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Chapter 4

The Future of *Opuntia* spp.: Sustainability and Global Impact

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1 Introduction

The future Earth is envisioned as a world with an ever-growing population that will increasingly demand food, housing, various services, and technological products. The fulfillment of these needs is limited by the depletion of natural resources, as the rate of product and service generation does not guarantee their timely renewal. It is already possible to estimate the exact day each year when the planet's resource consumption surpasses its capacity for replenishment. Alarmingly, while this point was reached in December back in 1971, it has been occurring earlier each year. From 2021 to 2024, the so-called "Earth Overshoot Day" has fallen in August (Earth Overshoot, w.d.).

Among the resources that limit the sustainability of our global ecosystem is water (Dolan et al., 2021), which is consumed in great amounts in agriculture, industry, mining, and other human activities. The ecological footprint of human activities takes into account their impact on elements such as cultivated land, forest areas, carbon dioxide emissions, fishing zones, grazing areas, and urbanized regions (Carlsen, 2024).

In the agricultural and livestock sector, the consumption of water, fertilizers, pesticides, processed animal feed, fuels, and other inputs—along with their resulting ecological

footprint—is of significant magnitude. As a future projection toward achieving sustainable agriculture, it is essential to establish crops that can provide acceptable yields and a diverse range of products at low ecological costs.

The genus *Opuntia*, belonging to the family of Cactaceae, is native to Mesoamerica and includes over 300 species that have spread to the rest of the continent, in addition to to Asia, Africa, Australia, and the Mediterranean (Corral-Martínez et al., 2024). Species of this genus perform photosynthesis through the process known as Crassulacean Acid Metabolism (CAM): at night, they open their stomata and assimilate CO_2, which they convert and store as malate in their vacuoles, and during the day, they complete the rest of the photosynthetic process (Niechayev et al., 2023). This characteristic, along with anatomical modifications in their leaves and cladodes, makes them highly efficient in water use. Additionally, *Opuntia* species have multiple applications not only in human but also in animal nutrition, biotechnology, the pharmacological industry, and even electricity generation (Corral-Martínez et al., 2024), highlighting their potential for future agriculture.

This section analyses the uses of the *Opuntia* genus and the latest research findings on this topic.

1.1 Diversity of The *Opuntia* Genus Uses

The flowers, cladodes, and fruits of *Opuntia* species have been used by humans for various purposes since earliest eras. Advances in scientific knowledge regarding the biological, chemical, and physical properties of these plants have allowed for the diversification of their applications. Below is a brief analysis of the main areas in which these biological materials are utilized.

Human food and nutraceutical properties

When the Spanish arrived in America, the consumption of *Opuntia* fruits had already spread across the continent. Upon reaching the island they called La Española (now the Dominican Republic and Haiti), they observed the natives eating these fruits and tried them for the first time (Ochoa & Barbera, 2018). Some species produce sweet fruits, such as *O. ficus-indica*, the greatest widely cultivated; others, such as *O. robusta*, *O. joconostle*, and *O. streptacantha*, produce sour fruits. In all cases, the fruits contain vitamins, minerals, antioxidants, and other bioactive compounds (Corral-Martínez et al.,

2024). Indeed, such properties of the edible parts of these plants make them valuable foods, not only for their taste but also for their health benefits and nutritional value.

Among the substances with detectable nutritive and medicinal properties in *O. ficus-indica* is inulin (Di Bella et al., 2022), a carbohydrate whose consumption reduces cholesterol and blood sugar levels, increases calcium absorption, acts as a probiotic, and helps control body weight. Amino acids such as glutamine (in the cladodes), glutamic acid (in the seeds), proline, and taurine (in the fruits) are also present (Shoukat et al., 2023). It additionally includes fatty acids such as linoleic acids, oleic, and palmitic (Albergamo et al., 2022), which, with adequate intake, can be beneficial to health. Vitamins such as ascorbic acid, tocopherol in its various forms, folic acid, niacin, and others are present in several parts of the crop in varying concentrations (Shoukat et al., 2023).

Opuntia ficus-indica L. (Mill.) contains minerals such as iron, magnesium, potassium, calcium, and phosphorus, in addition to various bioactive substances. Among them, polyphenols, pigments like anthocyanins, and carotenoids have antioxidant properties (Berrabah et al., 2019). For this reason, it has been included as an additive in food. Aiello et al. (2018) prepared a wheat paste with 3% *O. ficus-indica* extracts, and in a study with volunteers, they detected hypoglycemic, anti-inflammatory, and antioxidant effects, which could have an impact on diseases associated with aging. Oniszczuk et al. (2020) prepared a similar product with rice and bean flour, to which they added *O. ficus-indica* fruits in proportions ranging from 2.5% to 15%. At higher concentrations, an increase in polyphenols and free phenolic acids, primarily isoferulic acid, was observed, along with high antioxidant activity in the food, making it potentially useful as a source of these important compounds.

Undoubtedly, the value of the *Opuntia* genus as food or dietary supplement goes beyond the nutrients it contains and focuses on nutraceuticals, considering the presence of health-beneficial substances in the species that make it up. Even in the peel of the fruits, which is typically discarded for consumption, substances with antioxidant activity have been detected in *Opuntia dillenii, Opuntia ficus-indica,* and *Opuntia robusta* (Marhri et al., 2024), highlighting an untapped potential in these species. Interestingly, due to their sour or slightly acidic taste, the fruits of *O. robusta* and *O. dillenii* are not highly

appreciated for direct consumption. However, they could be useful as additives and supplements in other food products, as the nutraceutical value of these sour fruits, also known as "xoconostles," has also been demonstrated.

Fernández-Luqueño et al. (2021) detailed the properties of extracts from xoconostles, either for direct consumption or as part of meat, dairy, and fruit products. Among the highlighted species are *Opuntia matudae*, with effects on diabetes, obesity, and respiratory diseases, as well as others like *O. joconostle*, *O. duranguensis*, and *O. oligacantha*.

Animal feed

The nutritional quality of *Opuntia* species has suggested their use as animal feed. Their succulent composition also provides water to the animals that consume them; Torres-Ponce et al. (2015) note that the water content in their tissues is 90-95%. They also contain vitamins, minerals, and other nutrients beneficial to animals. Additionally, these species can be planted in arid lands, where other types of plants do not grow, helping to preserve the soil and protect it from erosion (Dubeux Jr et al., 2018). Another advantage of their use is that when mixed with other forages, such as corn, they can reduce animal methane emissions, which contribute to the greenhouse effect (Espino-García et al., 2020).

A relevant aspect in the utilization of these species is their invasive capacity, particularly in desert or semi-desert areas, which allows for their use with minimal investment. However, the presence of spiny species, which can significantly harm livestock, is a limitation (Sipango et al., 2022), which can be addressed through genetic improvement. In goats, Albuquerque et al. (2020) observed that the inclusion of up to 42% *O. ficus-indica* in the nutrition regimen led to improved absorption of calcium, magnesium, and sodium, as well as increases in food digestibility, reduction in rumination time, and a decrease in the animals' water consumption. The cladodes of this species have been successfully used as substitutes for alfalfa to feed sheep in the final trimester of pregnancy (Cuevas et al., 2020), resulting in increases in milk production and in the growth of the lambs. In cows, the partial replacement of sugarcane in the diet (between 34% and 38%) with *Opuntia stricta* cladodes increased both the quality and quantity of milk produced (Sánchez et al., 2022).

The benefits of using *Opuntia* spp. in the direct feeding of ruminants and its silage for use as forage have been documented (Abidi et al., 2009, 2013), and are based on its high content of water, minerals, vitamins, easily assimilable carbohydrates, and fatty acids (Pastorelli et al., 2022). However, due to its low protein content, preparations made from *Opuntia* spp. must be enriched; techniques such as solid or semi-solid fermentation with *Saccharomyces cerevisiae* have been developed for this objective (Araújo et al., 2005; Flores et al., 2019).

In other animal species, results have also been obtained that encourage the utilization of parts of *Opuntia* spp. plants as food or as a supplement. In broiler chicks, Badr et al. (2019) observed that partial substitution of the corn-based diet with 15% *O. ficus-indica* fruit peels improved their nutritional status, daily weight gain, and meat quality. Cherif et al. (2022) observed weight increases in chickens when 10% and 20% of the corn and soy diet was replaced with *O. ficus-indica* seeds. Additionally, similar to humans, this species has shown pharmacological effects in birds; extracts from its flowers are capable of destroying the oocysts of *Eimeria* spp., a parasite that causes coccidiosis (Amrane-Abider et al., 2023).

In fish such as Nile tilapia (*Oreochromis niloticus*), *Opuntia* species have also been successfully utilized for both nutritional and health purposes. The incorporation of 20% *O. ficus-indica* fruit peels to the diet of these fish increased immune response and resistance to *Aeromonas sobria*, a bacterium that causes hemorrhagic septicemia (Ahmed et al., 2020). In this animal species, the positive result of including *O. ficus-indica* fruit peels on salinity tolerance, weight gain, and immune activity has been demonstrated, with increases in lysozyme activity and phagocytosis (Salem et al., 2024). The addition of 2% *Opuntia littoralis* (coastal prickly pear) fruits to the tilapia diet increased their tolerance to cadmium by enhancing the function of antioxidant enzymes, like catalase, superoxide dismutase, and glutathione peroxidase (Abbas et al., 2024).

Pharmacology and cosmetics industry

Betalains, detectable only in certain plant species, including cacti, are plentiful in *O. ficus-indica*, and their effects on cardiovascular health, as anticancer agents, antioxidants, and more, are recognized (Calva-Estrada et al., 2022). Among them, indicaxanthin has excitatory properties on intracortical circuits (Gambino et al., 2022),

which could be useful in the rehabilitation of neurons linked to movement and cognitive processes affected by trauma, or in the fight against Alzheimer's or Parkinson's disease. The dehydrated flowers of *Opuntia* spp. are used in countries such as Tunisia for the lysis of kidney stones (Ammar et al., 2014), and flower extracts are used to relieve depression. This latter therapeutic function is associated with the presence of isorhamnetin in various chemical forms and a 5α-reductase inhibitor of testosterone (De Leo et al., 2010). These plant organs also contain polyphenols, which have recognized antimicrobial and anti-inflammatory activity (Rodrigues et al., 2023). The diversity and abundance of minerals, vitamins, and antioxidants they contain make them valuable for application in cosmetics manufacturing because of their beneficial health properties (Prisa, 2023).

In simulated *in vitro* human digestion conditions, the activity of α-amylase was inhibited by more than 60%, and α-glucosidase activity by more than 45%, upon the addition of *Opuntia oligacantha* fruit extracts (Medina et al., 2019), which enhances its potential as a diabetic treatment. Izuegbuna et al. (2019) analyzed the pharmacological properties of *Opuntia stricta* cladode extracts obtained with different solvents. All extracts (aqueous, ethanolic, and acetonic) exhibited antioxidant activity, several showed anti-inflammatory effect in RAW 264.7 mouse cells, and the acetonic extract presented cytotoxic effects on the U937 cell line, suggesting its potential use in treatments for histiocytic lymphoma.

In general, the current and potential applications of the extracts and metabolites present in parts of *Opuntia* species plants are diverse and still underexplored. A detailed review of these topics and the latest findings in this area was recently published (Chahdoura et al., 2024).

Other applications

Aguirrezabala et al. (2013) purified two low-molecular-weight trypsin inhibitors (OjTI 1 and OjTI 2) from *Opuntia joconostle* seeds, capable of inhibiting digestive enzymes of insects that attack maize, alfalfa, and beans (*Loxostege cyclades*, *Spodoptera frugiperda*, *Prostephanus truncatus*, and *Callosobruchus maculatus*). This property suggests their potential use as bioinsecticides. However, this issue should be handled

with caution, as the inhibition is also effective against different species of the genus *Chrysoperla*, extensively used in agriculture as biological controllers.

Extracts from *O. ficus indica* and *O. stricta* flowers tested *in vitro* caused inhibitory activity against fungi and bacteria harmful to human health, including *Pseudomonas aeruginosa, Escherichia coli*, and *Staphylococcus aureus* (Ammar et al., 2012). The fruits of *O. oligacantha* have antibacterial activity against *Salmonella typhimurium* and *Staphylococcus aureus* (Espinosa-Muñoz et al., 2017), indicating their potential application in preserving agri-food products, the cosmetics industry, and pharmacy.

The production of ethanol through fermentation with *Saccharomyces cerevisiae* is another application of these plants. Udeh & Erkurt (2017), using *Opuntia ficus indica*, achieved an excellent yield of 14.71 g L^{-1}, after performing an enzymatic hydrolysis to remove lignin, which interferes with the fermentation process. In the same species, López-Domínguez et al. (2019) performed hydrolysis with *Acinetobacter pittii*, a bacterium that grows on decaying cladodes, and used *Kluyveromyces marxianus* for fermentation, yielding approximately 13 g L^{-1}. Similarly, fermentation of *Opuntia ficus indica* waste with *Lactococcus lactis* subsp. *lactis* has been used to produce lactic acid (Tamine et al., 2018). Additionally, 17 strains of lactic acid bacteria that naturally grow on the fruits of *O. ficus indica* were isolated and four of them were reported as useful for producing fermented beverages from the fruit, thereby adding value to the natural product (Verón et al., 2017).

Opuntia spp. plants can also be used for energy generation. Ciriminna et al. (2019) mention that in Chile and Mexico, there are some projects aimed at producing biogas and biofuel from the waste generated by the production and consumption of these plants. Direct electricity generation from biobatteries, known as Plant-Microbial Fuel Cells (P-MFC), is another possibility (Helder et al., 2012). These devices combine the activity of soil microorganisms and plants as a food source. The organic root exudates of the plants are converted by microbes into CO_2, electrons, and protons. These electrons move toward the cathode of the P-MFC, reducing oxygen to water and generating electricity (Wetser et al., 2015).

Apollon et al. (2020) evaluated the usefulness of *Opuntia* species (*O. ficus-indica, O. robusta, O. albicarpa,* and *O. joconostle*) for electricity generation in a P-MFC. The

study demonstrated the feasibility of using all four species for electricity generation, with the best results obtained with *O. albicarpa* (3.66 Wh m^{-2} over 30 days), which is considered a medium to high value for this type of system. It was also shown that electricity generation was positively correlated with the plant's height. Amayreh (2021) described the construction of an electric battery from *Opuntia* cladode fragments, using Mg/Cu electrodes, which kept an LED lamp lit for more than four days. Later, Apollon et al. (2022) increased the plant height (and consequently the electricity production) by applying ammonium nitrate nutrient solutions to the soil weekly.

1.2 The Genus *Opuntia* and The Bioeconomy

The contemporary world is characterized by an extractive economy that indiscriminately uses the planet's resources and generates an abundance of waste, pollution, and environmental damage. In contrast, the bioeconomy relies on the efficient utilization of natural and biological resources, maximizing waste recycling, which leads, among other things, to a decrease in the consumption of fossil fuels and the emission of greenhouse gases (Hodson et al., 2019).

Latin America is a megadiverse subcontinent, home to countless animal and plant species, many of which are directly linked to the culture and ancestral practices of indigenous peoples (Héctor & Millet, 2019), and can be employed in the bioeconomy. Examples of species with bioeconomic potential include the black soldier fly (*Hermetia illucens* L.), which is high in protein, and the *Annonaceae* family, many of whose species are of American origin, from which acetogenins are extracted, useful in the fight against cancer. This area is also the center of origin for *Opuntia* spp., and thus a source of biodiversity that supports genetic improvement and commercial exploitation of species within this genus.

The findings on the usefulness of species from this genus, such as for human and animal food, in pharmacology and cosmetics, and their various industrial uses, have started to generate a demand for products derived from *Opuntia* spp., even in countries where these plants do not grow naturally (Ciriminna et al., 2019). This demand, however, does not align with the potential supply of products derived from these plants, possibly because consumers are not well informed about them, and potential investors also lack sufficient knowledge on the topic. Therefore, the development of information programs, along

with a suitable market strategy, could contribute to the proper management of these species for the extraction and industrialization of their products (Fig. 1.1), leading to rational exploitation with economic benefits and a favorable environmental impact.

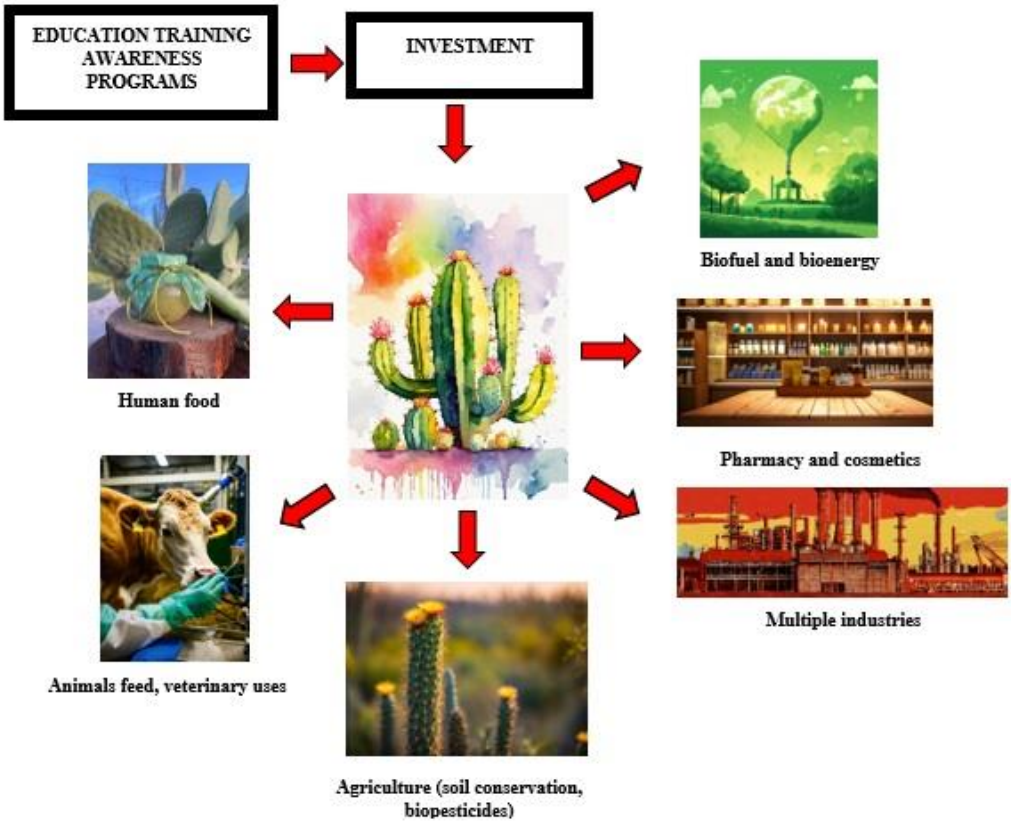

Fig. 1.1 Development strategy and main areas of use for products derived from *Opuntia* spp.

Conclusions

Without a doubt, the diversity of useful substances present in the parts of *Opuntia* spp. plants makes this genus a plant universe applicable in numerous processes. These include healthy food for humans and animals, the manufacture of pharmaceutical and cosmetic products, energy generation in various forms, the production of ethanol and lactic acid, plant protection, and soil preservation, among others.

However, most of the results obtained are still in the phase of demonstrated possibilities and small or medium-scale ventures, without a true scaling up of these applications. This

is influenced by the absence of information among investors and the general public regarding the benefits of consumption and use in various productive sectors. A higher level of knowledge about its favorable economic, social, and environmental outcomes could contribute to the widespread use of *Opuntia* spp. and its derived products in the global economy.

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