> and <i>P. aeruginosa</i>	(41)
<i>M. crucigera</i>	Stem extract	HPLC-DAD	Antibacterial activity: Micro-dilution assay with MIC and MBC study against <i>B. cereus</i> , <i>L. monocytogenes</i> , <i>E. coli</i> , <i>M. flavus</i> , <i>S. aureus</i> and <i>P. aeruginosa</i>	(41)
<i>M. geminispina</i>	Stem extract	-	DPPH scavenging assay, brine Shrimp Assay, microdilution assay and MIC study against <i>L. monocytogenes</i> , Methicillin-resistant <i>S. aureus</i> , <i>Acinetobacter baumannii</i> , <i>E. coli</i> , <i>Klebsiella pneumoniae</i> and <i>P. aeruginosa</i> and fungal strains <i>Candida albicans</i> and <i>Cryptococcus neoformans</i>	(46)
<i>M. hahniana</i>	Plant extract	-	Cytotoxicity effect on mouse glioma C6, acute myeloid leukemia U937, human epidermal skin HaCaT and human acute monocytic leukemia THP-1 (MTT assay). Anti-inflammatory activity on THP-1 cells with ELISA kits	(45)
<i>M. springlei</i>	Plant extract	-	ABTS and DPPH free radical scavenging capacity	(45)
<i>M. polythele</i>	Plant extract	-	ABTS and DPPH free radical scavenging capacity	(45)
<i>M. spinosisima</i>	Plant extract	-	ABTS and DPPH free radical scavenging capacity	(45)
<i>M. supertexta</i>	Plant extract	-	ABTS and DPPH free radical scavenging capacity	(45)
<i>M. uncinata</i>	Fruit extract	-	Antiradical activity (DPPH assay)	(19)
<i>M. candida</i>	Fruit extract	-	Antioxidant activity (DPPH assay)	(53)

Pseudomonas aeruginosa (*P. aeruginosa*), *Candida albicans* and *Cryptococcus neoformans* (MIC 200 $\mu\text{g/mL}$). Chlorogenic acid was identified as the bioactive compound responsible for these antimicrobial effects (46).

Moreover, the antifungal activities (% inhibition) of *M. huitzilopochtli* against 8 phytopathogen fungi were evaluated. The fungi studied were *Fusarium* sp., *Cladosporium* sp., *Alternaria* sp., *Phoma* sp., *Helminthosporium* sp., *Rhizoctonia* sp., *Fusarium moniliforme* and *Phaeclomyces* sp. It was reported that the *Phoma* fungus was completely inhibited by the total extract of *M. huitzilopochtli* at a concentration of 400 $\mu\text{g/mL}$ 100 %. Hence, it could be used to eliminate *Phoma* fungus, which is a pathogen of

potatoes. All the other fungi evaluated showed some degree of inhibition by the extracts at 100 $\mu\text{g/mL}$, but not 100%. The antifungal activity of *M. huitzilopochtli* was attributed to the presence of phytoalexins in its extract (65).

Antioxidant activities of *Mammillaria* species

The production of reactive oxygen species in the human body is known to significantly contribute to the advancement of numerous diseases associated with oxidative stress (45). Methanolic stem extracts of *M. rhodantha*, *M. spinosissima* and *M. muehlenpfordtii* exhibited high antioxidant activities using DPPH, β -carotene bleaching and ferric reducing antioxidant power (FRAP) assays. In

this study, *M. rhodantha* showed the best antioxidant activity as revealed by its lowest IC₅₀ value. However, it was also reported that the antioxidant activities of butylated hydroxytoluene (BHT) and Trolox were higher in comparison with the *Mammillaria* spp. extracts (43). The antioxidant activities of these extracts were attributed to gentisic acid, chlorogenic acid, caffeic acid and protocatechuic acid. Previous studies have shown that these compounds have been isolated from many plant species, especially the medicinal ones (66) and their antioxidant activities have been reported. Gentisic acid is known to be a strong antioxidant with many health benefits; gentisic acid and protocatechuic acid were demonstrated to impart oxidative stability in sardine oil (61). Chlorogenic acid possesses strong antioxidant properties and modulates antioxidant enzyme activities (58). Moreover, *in vitro* and *in vivo* investigations of chlorogenic acid (66) revealed that it has the capacity to mitigate oxidative stress, while the antioxidant activity of caffeic acid has also been reported (62). Also, the shoot and callus extracts of *Mammillaria herrerae* (*M. herrerae*) Werdermann showed metal chelating activities (44).

The antioxidant activity of the ethanolic extract of *M. geminisipina* was determined using the DPPH method (46). From this investigation, it was reported that *M. geminisipina* accounted for 9.54 % inhibition with an IC₅₀ value of 1.57 mg/mL. Although this antioxidant activity was low in comparison with ascorbic acid (83.08 %), it could be confirmed and ascertained using other antioxidant assays, as a single assay is insufficient to measure the antioxidant activity of a substance (67). Phytochemical analysis of *M. geminisipina* showed that it contains tannins, among other compounds and tannins have been reported to have antioxidant properties (68).

The previous study (45) also determined the capacities of five extracts of *Mammillaria* species to scavenge free radicals using ABTS and DPPH assays with Trolox as the control. The results showed that the percentage of inhibition recorded with the ABTS assay was in this order: *M. spinosissima* > *M. polythale* > *M. supertexta* > *M. springlei* > *M. hahniana*. However, the DPPH assay showed a lower percentage of inhibition but in a similar order. The antioxidant activity of these species was attributed to the presence of sterols, tannins, saponins, flavonoids and alkaloids in their extracts (Table 3) (45).

The methanolic extract of *M. uncinata* fruits exhibited 16.77 ± 0.024 % antiradical capacity (ARC), equivalent to the ARC of a butylated hydroxytoluene solution at a concentration of 35.42 μ M. Extensive research exists on the antioxidant capacity of other cactus plants and fruits (69, 70). These studies consistently confirm the presence of antioxidant components in cactus fruits. Furthermore, *M. uncinata* fruits showed potential as a food source and a reservoir of bioactive compounds, including ascorbic acid and flavonoids, which, along with betalains, render the species a promising source of phytochemicals for use in food and pharmaceutical industries (19).

Anti-inflammatory activities of *Mammillaria* species

The anti-inflammatory activity of the ethanolic extract of *M. geminisipina* was evaluated in an *ex vivo* model of human monocyte-derived macrophages (THP-1 cells), which revealed the secretion of pro-inflammatory cytokines IL-6 and TNF- α , as well as the anti-inflammatory cytokine IL-10 (46). Moreover, *M. geminisipina* had lower concentrations of the pro-inflammatory cytokines. The anti-inflammatory activity of *M. geminisipina* was attributed to the presence of myristic acid in the extract. This compound has been

previously identified in other cacti, such as the stems of *O. dillenii* (49) and was reported for its anti-inflammatory property, demonstrating an increase in the secretion of the anti-inflammatory cytokine IL-10 upon LPS induction in the murine macrophage cell line J774A-1 (71).

Enzyme inhibition abilities

The enzyme-inhibitory activity of *M. herrerae* extracts was investigated against four enzymes, namely AChE, BChE, tyrosinase and amylase. The shoot extract showed more activity than the callus extracts. These enzyme inhibition abilities of *M. herrerae* extracts were attributed to the presence of phenolic compounds and flavonoids in the extracts (44).

Factors affecting the nutritional composition of *Mammillaria*

Environmental conditions

The unique interplay of climate, soil quality and microhabitat that forms the prevalent environmental condition across diverse regions not only influences the endemism of the different species of *Mammillaria* cacti but also affects the nutritional composition of edible species, like *M. uncinata*, *M. prolifera* and *M. glasii* (72, 73). While limited information exists on the effects of environmental conditions specifically on the nutritional composition of *Mammillaria*, general studies on cacti, especially widespread genera like *Opuntia*, give necessary insights.

Influence of climate: The chemical composition of cacti is impacted significantly by the rainfall and temperature levels of different seasons. Cacti exhibit higher chemical composition values during the rainy seasons than in the dry seasons (73). The disparity has been attributed to their physiological adaptations to environmental stresses, such as drought, intense sunlight and cold, peculiar to each season, resulting in higher concentrations of certain nutrients but lower concentrations of others (74, 75). As reported, seeds from an evaluated cactus fruit had fructose and sugar contents that were 2.4 times and 1.8 times higher, respectively, in winter fruits than in summer fruits. The whole cactus also increased in Vitamin E content by 2.3-fold during the winter months (periods of low temperature and high moisture), compared to summer months (high temperature, low precipitation). Higher moisture and carbohydrate contents and lower crude protein content were also reported for winter fruits (75).

Due to water loss and calcium accumulation, organic matter and carbohydrate contents in some cacti decrease when the temperature level is high and rainfall is low. In contrast, fiber, protein and dry matter contents, along with bioactive properties, were enhanced under the same climatic conditions (74, 75). In addition, the maturity of fruits in *Mammillaria*, usually associated with reduced ash content and increased fat content, is favoured by higher precipitation and optimal temperatures (76). Conversely, extreme temperatures (below 15 °C or above 30 °C) may negatively affect photosynthetic activity, resulting in lower sugar content (77).

Influence of soil condition: The nutritional composition of *Mammillaria* is affected by soil properties, such as nutrient levels, pH, organic matter and moisture. It was noted that high nitrogen and calcium in the soil increased sugar and mineral contents in cactus fruits (78). Comparably, the potassium content in a cactus fruit was proportionally influenced by the soil potassium level (79). Nutrient levels in edible cactus pads were reported to increase upon application of NPK fertilizer to the soil, confirming that soil nutrient levels will impact the nutrient composition of edible *Mammillaria* fruits.

Secondly, nutrient bioavailability for plant uptake is significantly affected by soil pH. The genus *Mammillaria* is adapted to slightly acidic soils with an optimal pH range of (5.0–6.5). Nutrient solubility and absorption are optimized, ensuring their accumulation in the cactus fruit at this pH range and their nutritional composition is consequently impacted. Soil organic matter also plays a major role. Enhanced soil organic matter was reported to increase the sugar, vitamin A, vitamin C and vitamin E contents in the fruits of *M. prolifera* and *M. glassii* (12).

Although cacti, including *Mammillaria*, are well-adapted to arid soils, controlled irrigation can improve fruit nutritional composition by increasing soil moisture, which is necessary for mineral availability. Maintaining soil moisture above 30 % of field capacity through controlled irrigation was found to significantly boost nutrient levels, including total soluble solids, vitamin C and antioxidants, in cactus fruits (80).

Influence of habitat: *Mammillaria* grow in various ecological environments, including desert plains, rocky hillsides, crevices and mountaintops (81, 82). Factors such as temperature, moisture, altitude and soil conditions peculiar to these microclimates may cause differences in the nutrient content of *Mammillaria*, even among individual plants of the same species (83). For example, saxicolous species like *Mammillaria fraileana* (*M. fraileana*) inhabit rocks rich in silicon, potassium and sodium (81); Nobel showed notable variations in mineral levels in a related cactus that reflected the mineral content of the rocks they grow on, suggesting the same could be true for saxicolous *Mammillaria* (84).

On desert plains, cacti produce more antioxidants, flavonoids, polyphenols (75) and less soluble carbohydrates and malic acid because they are exposed to water scarcity and direct sunlight (85). Altitude-related abiotic stresses, such as extreme temperature fluctuations and increased UV radiation, can influence soil nutrient availability and the resulting mineral composition of plants, including *Mammillaria*, grown on mountaintops (83).

Genetic variability: Although there is limited information, considering that the *Mammillaria* genus comprises approximately 200 species, their nutritional profile will most definitely be impacted by genetic variability, as observed in other cacti. Genetic differences impact carbohydrate content, dry matter and crude protein levels across species, varieties and cultivars of related cacti (73, 86). Additionally, the flavonoid and phenolic acid profiles in *Mammillaria* are species-specific (87). In general, genetic factors interact with environmental factors to influence fruit quality in most cacti (76).

Some studies highlight the genetically driven variability in the nutritional composition of a few *Mammillaria* species. For instance, *M. uncinata* fruit contained a significantly higher amount of vitamin C (1.395 g) than *M. prolifera* (8.45 mg) and *M. glassii* (7.36 mg) (19, 12), indicating that the *M. uncinata* species is particularly rich in ascorbic acid. Furthermore, the vitamin A and vitamin E contents of *M. prolifera* and *M. glassii* differ significantly. While *M. prolifera* contained higher vitamin A (7.36 mg) than *M. glassii* (6.14 mg), *M. glassii* contained more vitamin E (12).

Harvesting, post-harvesting processes and storage conditions

The harvest, post-harvest and storage processes to which *Mammillaria* are subjected may affect nutrient composition and retention, as observed with other cacti. According to previous study (88) fully ripe cactus fruits harvested in summer had higher amounts of vitamin C, which dropped after five days of storage, while those

harvested in late season showed higher soluble solid content (88). Additionally, fully ripe summer fruits had the lowest levels of β -carotene. Extended storage may affect the contents of dry matter, crude protein, crude fibre and water-soluble carbohydrate, as *Mammillaria* fruits lose water due to evapotranspiration (89).

Furthermore, it has been observed that treating cactus fruits with chemicals such as calcium chloride, packaging them in low-density polyethylene and storing them under controlled conditions (low temperature and high relative humidity) can help retain their high sugar content (90). Generally, preserving antioxidants, vitamin C and other nutrients in cactus fruits is better achieved with minimal processing techniques rather than with high processing methods (91). Optimizing nutrient retention in *Mammillaria* fruits may therefore be achieved by combining minimal processing with appropriate packaging and short storage times under controlled conditions.

Challenges and Limitations of the genus *Mammillaria*

Lack of comprehensive data on the nutritional composition of *Mammillaria* species

A significant knowledge gap exists in the nutritional composition of *Mammillaria* cacti. This was caused by the lack of research focus on the nutrient content of their edible fruits, resulting in a lack of comprehensive data. Nutritional profiling has been conducted on only a few species, such as *M. uncinata* (19). There is, therefore, a need to comprehensively evaluate various *Mammillaria* species to gain full insight into their nutritional composition and food potential.

Researchers have observed that *Mammillaria* bears very small fruits, making it almost impossible to consume them in large enough quantities to gain significant nutritional benefits (92). Nutritional profiling is more common for larger cacti like *Opuntia* (73, 74, 77). This may be a key reason why researchers are less likely to focus on detailed nutritional assessments of *Mammillaria*.

Variability in nutrient content due to environmental and genetic factors

The significant variation that exists in the nutritional composition among species and cultivars of most cacti, including *Mammillaria* (73, 76) poses a major challenge to promoting *Mammillaria* fruits as a viable food source. These variations are due to a wide range of environmental and genetic factors (76, 87). Additionally, the wide variability in nutrient content, which may also exist among individual plants of *Mammillaria* cacti, makes it difficult to develop standardized cultivation practices, such as optimal planting and harvesting seasons, fertilizer application and other agricultural techniques, for each variant of the cactus. Consequently, research is needed to develop appropriate methodologies to mitigate the effect of environmental and genetic factors on the nutritional composition of *Mammillaria*.

Potential toxicity and allergenicity associated with certain compounds

Cacti are rich in phytochemicals, some of which have been found in several *Mammillaria* species, including calcium oxalate and saponins (19). Oxalates perform the biological functions of defence, mineral storage and stress tolerance in cacti, whereas saponins exhibit anti-inflammatory, antibacterial, antioxidant and anticancer properties (93). Nonetheless, they both hold potential for toxicity or allergenicity. Oxalates can be an anti-nutritional factor because, consumed in large amounts, they reduce mineral bioavailability by

blocking the body's ability to absorb essential nutrients, such as calcium (94, 95). Some forms of oxalates can also irritate the mouth, while saponins can cause gastrointestinal upset if consumed in high doses (96), leading to allergenic and toxic risks. It is important to prioritize phytochemical profiling, quantification and evaluation in future studies to ensure consumer safety, as such information is currently scarce.

Conservation Concerns

Most *Mammillaria* species are at risk of extinction due to global climate change, habitat specialization, propagation difficulties, habitat conversion and illegal collection for trade (97). *Mammillaria* cacti have often been listed as near threatened, vulnerable, endangered, or even critically endangered by the International Union for the Conservation of Nature (82). *Mammillaria* cacti are especially susceptible to extinction due to their restricted range and habitat specialization. They are mainly endemic to Mexico, with a few species occurring in other areas of North and Central America (93). There is also serious conservation risks associated with habitat destruction and land use changes in these areas. Moreover, *Mammillaria* cacti are likely to die off gradually due to global warming, as their shallow roots are highly susceptible to increasing soil temperature (87).

In addition, some species, such as *M. guameri*, have low population growth rates, germination percentages and fecundity, indicating propagation challenges (98). Species of *Mammillaria* are also illegally collected for sale due to their ornamental value. Urbanization and land conversion for farming and ranching increase their susceptibility to extinction. Strategic conservation approaches and strong policy initiatives are measures that must be adopted to safeguard the *Mammillaria* population. These include the use of forensic tools to trace illegally harvested plants, the identification of species most prone to climate extremes and the development of conservation and restoration methods for *Mammillaria* outside their natural habitats (97).

Perspectives

The diversity of the genus *Mammillaria*, along with the variability and quantity of compounds that they contain, makes their study and utilization worthwhile. The first step is developing *Mammillaria* cultivation in arid or semi-arid regions to promote the genus' prevalence. Since the different *Mammillaria* species have localized geographic distributions, it is important to raise awareness and train local populations on the domestication of the species available in their area, promote *ex situ* propagation, develop community management plans and seek local benefits. This will subsequently lead to the development of standards and processes for the agricultural cultivation of these species, thus providing a source of income from them (97, 99).

This exploration would begin by determining the specific nutritional and biochemical profile of one or more *Mammillaria* species that have been cultivated in the region. These profiles depend largely on growing conditions, such as soil type, annual rainfall and average annual temperature. The *Mammillaria* species to be cultivated would depend on the application the research group wishes to obtain. For example, if a protein-rich fruit extract is desired, *M. elongata* would be used; if fruits with vitamins A, C and E are desired, *M. glassii* would be used. Similarly, the fruit of *M. glassii* could be used as a carbohydrate source to produce a fermented product with potential health benefits (19, 1, 100, 101, 12).

Furthermore, having a dedicated cultivation site for the research would enable them to determine the biochemical profile of all plant parts, including seeds, shoots, calluses, bark, pulp, flowers and fruit. This would facilitate the decision to utilize certain parts of the plant or the entire plant. Similarly, various compounds, including phenolic acids, flavonoids, tannins and sesquiterpene lactones, can be extracted from different parts of the plant. The species *M. rhodantha* and *M. spinosissima* stand out as those that have shown the highest concentration of phytochemicals (34, 46). Just as *Mammillaria* extracts have shown antiproliferative and cytotoxic effects, research could be conducted in animal models to further investigate these effects while simultaneously demonstrating the absence of toxicity in healthy tissues. This would allow for progress in the development of adjuvant therapies against certain types of tumours (34). Furthermore, if the absence of toxicity is demonstrated in animal models, research could continue toward the development of new antimicrobial therapies from natural sources, offering an alternative to traditional treatments. Antimicrobial activity has already been demonstrated against certain pathogenic species, such as *L. monocytogenes*, *E. coli*, *Staphylococcus aureus* (*S. aureus*) and *Pseudomonas aeruginosa* (*P. aeruginosa*) (34).

Conclusion

The biochemical profile of the genus *Mammillaria* makes it an area of interest for preservation through cultivation and sustainable utilization, as its compounds have shown biological activities that can benefit health, primarily antioxidant and anti-inflammatory activities. At the same time, its antimicrobial activity can be harnessed for natural food preservation in the food industry. In addition, the remarkable adaptation of the genus *Mammillaria* to arid and semi-arid environments highlights their value as sustainable plant resources under changing climatic conditions.

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Authors' contributions

BRF designed and conducted the research. GOA, AAA, IANV and OEA also conducted research and wrote the original manuscript. RRH designed, supervised and ensured proper writing of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors do not have any conflicts of interest to declare.

Ethical issues: None

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