Nopal: The Mexican National Symbol

A Systemic Study on Rural Production

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Politecnico di Torino
Master's Degree
Systemic Design

Master's Thesis
September 2026



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Abstract - Eng

The prickly pear (Opuntia ficus-indica), Nopal in Spanish, is a species native to Mexico, but still present in areas with a mild climate such as the Mediterranean, including Italy.

Given its great historical, artistic, and gastronomic presence, the plant has become an important resource for rural populations, especially those of Milpa Alta.

Starting from this, the current state of the art of various cultural, social, and technical aspects is analyzed, from cultivation to consumption, alternative uses, and technological innovations on the material that makes up prickly pear pads.

An analysis of the case study of Milpa Alta, Alcaldía in Mexico City, one of the largest producers of Nopal and holders of a strong culture based on the cultivation of the plant, highlights several issues affecting agricultural populations.

The rural community of Milpa Alta lives in a state of self-management determined by the almost total presence of municipal, and therefore shared, states that have created a structure of internal self-management and democratization of assets, accustoming citizens to a constant and strong social and decision-making presence.

The presence of Nopal monoculture has generated an oligopsony situation that forces producers to have limited bargaining power with intermediaries (coyotes) at the Centro de Acopio, where farmers in Milpa Alta sell their crops.

Furthermore, due to the seasonality of the production of nopalitos (prickly pear pads intended for direct consumption), more than half of the product becomes waste along the supply chain, not only for cleaning activities, but above all for the generation of unsold goods, which causes the waste of approximately 60% of the Nopal produced domestically.

The condition that causes the amplification of the problems that afflict Nopal and the communities that cultivate it is the low level of knowledge, on the part of ordinary people, around the cactus.

Attempts made to improve the social and economic situation of rural communities in Nopal, for example the SUEMA case study, have taken an overly technocratic and top-down approach, excluding from participation the very communities that should have been the subjects and benefited from them.

Finally, the goal is to identify a strategy that allows for innovation in the common use of Nopal and to generate initial inspiration to initiate the circular use of a plant with very high potential.

The solution identified is the opening of a pilot community museum-and subsequent expansion into all twelve original pueblos of which Milpa Alta is formed-that would allow the establishment of a tourist route within Alcadia to benefit the community's strong social identity. Furthermore, the construction of domestic biodigesters, again with a pilot project and subsequent expansion, would allow the reuse of Nopal waste, the production of biogas useful for the community and a residue (called digestate) usable for fertilizing Nopal fields.

The end result, therefore, is not just a project for its own sake, but a system built around the rural community that allows for the preservation of its historical culture, improved conditions within the market, and the possibility of redemption for overproduced material.

Abstract - Ita

Il fico d'india (Opuntia ficus-indica), Nopal in spagnolo, è una specie originaria del Messico, ma comunque presente in aree dal clima mite come il mediterraneo, Italia compresa.

La pianta, data la grande presenza storica, artistica e gastronomica, è diventata un'importante risorsa per le popolazioni rurali, specie quella di Milpa Alta.

A partire da ciò, viene analizzato lo stato dell'arte attuale dei vari aspetti culturali, sociali e tecnici, dalla coltivazione al consumo, utilizzi alternativi e innovazioni tecnologiche sul materiale che compone le pale del fico d'india.

Un'analisi sul caso studio di Milpa Alta, Alcaldía della Città del Messico, nonché uno dei maggiori produttori di Nopal e detentori di una forte cultura basata sulla coltivazione della pianta, fa emergere svariate problematiche che affliggono le popolazioni dedicate all'agricoltura.

La comunità rurale di Milpa Alta vive in una condizione di autogestione determinata dalla presenza quasi totale di demani comunali, quindi condivisi, che hanno creato una struttura di autogestione interna e democratizzazione dei beni, abituando i cittadini ad una costante e forte presenza sociale e decisionale.

La presenza della monocoltura del Nopal ha generato una situazione di oligopsonio che costringe i produttori ad un limitato potere di contrattazione nei confronti degli intermediari (coyotes) presso il Centro de Acopio, punto in cui gli agricoltori di Milpa Alta vendono il loro raccolto.

Inoltre, a causa della stagionalità della produzione di nopalitos (le pale di fico d'india destinate al consumo diretto), più della metà del prodotto diventa scarto lungo la filiera, non solo per le attività di pulizia, ma soprattutto per la generazione di invenduto che causa lo spreco di circa il 60% del Nopal prodotto a livello nazionale.

La condizione che provoca l'amplificazione delle problematiche che affliggono il Nopal e le comunità che avrebbero dovuto essere i soggetti e trarne beneficio.

L'obiettivo, infine, è l'identificazione di una strategia che permetta un'innovazione nell'uso comune del Nopal e la generazione di uno spunto iniziale per dare il via ad un utilizzo circolare di una pianta dal potenziale molto alto.

La soluzione individuata é l'apertura di un museo comunitario pilota - ed una successiva espansione in tutti i dodici pueblos originarios di cui Milpa Alta é formata - che permetta l'istituzione di una rotta turistica all'interno dell'Alcadia a beneficio della forte identità sociale della comunità. Inoltre, la costruzione di biodigestori domestici, sempre con un progetto pilota ed una successiva espansione, permetterebbe il riuso degli scarti di Nopal, la produzione di biogas utile per la comunità e un residuo (chiamato digestato) utilizzabile per la fertilizzazione dei campi di Nopal.

Il risultato finale, quindi, non é solo un progetto fine a se stesso, ma un sistema costruito attorno alla comunità rurale che ne permette la conservazione della cultura storica, un

Nopal

Nopal (Opuntia Ficus Indica, in Italian prickly pear) is a plant native to Mexico, extremely widespread throughout the world, but still partially unknown from the point of view of applications in various fields. It is part of the Cactaceae family of plants (also known as cacti) which have great capacity for storing water inside themselves, which is why they are also identified as succulent plants.

Their great capacity to accumulate fluids makes them extremely resistant in arid places and poor soils, which allows them to survive in areas where, climatically and geologically, many other plants would not be able to, or for the restoration of degraded soils.

1



1.1 Nopal as a Plant

Nopal, a plant of the Cactaceae family and the Opuntioideae subfamily, is a plant present in the arid landscapes of the American continent. With over 200 species identified globally-the genus Opuntia represents the largest and most geographically widespread grouping in its family-Mexico is the place with the greatest genetic diversity, home to approximately 60 of the aforementioned species. Among these, Opuntia ficus-indica stands out as the species of greatest agronomic and economic importance, being the result of a thousand-year-old artificial selection that transformed wild variants into domesticated plants, sometimes thornless and optimized for human needs (Inglese et al., 2018).

From a taxonomic point of view, Nopal is a difficult plant to catalogue due to its high “phenotypic plasticity” (the ability to modify morphology and physiology based on the context in which it is found), due to natural hybridization caused by the cross-diffusion of different Opuntia species and some peculiar chromosomal conditions that make the plant the subject of constant revisions in its cataloguing.

Plants belonging to the genus Opuntia having joints made of flat appendages - which are called cladodes - are called Platyopuntias and are among the most widespread of the genus, seeing species such as O. ficus-indica (which is certainly the most relevant) but also O. megacantha, O. streptacantha, O. albicarpa, O. amyclaea, O. robusta and O. hyptiacantha (Inglese et al., 2018).

The common ancestor of these species originated in the Andean regions of South America during the Pliocene - between 5 and 3.5 million years ago - and then migrated and diversified in the arid areas of central Mexico, now considered the evolutionary center of the plant (Gerson Gerardo, 2024).



Image 1: A young Nopal plant

Analyzing how the plant was “designed”, we realize that each of its components promotes resource optimization and reduces water waste, keeping it inside. For example, the plant does not have conventional leaves, which have been replaced by the aforementioned cladodes (known in Italy as “pale” and in Mexico as “pencas”) which perform the dual function of photosynthesis and water reserve. The pads are protected by a waxy, waterproof layer called the cuticle (composed of a mixture of fatty acids called cutin, which takes its name from the layer it makes up): as if it were a skin, it prevents internal evaporation, and thanks to its whitish color, it reflects solar radiation, reducing the temperature of the tissues, which again allows for a reduction in the evaporation of the water inside it. Below the surface is the epidermis, which houses the stomata, small pores responsible for gas exchange located in deep cavities to further minimize water loss during the nocturnal opening typical of CAM metabolism.

Within the cladode, the structure is organized into specialized layers: the chlorenchyme, the external green part rich in chloroplasts for photosynthesis, and the parenchyma, the internal white tissue which, containing a lot of water, acts as a reservoir of fluids. It is in these tissues that mucilage abounds, the viscous fluid (commonly called “baba” in Mexico) capable of retaining water, acting like a sponge that determines the plant’s turgidity even after months of total drought.

Structural rigidity is instead determined by a system called eustele, a ring of vessels that carries nutrients and water, supported by tissues that can lignify in older plants, forming a much more rigid skeleton [1].

[1] To understand better the sofisticated structure of a Nopal plant, it is suggested the book “Morfologìa y anatomìa de las Platyopuntias” by Prat et al., 2018.

Areolas are central elements in the life of a prickly pear plant as they are the initial points for the sprouting of new cladodes or flowers - therefore for the growth and reproduction of the plant. Alternatively, the areoles themselves are responsible for producing the spines needed to defend the integrity of Nopal. These same spines can be interpreted as an evolution of the leaves suitable for resisting in arid or generally hostile climates, since they minimize transpiration (and therefore heat exchange) and discourage the consumption of cladodes (Inglese et al., 2018).

Spines can be divided into two types: glochidia (in Spanish “ahuates”), small, thin and gathered in dense tufts that detach easily, and spines proper, larger and lignified. In the areoles of very young cladodes, small green, cylindrical structures can also be observed, but they wither and fall off within a few days, and could also be compared to rudimentary leaves.

Below the surface, nopal extends a fleshy root system that prefers a horizontal development in the first 30 centimeters of depth, being able to expand laterally between 4 and 8 meters. This conformation of the roots allows the plant to intercept even the water resulting from the scarcest rain even before the heat causes it to evaporate (Inglese et al., 2018).

A further element that highlights the optimization of Nopal in arid climates are temporary roots that in Spanish are called “Raicillas de lluvia” (Rain Roots), which grow in contact with the humidity of the rains, carry out their work of collecting liquids and then drying out as soon as the soil becomes dry again, thus avoiding energy waste for unnecessary maintenance during periods of drought. Finally, from the upper edges of the cladodes emerge the flowers that will give rise to the fruits, the tuna or xoconostle, fleshy berries that inherit the anatomy of the stem, including the presence of areoles and glochidia on the peel (Inglese et al., 2018).

1.2 CAM Plants

What allows Nopal to survive in arid environments is its metabolism called Crassulaceae Acid Metabolism (“MAC” in Italian and Spanish, “CAM” in English).

The difference with plants with a common metabolism is the shift of some diurnal and nocturnal phases of photosynthesis: if common metabolisms open the stomata during the day to absorb carbon dioxide, Nopal keeps the stomata closed during the day or during the hottest hours and then opens them at night.

The problem that has conditioned Nopal to such an evolution is the strong transpiration that occurs when plants open their stomata with a consequent loss of fluids, which in arid climates would be significantly accentuated (Inglese et al. 2018) [2].

Nopal, therefore, opens its stomata only when temperatures drop and the humidity in the air rises, so as to absorb carbon dioxide and store it inside in the form of malic acid inside organelles called “vacuoles”. As the sun rose, the diurnal phase began and the nopal closed its stomata to block any possible leakage of fluid. Thanks to this insulation, the plant is able to reduce water dispersion by three or five times compared to traditional plants. At this point, nopal begins to use the carbon dioxide it had previously stowed overnight in the form of acid, releases it internally, and, using the energy of the sunlight that strikes it, completes the photosynthesis process to produce the nutrients necessary for its growth (Inglese et al. 2018).

[2] Note. The capacities given to Nopal by the CAM metabolism affect also other plants of the Cactacea family often present in the American continent and all over the world.

This buildup causes the plant to become physically more acidic at night, a detail that is well known in Mexican food culture: nopal harvested at dawn is much more tart than that harvested in the afternoon. This evolutionary process is also due to the absence of branches in Nopal replaced by cladodes and leaves replaced by thorns: a structure that minimizes internal temperature and, therefore, minimizes the loss of fluids contained in the mucilage, allowing the plant to remain alive and well hydrated even after weeks or a few months of drought (Inglese et al. 2018).

All these characteristics, from MAC metabolism to its structure, make Nopal a sustainable and extremely resistant resource for the future of the planet

1.3 Gastronomy - Nopalitos and Tuna

Nopal-related gastronomy is a cultural element with a strong impact on Mexican identity, which can count on a census of approximately 240 traditional preparations. Nopal can be used raw or cooked, in salads or in hot and cold dishes, often combined with proteins and lipids (Flores 1992, Flores et al. 1996).

This culinary diversity is due to a thousand-year history that has inextricably linked the prickly pear and the Mexican people, which will be analyzed in chapter 2.

The consumption of prickly pear is based on two of its main components: Nopal vegurita and tuna.

Nopal Verdura are the young, tender cladodes (also called nopalitos in Spanish) that are eaten fresh as well as in processed dishes, such as in brine or with prolonged cooking in salted water, which rid the vegetable of large quantities of mucilage and fix its green color while avoiding oxidation. Similarly, prickly pear pads can be dehydrated and ground into Nopal flours used in low-glycemic, low-calorie baked goods and tortillas (Inglese et al. 2018).

Tuna, on the other hand, is the fruit that arises from the most mature cladodes and is characterized by a juicy and sugary pulp, ideal for fresh consumption or for processing into jams, juices and concentrates. Furthermore, there is one species in particular of Nopal - Opuntia joconostle - which produces tuna-like fruits called “xoconostle”, characterised by a more acidic flavour which sectorises its use as an acidifier or for the production of sauces, mole (a typical Mexican dish with a lot of spice) or savoury preparations (Sáenz, 2000).

In addition to nutrition, nopal plays a historic role in the preparation of traditional Mexican beverages: examples include colonche, a fermented liquid obtained from the



Image 2: Nopal con longaniza, a traditional mexican dish



Image 3: Nopal with meat, served in a restaurant

juice of red fruits, and pulque, an alcoholic agave-based drink where nopal is used to clarify the drink and catalyze its fermentation.

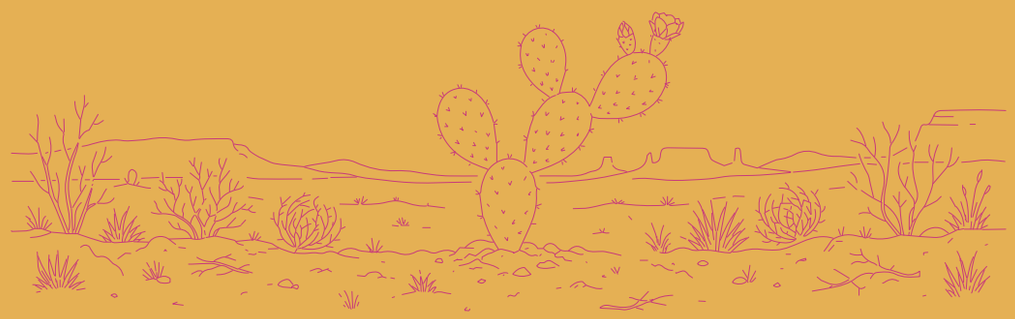
In the Mediterranean - with particular reference to Sicily and Tunisia - the supply chain and gastronomic interest remain strictly limited to the harvesting and marketing of fresh seasonal fruit, often enhanced through territorial marketing channels such as festivals and certificates of origin. In the North American and Asian markets, however, the trade and production of nopal are mainly driven by the nutraceutical and pharmaceutical nature of the plant, which is in fact included in diet protocols aimed at managing metabolism, exploiting the ability of soluble fibres to modulate the glycemic response and reduce the absorption of LDL cholesterol, highlighting the properties of nopal not only as a rural subsistence resource but as a strategic ingredient for global health and wellness markets (Inglese et al. 2018).

In general, if the consumption of Nopal as a fruit, therefore Tuna, is standardized and recognized almost globally, the same cannot be said for nopalitos, which are considered a vegetable for daily consumption almost exclusively in Mexico and, although to a much lesser extent, some Latin American countries [3].

[3] *Note. Despite nopalitos are mostly common in Mexico, standing on the oral lore of southern italian people, the Nopal Verdura was also consumed in South Italy, known as "Pane dei Poveri", the poor's bread*

History and Cultural Heritage

2



2.1 Mexico

The Nopal represents an important pillar of Mexican culture, to the point of being present within the Escudo de Mexico, which in turn is brought back to the center of the Mexican flag.

2.1.1 Prehispanic history

Mexico's pre-Hispanic history is closely linked to Nopal, both as a subsistence element, culturally, and in medicine and pharmaceuticals.

A study by Reyes Agüero et al., (2005) demonstrated how Nopal was domesticated by Mesoamerican civilizations between 8,000 and 9,000 years ago, and then became a typical gastronomic element in the diets of Mesoamerican populations themselves.

Pre-Columbian populations are estimated to have consumed Nopal as early as 5,200 BC, dating some coprolite fossils found in the cavernous complexes of the Tehuacán Valley, Puebla (Callen, 1965).

While for nomadic Mesoamerican populations Nopal could have served as a water reserve that allowed the replenishment of fluids, the cactus itself may have influenced the arrangements of settlements on the highlands of central Mexico.

An example of fundamental importance is that of the ancient Mexican city of Tenochtitlan, whose meaning is "rocky area where the Tunas abound" (in Spanish "El pedregal donde abundan las Tunas"). It is no coincidence that the myth of the founding of Tenochtitlan is depicted in the Codex Mendoza, later reported as Escudo Mexicano at the center of the current flag of Mexico: it depicts the myth of the founding of the



Image 4: The Mendoza Code



Image 5: An explaination about the name of the old city of Tenochtitlan, now Mexico City

ancient city of Aztec with a golden eagle devouring a serpent perched on a Nopal (Inglese et al. 2018).

Historically, while fresh cladodes were used as an immediate remedy against dehydration in arid climates, traditional medicine of the time shows an extraordinary diversification of use: contemporary sources describe the administration of juice with antipyretic and body temperature control functions, the topical use of mucilage to soothe skin infections and inflammation, its use for the treatment of gastrointestinal disorders and, finally, the use of roots for the treatment of ulcerative lesions or hernias. The natives therefore had a thorough empirical knowledge of the plant's properties, a symptom of assiduous use and constant applications and experiments (Hoffmann, 1995; Velázquez, 1998) [4].

Furthermore, from a purely economic and manufacturing perspective, the cultivation and management of nopal were closely linked to the production of nocheztli, a carmine red pigment obtained through intensive breeding and subsequent drying of Dactylopius coccus, the parasitic scale insect that colonizes cladodes. The extracted carmine red, used both in the writing of pictographic codices and in the dyeing of high-ranking ceremonial fabrics, fueled such a thriving domestic market that, in the aftermath of the Spanish conquest, it immediately became one of the most protected luxury goods exported along the transoceanic trade routes to Europe (Inglese et al. 2018).

[4] *Note. The knowledge of native americans about Nopal, was rudimental but extremely deep, also the economy around Nopal was well developed much before the arrival of the Spanish Conquistadores. To know more about the topic, it is suggested reading the article "¿Qué fue, qué es y qué será el nopal?" by Reyes Agüero (2011).*



Image 6: Nopal under the Pyramid of the Sun, Teotihuacan

2.1.2 Modern history

The meeting between the Old and New Worlds marked the beginning of a global expansion for nopal, the value of which was immediately perceived by the Spanish conquerors, although, as already mentioned in the previous paragraph, initially with purposes divergent from those of food

The first documented testimonies, starting from the chronicles of Gonzalo Fernández de Oviedo in 1515 and in the texts of Hernán Cortés in 1519, reflect the conquerors' effort to classify an unpublished plant morphology, in fact the adoption of the name "higo de Indias" responded precisely to the need to assimilate the biological novelty of the fruit to the familiar taxonomic categories of the European fig.

Arriving in Spain in the early 16th century, Nopal was initially an exotic element, confined to the botanical gardens of the aristocrats where it immediately became the object of study by naturalists such as Mattioli and Aldrovandi, who documented its peculiarities in their Renaissance writings (Inglese et al. 2018).

The initial collecting approach was abandoned for economic purposes by Madrid when the latter understood the potential economic importance that Nopal bore (literally) on itself: the cochineal (Dactylopius coccus).

As mentioned above, this Nopal pest can be used to extract a red pigment that will easily become of great importance to high-ranking textile industries, quickly exceeding - in some accounting - value streams higher than some precious metals (FAO, 2018).

The prominence emanating from Nopal in the form of cochineal led the Crown to establish a trade monopoly regime, to avoid infested Nopal exports for nearly two centuries.

In reality, one of the potential of Nopal had already been



Image 7: The Eagle that eats the Snake on Nopal, Castillo de Chapultepec

discovered on the naval routes between the Americas and the Old Continent: the doses of ascorbic acid (Vitamin C) present in the cladodes combined with the ability to remain “live” even if detached from the ground for a long time, made the prickly pear cladodes real reserves of antiscorbutic medicine aboard galleons.

Following the exit of Nopal from Spain’s geographical borders, it will easily stabilize in the Mediterranean context, especially in Sicily, Sardinia and Mediterranean Africa. Colonial expansion in the late eighteenth and nineteenth centuries, driven by British and Dutch routes, pushed the cactus into even more remote geographies, with targeted introductions to South Africa in 1772, India in 1780, and later Australia around 1840, where the plant was used as a fire barrier, live cattle fence, and emergency fodder (Inglese et al. 2018).

This massive introduction into ecosystems free from natural parasitic pressures, however, caused a vast ecological disaster, particularly in Australian territories, where the uncontrolled proliferation of the plant led to the expropriation of millions of hectares of agricultural land and required, in the early decades of the twentieth century, one of the most famous and pioneering biological control interventions in agricultural history through the targeted introduction of Cactoblastis cactorum, species of lepidopteran native to Argentina also called “cactus butterfly” that lays its eggs in cacti and leads to the death of plants.

In the Mexican context, the historical paradox has meant that, despite millennia of traditional consumption, Nopal’s transition to commercial and intensive horticulture was only consolidated in the mid-20th century. Until the 1940s, the plant remained linked to dynamics of spontaneous harvesting or domestic subsistence in family gardens: the change occurred between the 1970s and 1980s, when the Mexican state, in an attempt to reconvert the semi-arid areas affected by recurring crises, implemented massive subsidy and technical assistance programs aimed at replacing the traditional corn and bean crops, which were now ecologically unsustainable, with specialized Nopal plantations. The outpost of this economic restructuring was the Milpa Alta district, on the southern outskirts of Mexico City, where the transition begun in 1938 transformed a marginal peasant economy into the country’s densest nopalitos production hub, redefining the community’s social structure and laying the foundation for Mexico’s current global leadership in the Nopal agri-food sector (Gerson Gerardo, 2024).

Today, Nopal cultivation is characterized by a social stigma arising from the fact that nopalitos have always been a poor and low-cost food and, due to the lack of technical, pharmaceutical and nutraceutical knowledge, its properties are not recognized.

2.2 Italy - What we know

As in Spain, Nopal was also a phenomenon of botanical and aristocratic gardens in Italy. The botanist Pier Andrea Mattioli made the first drawing based on plants grown in Europe (1558), calling it a “miracle of nature”. Unfortunately, Nopal encountered many difficulties in being appreciated in Northern Italy, due to the rare fruiting of the Tuna, caused by temperatures and, in general, the colder climate. Despite everything, however, Opuntia found a more than favorable environment in the Mediterranean basin, in Italy especially in Sicily, Sardinia and the rest of southern Italy (Inglese et al. 2018).

The fundamental element that determined its diffusion was the dispersal of Tuna seeds by birds, which led to the rooting of Nopal in the south of the boot. Gian Lorenzo Bernini was already so influenced by the presence of the cactus that he decided to represent it inside the Fountain of the Four Rivers in Piazza Navona, Rome, under the personification of the Rio de la Plata - depicting the American continent (Inglese et al. 2018).

From an agricultural point of view, Nopal in Italy was used primarily as live fences for plots of land, but also as emergency fodder.

Human consumption, however, did not find great uses outside the Tuna: nopalitos were considered “the poor man’s bread” and therefore limited to emergency consumption or subsistence in case of need. Italy, however, was the scene of a discovery within the agricultural techniques linked to Nopal: “grooving”. This technique consists of removing the first spring bloom in order to obtain a second late bloom that matures later, until the November period. The fruits obtained through this technique are called “bastardoni” and represent a fundamental element of Tuna production in Sicily today. The region of the far south of Italy is responsible for 90% of the national cultivated area, with approximately 15,000 hectares in total which, although it saw the beginning of intensive production in relatively recent periods, around 1975, concentrated its production on the slopes of Etna and in places such as San Cono, Roccapalumba and Santa Margherita Belice, achieving yields up to 25 tons per hectare and obtaining recognition such as the adoption of DOP (Protected Designation of Origin) marks for the Yellow, Red and White Tuna variants, achieving national relevance (Inglese et al. 2018).

2.3 Nopal as a unifying cultural element

Nopal can act as a powerful cultural unifying node between Italy and Mexico, transforming itself from an identity symbol of a thousand-year-old civilization to an iconic element of the Mediterranean landscape and art. In Mexico, the plant is the mainstay of Tenochtitlan's founding myth, where the image of the eagle perched on a nopal has become the heart of the feeling of national unity and the emblem of the modern state. This deep connection is reflected in Italy, and specifically in Sicily, where nopal has naturalized with such vigor that it has become a distinctive feature of the local landscape, celebrated on postcards and tourist posters as if it were a native species.

If in Mexico Nopal has also become an element to be represented artistically - see Frida Kahlo and Diego Rivera - the same thing happened in Italy, first with Bernini (as in the previous paragraph), then with artists of the calibre of Casorati and Renato Guttuso but, in general, in many artistic works - for example - of typically Mediterranean landscapes.

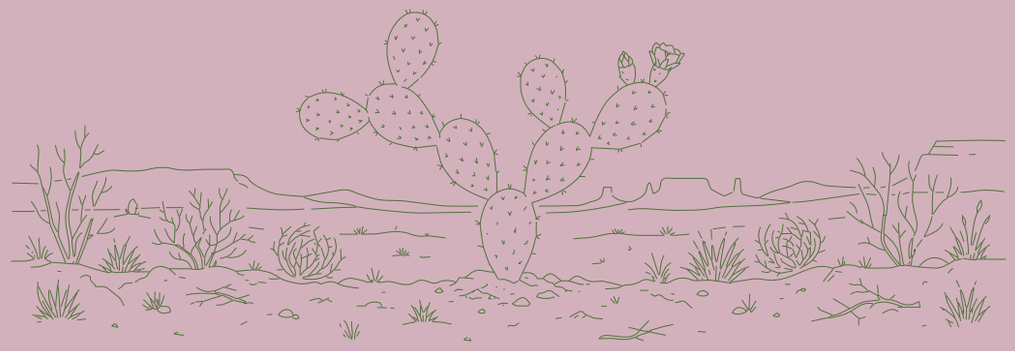
Another connecting point is the simple visual presence, both in Mexico and Southern Italy, the landscapes are strongly marked by the presence of the cactus (Inglese et al. 2018).

Already at the international level, Nopal has received the attention of the FAO, where Italian and Mexican experts have been collaborating for years.

Finally, in both countries, Nopal has been recognized with strong bipolarity: on the one hand, the figure of "poor man's bread" still exists, or at least a social stigma linked to poverty; on the other, there is a cultural background, on the one hand, the myth of Tenochtitlan; on the other, DOP brands and the recognition of the product's excellence.

Cultivating Nopal:
The Mexican case study

3



Over the years, the Opuntia genus has been the subject of studies and artificial selection processes aimed at simplifying its cultivation and increasing production yields and the plant's chances of survival. An example is that of Opuntia Robusta, a species present mainly in the wild with marked traits of hardiness such as the high lignification of the tissues - therefore a very hard structure, with a stiffer pulp - and the presence of higher, denser thorns that are effective in protecting the plant. This species is rarely used in the gastronomic field, precisely because of its predilection for species that are simpler to manage due to the presence of thorns and the qualitative gastronomic perception, for which Opuntia ficus-indica is the favourite (Benson, 1982).

In modern agricultural culture, despite the decomposition of the Opuntia genus into hundreds of singular species, Nopal is divided into two macrocategories: Tunero and Verdulero. This subdivision is made according to the output of production - and therefore the domestication process which led them to that selection - but this does not necessarily mean that they cannot be employed for the same purposes, despite the differences (Sáenz et al., 2006).

Nopal Verdulero has been domesticated over the years due to the yield on the production of the plant's cladodes, which are commonly eaten in Mexico and are a fundamental part of the country's gastronomic culture. Over the years, varieties have been selected with the aim of reducing (or sometimes eliminating) the presence of areolas and superficial glochidia, forcing a drastic decrease in the presence of spines. This selection is aimed at optimizing cladode harvesting processes, commonly and traditionally carried out without the aid of machinery, improving working conditions during harvesting by reducing the risk of injury to farmers, and reducing the timeframes for cleaning processes during sales (Inglese ei al., 2018).

Nopal Tunero, on the other hand, is intended for the production of Tuna - or fruits - as the name suggests. Commercial interest is closely related to the quality and quantity of the internal pulp, and therefore the sugar index contained within the fruits, and the size of the Tuna itself. Even in these varieties, the selection is aimed at reducing the number of thorns present on the fruits, with all the advantages described previously of Nopal Verdulero, however translated on the fruit. In fact, the cladodes of this variety maintain a strong presence of areoles and spines and a more rigid and lignified blade structure, as producers often do not have plantations in which they grow the same Opuntia species for the purpose of harvesting nopalitos and tuna simultaneously (Inglese et al., 2018).

3.1 State of the art of the techniques

Mexico's production system, the global leader in Nopal production, has a stable production volume of between 800,000 and 900,000 tons per year. These impressive volumes are compared to the same values as other global countries. Indeed, although there are no precise global estimates, Mexico alone is estimated to produce at least 80% of the world's Nopal (Inglese et al., 2018). These values are due to a high level of gastronomic and cultural interest, due to the history of Nopal in Mexico and the daily consumption of it and the technological and methodological development, in a system that prefers extensive to intensive cultivation (Garcia et al., 2003).

Precisely starting from the cultivation methods, historic areas such as Milpa Alta in Mexico City, which alone covers almost the entire Nopal needs of the capital, base the entire growth process of the plant on volcanic and mineral-rich soils but with the almost total absence of irrigation systems, favoring rainfed cultivation, exploiting the plant's water resilience. The consequence is the fluctuation of production levels throughout the year, maximized in hot periods but almost at a standstill in cold periods (Inglese et al., 2018).

Frosts, common in winter, represent one of the plant's weak points, jeopardizing the growth of young cladodes (weaker and less resistant than adult ones) and halting the vegetative development of Nopal. To overcome this problem, Mexican manufacturers have developed production systems organized in micro-tunnels combined with the use of polyethylene plastic films in order to create a microclimate inside the field with higher temperatures than outside. This technique, although it does not completely solve the temperature problem, allows producers not to completely halt production, exploiting the increase in nopalitos prices due to the scarcity of supply and increasing profits (Flores-Valdéz, 2003).

A further evolution of this technology is "macrotunnels" with the use of agricultural greenhouses: low-tech and expensive structures that allow for increased solar radiation, increasing internal temperatures thanks to the greenhouse effect and maintaining heat inside the tunnels, also protecting the plant from bad weather such as heavy rain and hail (Sáenz et al., 2006).

On the intensive - albeit restricted - production side, there are examples of high-density plants (up to 160,000 plants per hectare), with an arrangement that maximizes exposure of the cladodes to sunlight, increasing the efficiency of plant yield. Unlike extensive plants, intensive ones would be unlikely to survive without scheduled irrigation systems and controlled intensive fertilization, due to competition between plants for nutrient harvesting, which would lead to the death of weaker plants (Flores-Valdéz, 2003).

A middle ground between extensive and intensive cultivation, and therefore between environmental conservation and field productivity, is the use of "Callejones", a crop organized in rows and integrated with cereals and legumes, so as to mitigate soil fertility by recycling nutrients between the different plants present in the field and fixing nitrogen levels within the soil (Nefzaoui et al., 2011) .

Regarding the mechanization of agricultural processes, as mentioned above, all phases are carried out manually, although some practices exist, such as despinning, which can be achieved using machines equipped with cylindrical brushes that remove the thorns from the tuna, speeding up the process and reducing human intervention. Furthermore, motor cultivators can be used to reincorporate organic waste material into the soil, as well as automatic drip irrigation systems. In cases of adoption of these technologies, the profitability of the land can increase up to 100 tons per hectare under optimal conditions (Inglese et al., 2018)



Image 8: A Nopalera, where Nopal is cultivated, Estado de Mexico

3.1.1 Planting

While at a natural level, Nopal multiplication occurs through the dispersal of seeds by the wind or by animals consuming the plant's fruits, the standard agricultural technique is the collection and planting of cladodes directly in the soil, which allows for faster establishment and growth of the plant than natural reproduction (Inglese et al., 2018).

The process begins with selecting the cladodes you intend to plant, which must be one or two years old and taken from medium or high portions of the plant. The chosen pads must be healthy, without superficial lesions and are generally chosen by plants that have demonstrated the best level of productivity of the entire plant, since this technique allows for the genetic replication of an existing plant (Tapia, 1983).

Once the chosen cladode has been removed - a process that occurs simply by incising it linearly at the base to detach it from the rest of the plant without further damaging it - it is left to rest in a dry place protected from direct sunlight for a period that can vary from a few days to about six weeks, so as to heal the stab wound by preventing the cladode from being attacked by bacteria and fungi present in the soil, which would cause the tissues to rot. To increase the healthy safety of the shovel, it can be disinfected beforehand, thus completely eliminating the parasitic risk resulting from the presence of parasites such as cochineal, often almost invisible in the early stages of deposition (Inglese et al., 2018).

The actual planting is generally done during the dry season, between February and April, to reduce the risk that soil moisture could cause the risk of infection to proliferate before the cladode can develop its roots.

In the most practical stage of planting, the shovel is buried for about a third of its length, ensuring that the plant is both sufficiently inside the soil to remain stable but still exposed to sunlight. To improve this last aspect, the standard plant planting technique requires the cladode to be oriented in the ground so that the larger surfaces are exposed to the east and west, so as to be able to intercept the maximum solar radiation (Rodríguez et al., 1975).

Following the burial phase, the cladode rapidly develops its root system in the first thirty centimeters of soil: this formation is naturally optimized for rapid development and to maximize the capacity for collecting nutrients and water in the early stages of growth of the new plant. To help the newborn Nopal in the first years of growth, it is advisable to remove the flowers and small fruits that have developed, so as to avoid the dispersion of nutrients and energy necessary for reproduction, concentrating all resources for the structural growth of the cactus which, generally, takes about four years to enter a full production regime (Griffith, 2004).



Image 9: A young Nopal cladode

3.1.2 Fertilizing

Although Nopal is a hardy plantation and capable of withstanding in the driest environments, the plant's productivity is that of the entire nopalera. It can be improved with the use of mineral and organic fertilizers to fill the nutritional deficiencies that undermine the plant's metabolism.

As explained by Jesus, a Nopal producer interviewed during the research phase in Mexico, although Nopal may be almost without water, the more you give and the better it grows, the more fertilizer you give and the higher the quality of the same fertilizer, the higher the productivity increases.



Image 10: A rainwater reserve, used to irrigate Nopal in case of emergency

Considering the types of nopaleras examined previously (intensive and extensive), if fertilization is perfectly optional in the case of extensive crops, which have enough space to live without competing with other plants, in intensive plants the situation changes: plant density, the removal of large quantities of biomass between harvesting and pruning, competition between plants, they are all factors that make the fertilization of the soil necessary (Orona Castillo et al., 2004).

An example of a Nopal nutrient is nitrogen, with high concentration doses in young cladodes. Its low soil content would limit growth, preventing fruiting and the growth of new pads. Excessive intake, however, would disproportionately increase vegetative growth at the expense of creating new fruits or ripening them if already present and would cause an increase in the quantity of nitrates within the cladodes, becoming inedible, under penalty of consequences for food safety (Potgieter and Mkhari, 2000).

Organic fertilization of Nopal in Mexico is mainly based on the use of manure (bovine, ovine and porcine) and in areas such as Milpa Alta, Mexico City, doses of up to 800 tons per hectare are reached (Fernández et al., 1990).

According to manufacturers, these massive doses are used to improve the long-term fertilizing effect and to improve soil structure, although the use of fresh material in particularly hot periods could cause chemical burns of the plant's tissue.

The scientific sector, particularly the study of Galicia-Villanueva et al. (2017) and Aguilar (2007) actually suggests the use of composting, as organic matter, once stabilized, reduces the risk of nitrogen becoming stuck in the soil, prevents pests from spreading, and decreases soil salinization. The strategic solution is actually already present: use Nopal pruning waste, shredding it and leaving it on the ground, thus increasing overall humidity and total biomass.

At the stages of higher product demand, organic fertilization is often combined with chemical fertilization, for example

with the addition of potassium, phosphorus, calcium and magnesium. These minerals are essential for Nopal, which absorbs them in high quantities from the soil and concentrates them in cladodes. During harvesting or pruning, when matter is removed, the level of minerals generally present in the plant is drastically reduced (Mondragón Jacobo and Pimienta Barrios, 1990; ICAR, 2017).

In rainfed nopaleres, fertilization generally occurs at the end of the wet season, so that the last rains can be used to dissolve nutrients and allow them to penetrate the soil, without the water itself carrying them too deep and allowing the plants to absorb them before the onset of the dry season. In irrigated systems, however, minerals are distributed differently: all phosphorus and potassium and half of the nitrogen are distributed at the beginning of flowering, and then it is completed with the remaining nitrogen after harvesting, thus replenishing it (Wessels, 1988b).

The effectiveness of fertilization is directly proportional to the amount of water available in the soil (up to excess water). In fact, fertigation has taken hold in some intensive crops, resulting in the simultaneous distribution of water and chemical fertilizers, which not only precisely distributes the amount of fertilizer needed for each plant but also reduces the need for labor in the processes (Ochoa and Urhart, 2006c).

Despite these advantages, the costs of fertigation plants force smaller producers (the majority of the total) to continue with manual fertilization, and this, combined with the “empirical” management of the quantities of fertilizers used, very often overdosed or used illegally, have a limited benefit on the plant, which sometimes sees an imbalance within the soil and an unnecessary increase in costs as reported by Valdés Cepeda et al., (2009). It is therefore necessary to further explore the issue, capable of resolving the existing problems regarding Nopal fertilization.



Image 11: Nopal residual from pruning, used to fertilize other plants

3.1.3 Pruning

As in other types of cultivation, including Nopal, pruning is a useful and sometimes fundamental intervention for optimizing the plant's productivity. The reduction in plant size has various beneficial effects, both on the final yield of the plant and on the harvesting phase that operators must carry out manually. As mentioned in the section on cladode planting, the first pruning stages are carried out from the earliest stages of plant growth, through the removal of the first flowers and fruits, with the aim of correctly setting the plant skeleton, which, weighing down in the early stages, could cause excessively low and horizontal growth (Nerd and Mizrahi, 1995b).

After the plant stabilizes, when it becomes adult, pruning takes place annually and serves to maintain a balance between vegetative and reproductive development (fruits), renewing the terminal cladodes from which the production of fruits and nopalitos intended for harvesting will then begin.The important objective is also to control the height of the plant, which is generally maintained between 1.8 and 2.5 meters in height, in order to allow for easier harvesting of the products (Mulas and D'Hallewin, 1992).

For older and less productive plantations, more drastic pruning, called "rejuvenation", is used, that is, cutting all the cladodes to bring the plant back to about 50 cm above the ground, leaving only distinct and separate sections of Nopal den, stimulating the production of a new structure that brings the plant back into full production within two or three years.

Another type of pruning is sanitary pruning, used to remove rotting, malformed, or parasitic sections (Mena Covarrubias, 2012).

The last type of pruning analyzed is the one developed in Italy and subsequently widespread in Tunisia: "scozzolatura". This technique involves removing the first spring flowering, in



Image 12: A pruning technique used to force Tuna production



Image 13: Detail of the pruning technique

order to stimulate a new regrowth of late fruits which, albeit with a reduced quantity, allows the production of higher quality prickly pears (the so-called Sicilian “bastardoni”) in a period of supply shortage and therefore in which prices are much higher (Barbera and Inglese, 1993).

In general, traditional pruning has a precise running period. In Mexico, for example, it is operated on during the winter rest period, between November and March, so as to bring the production of new cladodes into the warmer periods, so as not to expose them to temperatures that would block their growth and affect their quality (Mondragòn Jacobo and Pimienta Barrios, 1995).

The management of pruning residues requires particular attention to the possibility that cladodes, if abandoned on the ground, could take root and generate another plant in a place where they should not or would cause problems for existing plantations. To overcome this, shredding the brought pads is an acceptable solution, as it also allows the biomass to be reintegrated into the soil for fertilizing purposes (Mena Covarrubias, 2012; Galicia-Villanueva et al., 2017).

3.2 Weaknesses

While it is true that Nopal is known for its hardiness and ability to withstand harsh environments, its cultivation is also not without vulnerabilities, with effects ranging from a drastic reduction in productivity to the complete death of the plant.

Climate

From a climatic point of view, the main problem is the plant's low resistance to too low temperatures and hailstorms. Sub-zero temperatures, even for short periods, can cause irreversible damage to plants: in areas most often subject to winter frosts, this results in the total loss of flowers and crops. Conversely, temperatures consistently above 30 degrees- while not completely endangering the crop or the life of the plant-slow the photosynthesis activity of crassulaceae's acid metabolism but increase the speed of fruit ripening, reducing crop size and fruit quality. Even in the total absence of water, despite the known resistance of Nopal in this area, carbon dioxide absorption is significantly reduced after three weeks while it almost completely disappears at about fifty days, causing a significant weight loss of the plant. Hailstorms are the quintessential danger to the Nopal crop, as, in addition to becoming increasingly frequent and unpredictable, they cause physical damage to fruits and cladodes, potentially causing crop losses. Additionally, if hail-damaged fruits and cladodes are not removed or treated, wounds can become a gateway for fungi and bacteria, which can cause extreme damage such as plant death (Nobel and Hartsock, 1984).

Parasites

The most devastating insect globally for Nopal is the scale insect (Dactylopius opuntiae), which lays two eggs in its pads and fruits, causing them to deform, which in turn reduces the plant's productivity by up to 80%. Similarly, other parasites such as Cactoblastis cactorum and Metamasius spinolae destroy the internal tissues of cladodes causing them to collapse on themselves (Zimmermann et al., 2009)

The most dangerous fungi for Nopal are black spot (Pseudocercospora opuntiae), responsible for tissue necrosis, golden spot (Granata y Sidoti, 1997), and root rot caused by Phytophthora and Fusarium in poorly drained soils or in the presence of excessive moisture.

Regulations

A worsening of the situation, in light of all the dangers analyzed so far, is due to the shortage of specific drugs and pesticides authorized for use on Nopal. This condition often leads producers to use products intended for other crops, which is not only considered an illegal practice and therefore legally exposes the producers themselves, but potentially makes the plant unfit for consumption due to the possible dangerous chemical residues released by previously used products. Another issue highlighted during an interview with a Nopal producer is the uncoordinated use of pesticides: use too close to the harvest period makes the likelihood of toxic residues on the final products very high (Mena Covarrubias, 2013).

3.3 Fertilizers and pesticides

Fertilization and the general use of chemicals (e.g. pesticides) within Nopal are is, as mentioned above, a sensitive topic, since while it is true that there are regulations on the use of chemicals, it is also true that the availability of products authorized for direct use on Nopal is generally low. Fertilization of the plant, specifically speaking of green Nopal, is made necessary by the fact that the production of nopalitos is based on the removal of material that is directly part of the plant's structure, which in turn must continuously regenerate. Elements such as phosphorus, potassium, calcium, magnesium, and nitrogen are necessary for plant regeneration, especially the latter, which, if not adequately replenished, represents a limiting factor for plant growth (Galicia-Villanueva et al., 2017).

In areas of high agricultural production in Nopal, such as Milpa Alta, or producers tend to use fresh manure as a basic fertilizer, with high quantities ranging from 600 to 800 tons per hectare every two to three years. Although this can be considered a traditional technique, it presents problems such as the risk of contamination by pathogens such as Escherichia coli, the destabilization of nitrogen and salt absorption from the soil, and the possibility of chemically burning the plant tissues in contact with manure during the warmer months (Aguilar, 2007).

In addition to natural fertilization, there is also the use of chemical fertilizers such as urea and potassium nitrate. Assuming that Nopal cultivation occurs almost exclusively in rural areas with little control and rough approaches to utilization quantities, the generally exaggerated use of chemical fertilizers could result in a dangerous accumulation of substances, such as nitrates, inside the pads intended for consumption. For these reasons, studies such as the one conducted by Aguilar (2007) suggest a transition to compost- and vermicompost-based fertilization, stabilized solutions

that improve the yield and quality of the final product, reducing greenhouse gas emissions and the risk of contamination of Nopal and surrounding areas, including groundwater.

On the front of treatments for the health of the plant and against parasites in Mexico, the same problem mentioned above persists: the absence of drugs registered and authorized for use on Nopal. This regulatory vacuum forces producers to use products intended for other, better-normal crops, a process that, however, exposes producers to legal risks and the final product to contamination, becoming dangerous to health. The use of insecticides such as Malathion, Chlorpyrifos or Methomyl, which were detected in the state of Morelos during the research campaign conducted by Rives-Castillo et al. (2021) e Marín-Bustamante et al. (2018), is still frequent against cochineal, historically the most harmful parasite for cacti

The management of weeds and parasitic fungi is still generally entrusted to the use of glyphosate, atrazine, and copper oxychloride, all products that, if not used correctly and uncontrolled, can be highly dangerous, transforming a food with high organoleptic potential into a vehicle for substances harmful to the body. Fortunately, in recent times, producers are opening up to the use of less aggressive substances, which still allow satisfactory results when combined with an integrated strategy with the use of compost for fertilization and hygiene of producers during the harvesting phase (Kumar et al., 2018).

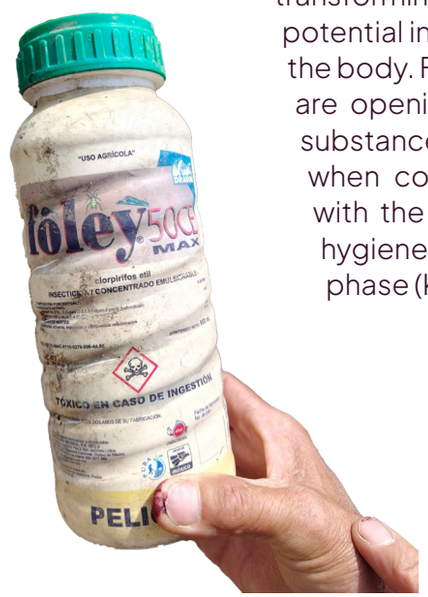


Image 14: A bottle of Foley 50CE MAX, a pesticide used to fight cochineal

3.4 Life cycle of Nopal

The life cycle of Nopal is characterized by a longevity of both the natural life of the plant and its productive life, reaching production for over 100 years. As previously described, the life of a Nopal plant begins by seed dispersal or by grafting a scarred shovel into the soil. Once planted, the cladode quickly roots and begins to produce edible fruits starting from the second or third year of life (Inglese et al., 2018).

The maximum production stage of the plant is generally reached at 6–8 years of age, while the actual structuring of the plant can take up to about a decade. At this stage, Nopal maintains stable production for a period of 20 or 30 years, depending on the intensity of production and the environmental conditions in which it lives. A Chilean study conducted by Acevedo e Doussoulin (1984) indicates a peak in the yield of tuna production between the ages of 16 and 20, and then began a phase of decline between the ages of 21 and 35. As the plant ages, the production of new cladodes decreases due to internal self-shading, so to overcome this problem and extend the plant's useful life, rejuvenation prunings are used after the first 10 or 20 years, thus removing the old parts, stimulating the birth of younger, more resistant and productive cladodes.

In the most intensive and modern nopaleres, there is a renewal cycle of the entire plants, which are replaced every 6–10 years to increase the yield and quality of the nopalitos and tuna (Ramírez-Arpide et al., 2017).

Certainly, Nopal life can be undermined or accelerated by attacks by parasitic insects and fungi such as cochineal and picudos or by extreme climatic events such as frosts.

At the end of the production cycle, the biomass generated by the plant is often shredded and reincorporated directly into the soil to be distributed among new plantations as compost,



Image 15: Detail of a red Tuna flower and other tunas growing on a cladode



Image 16: Detail of an orange flower growing on a cladode

thus re-soiling the nutrients and energy previously used to grow the old plant. To do this, you must be sure that the cut plant does not carry diseases or sores such as cochineal, which, in the event of direct redistribution on the ground, could lead to further infestation, leading to the removal of other plants in the field as well. Alternatively, the same end-of-life biomass as Nopal can be used for livestock feed as forage (Orona Castillo et al., 2002).

3.5 Other case studies in the World

In addition to Mexico, which is certainly the world leader in Nopal production, cactus cultivation has had a positive impact and is generally grown for fruit or fodder consumption.

America

Brazil is one of those countries where Nopal has become an important resource in animal nutrition. In fact, the South American nation holds the world record for fodder production, with approximately 600,000 hectares dedicated to Nopal alone, equipped with irrigation systems and mechanized processing and cleaning processes.

Chile has a strong tradition in the cultivation of Nopal Tunero, which is approaching applied scientific research for the production of bioenergy from biomass.

The United States, particularly California, produces mainly tuna, while Argentina has approximately 10,000 hectares of land dedicated to Nopal Tunero and Foraggero, integrating the crop into the most marginal areas of the country and producing tuna varieties such as “Tuna Amarilla sin espinas”, which has become a valuable product.

Peru, unlike other American countries, has become the world leader in the production of cochineal for the extraction of its dye, with 60% of the cultivated area of Nopal used for harvesting the parasite. The remaining percentage, however, is grown for the production of Tuna (Inglese et al., 2018).

Europe

In Italy, particularly in Sicily, prickly pear has become a case of excellence thanks to the production of vats. In places like San Cono or in the areas distributed along the slopes of Mount Etna, the production yield has reached values of 25 tons per hectare, particularly high values considering that the quantity includes only the fruit. The success of the production of quality tunas in Italy has been such that the same fruit has been made into Protected Designation of Origin (PDO) products.

In Spain, cultivation is concentrated in some areas of Andalusia and Murcia and in some areas of the Canary Islands, where Nopal is grown for the purpose of harvesting cochineal.

In Portugal, however, cultivation is concentrated in the Alentejo and Algarve areas, where there are government programs to introduce young people to agriculture (Inglese et al., 2018).

Africa

Tunisia presents a situation of rapid growth and evolution. Although there are no precise data on the quantities produced, the introduction of techniques such as “scozzolatura”, introduced by the Italians in the 1990s, is pushing Nopal towards an agriculture aimed at the cosmetics industry.

In South Africa, Opuntia is such an important fruit cultivar that it has led the country to be the world’s third largest producer of tuna, after Mexico and Italy.

Ethiopia and Eritrea see Nopal as a food subsistence crop. Cactacea has become a go-to source for emergency feeding for both humans and animals, given drought conditions and issues related to water scarcity.

Morocco has seen an increase in the area dedicated to Nopal

cultivation over the last twenty years, reaching 120 thousand hectares with production encouraged by state drought control programs.

Algeria has had a similar development, with a focus primarily on the production of tunas, with processing plants (such as that at Sidi-Fredj) capable of processing two tons of tunas every hour for pharmaceutical and cosmetic production (Inglese et al., 2018).

Asia

Jordan has approximately 300 hectares of land dedicated to the cultivation of Nopal, with irrigation systems that make cultivation possible in marginal areas.

In Syria, nopal has been successfully promoted as an emergency forage resource through international projects of ICARDA and IFAD.

In Israel, cultivation covers approximately 350 hectares, concentrated mainly in the Negev and Arava valleys where scientific research has focused on manipulating the plant's life cycles, thus inducing late blooms that produce fruits called "Ideas". Israeli production is also distinguished from the rest of the world by the use of dried Nopal flowers for the treatment of benign prostatic hypertrophy (Inglese et al., 2018)[5].

[5] *Note. Nopal is a plant characterized by a easy capacity of adaptation and diffusion, this brought Nopal to be present in much more places we may believe. To know more about the world diffusion of the plant is suggested the book "Historia e importancia agroecológica y económica" by Ochoa & Barbera (2018).*

3.6 Comparison between Mexico & Italy

Nopal, both in Mexico and in Italy (especially in the south), is a characteristic visual element of the territory. Mexico is certainly the original center of the plant and this is demonstrated by its indigenous history and by the fact that it is there that the greatest biodiversity of Nopal resides. Mexican cultivation sees 55 thousand hectares dedicated to the production of tuna and 12 thousand hectares dedicated to the production of nopalitos. Added to these are approximately 3 million hectares of land where Nopal grows spontaneously (Inglese et al., 2018).

In Italy, despite there being "only" 15 thousand hectares dedicated to the cultivation of the fruit, Nopal production ranks second in the world in terms of tons produced, approximately 90 thousand. To these cultivated areas, we should add those in which Nopal grows spontaneously, a common characteristic of all the regions of southern Italy, from Sicily to Molise, passing through Basilicata, Calabria, Puglia and Campania, with appearances also in Sardinia and Liguria (Inglese et al., 2018).

The main difference between the Mexican and Italian production hubs is the arrangement of the plant's seasonality: while in Mexico precipitation is concentrated in the summer and therefore the plant's maximum production period, in Italy the opposite occurs, with abundant precipitation in winter and dry summers. This means that in Mexico it is possible to grow in rainfed regimes, while in Italy the presence of irrigation systems is absolutely necessary to maintain acceptable production regimes (Gonzàlez Gaona et al., 2024).

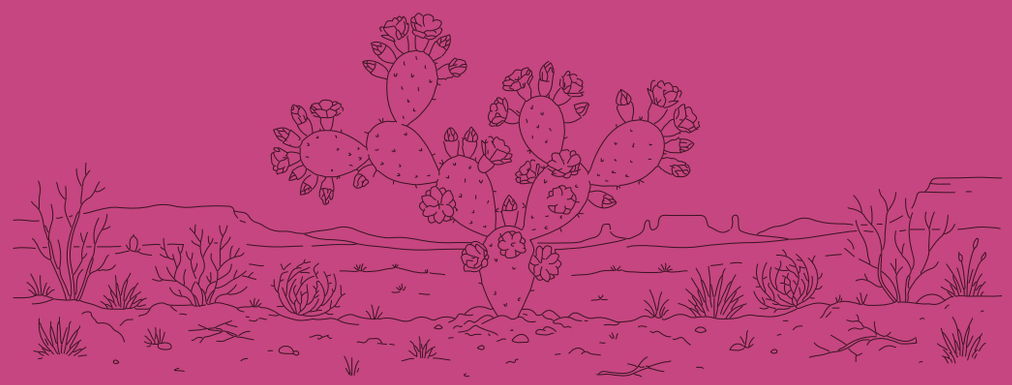
Another difference between the two is the composition of the nopalere, which in Mexico reach densities ranging between 10,000 and 40,000 plants per hectare (Inglese et al., 2018), typical of intensive cultivation. In Italy, however, production is the opposite, with very wide rows measuring 6×6 or 4×6 meters per plant, reducing the density to approximately 300 or 400 plants per hectare (Inglese et al., 2018).

During flowering, another difference emerges between the two systems. If in Italy in the eighteenth century the technique of "scozzolatura" was invented, which involves the removal of the first spring flowering to delay the ripening of the fruits that will be called "bastardoni" (in Sicilian "bastadduni"), in Mexico the application of the same technique should take into account the morphological and climatic characteristics: the height above sea level greater and the hot and dry climate typical of central mexico, in case of removal of flowers would not lead to the production of fruits, but new cladodes. Speaking of the "scozzolatura" technique, a further difference emerges between the two "schools" of production: in Sicily, for the production of Bastardoni, a maximum of six fruits are left for each shovel to maximize a larger size; in Mexico, small producers prefer a quantitative approach, since a smaller number of fruits produced necessarily translates into a lower profit (Inglese et al., 2018).

To conclude, although it is a structural difference, what varies between Italy and Mexico is the destination of production itself. In Mexico, Nopal cultivation is aimed at both fruit and vegetable production, as both are part of the (almost) daily Mexican diet. In Italy, however, fruit production is exclusive due to the lack of culture in the consumption of nopal vegetables, with the maximum valorization of "Fico d'India" which has become a Sicilian product of excellence and creating a strong bond with the region which has translated into the DOP brands of San Cono and Etna prickly pears (Inglese et al., 2018; Gonzàlez Gaona et al., 2024).

Nopal as a source of materials

4



4.1 Mucilage

The extraction of mucilage from nopal (in particular from the species Opuntia ficus-indica and related) is a process aimed at isolating the so-called “baba” from other rigid tissues. This process requires a series of simple operational steps, ranging from the preparation of the raw material to the use of physical and chemical methods for the separation and possible drying of the biopolymer, also being able to obtain a stable and water-soluble powder (Garcia Salcedo, 2025).

The process begins with the selection and collection of pads, generally favoring specimens between one and three years old, or with a specific degree of maturation (for example, around 100 days), since at this stage the mucilage content is optimal for industrial yields. Once collected, the cladodes are subjected to a cleaning process - and possibly disinfection, depending on the end use of the mucilage - which may involve the use of dilute sodium hypochlorite solutions to remove surface impurities and any microbial charges. Subsequently, decortication is performed, that is, the manual or mechanical removal of the external cuticle and spines, thus allowing direct access to the parenchyma, the fleshy internal tissue responsible for storing water and, therefore, mucilage. To facilitate extraction and increase the solvent contact surface, parenchymal tissue is shredded or cut into small fragments, which generally measure about one cubic centimeter (Mora-Palma, et al., 2023).

The most common technique for extracting mucilage from plant cells is aqueous extraction, a method that exploits the hydrophilicity of the material, i.e. its natural and strong chemical affinity with water. The nopal fragments are immersed in water, distilled or potable, following measured mass ratios the standard proportions oscillate from one part nopal to two parts water, but can reach higher dilutions (up to ratios of 1:6.8) in the yield optimization procedures for certain applications

analyzed subsequently. This liquid mixture is then subjected to controlled thermal heating where the temperatures employed typically range between 70 and 90 degrees Celsius for a period of time extending from one to three hours, applying constant mechanical agitation. Thermal energy plays a crucial role as it accelerates the breakdown of cell walls and the dissolution of the polysaccharides that mucilage is composed of in water. However, the thermal process requires accuracy, as exceeding these thermal limits causes structural degradation of the macromolecule, which would lead to an irreparable loss of viscosity and original properties. There is also a variant called cold maceration, in which the shredded biomass rests in water at room temperature (about 18–20 degrees Celsius) for twenty-four hours, promoting a slower but chemically conservative release (Garcia Salcedo, 2025).

Once the extraction is completed, a dense, cloudy suspension soaked in solid residues is obtained. To purify this solution, the compound is decanted and filtered by gravity through sheets, gauze, or filter paper, separating the liquid matrix from the coarse plant fragments. If necessary, in order to eliminate residual insoluble microfibers and obtain a high degree of purity, the pre-filtered liquid undergoes a centrifugation phase which, through the rapid rotation of the sample (with speeds ranging from 3500 to 10000 rotations per minute), forces the heavy particles to settle to the bottom. The result is a clear, viscous liquid highly concentrated in dissolved mucilage.

In case of the need to obtain a material that is stable over the long term, precipitation of the mucilage is necessary so as to separate it from the aqueous solution. Mucilage, although soluble in water, is totally insoluble in organic solvents due to its polysaccharide nature. Thus, if ethanol is added (typically at a concentration of 96%), in proportions ranging from one to four parts alcohol for each part liquid causes phase separation of the physically aggregating mucilage, precipitating as a whitish, gelatinous mass. This mixture requires a rest period,

at low temperatures, for the coagulation of the biopolymer to reach completeness allowing for easy separation by outcrop or decantation (Garcia Salcedo, 2025).

The gel thus recovered must undergo a dehydration phase to remove the water and residual alcoholic traces. The elimination of moisture prevents bacterial and fungal growth, increasing the useful life of the product and promoting its handling. Drying can be done in three main ways:

1. The conventional thermal method uses forced convection stoves, in which the precipitating gel is heated to stable temperatures (usually between 40 and 80 degrees Celsius) for several hours, until the material reaches a constant dry weight (Garcia Salcedo, 2025).
2. The atomization process (or spray drying) injects the liquefied mucilage in the form of very minute droplets into a chamber containing turbulent hot air (with incoming temperatures ranging from 130 to 170 degrees Celsius). Due to the large surface area of the drops, evaporation is almost instantaneous and allows obtaining a fine and highly water-soluble powder, although this technique often requires a strong preliminary dilution of the original solution to mitigate its high viscosity, the primary obstacle of this technology (Garcia Nauto, 2017).
3. The freeze drying process (or freeze drying), which consists of thermally breaking down the sample into a frozen solid state (for example at -55 degrees Celsius) inside a high vacuum chamber. In this depressurized environment, ice undergoes sublimation, passing directly into the gaseous phase without transiting from the liquid phase. This thermo-protective process, although it involves significantly higher energy and time expenditures, eliminates the impact of heat-related chemical-physical degradation, maintaining the structural integrity of the polymer lattice (Garcia Salcedo, 2025).

Regardless of the dehydration methodology adopted, the dry biopolymer is subsequently subjected to milling, then pulverized using special mills, with the aim of generating a thin and homogeneous powder. Pulverized mucilage has marked hygroscopic characteristics, namely the chemical propensity to instantly absorb moisture present in the environmental atmosphere, therefore it is imperative that packaging be carried out promptly in hermetic containers, storing them in environments with controlled humidity and temperatures in order to safeguard the properties for future uses (Mora-Palma, et al., 2023).

4.2 Nopal extract

The extraction of nopal juice or extract is a process that allows the liquid fraction contained in cladodes to be obtained through a series of mechanical and physical operations that tend to be simple to replicate.

As with mucilage production, the essential raw material is fresh cladodes, which are despinated and cleaned. If you do not want to obtain an extract with a strong greenish color, it is advisable to remove the layer of the outer cuticle.

Once the cladodes have been cut in a similar way to what was done to obtain mucilage, the pieces are crushed or blended, also using common blenders. To promote the breaking of the solidai part and to adequately fluidize the compound, water is added inside the mass and the use of distilled water is preferred to prevent unwanted chemical reactions with the minerals of ordinary water. This mixture is often prepared in a mass proportion of one to one, that is, one part nopal to a single part water, although in some protocols the fragments are previously left to macerate in water for twenty-four hours at room temperature. From a chemical-physical point of view, the aqueous solution that is generated has a rheological behavior (the discipline that studies the deformation and flow of matter) defined as “non-Newtonian of the pseudoplastic type”. This means that the viscosity of the juice is not constant, but decreases when the fluid is subjected to a shear force or mechanical agitation (Inglese et al., 2018).

A key methodological step in ensuring that the liquid extract lasts over time, inhibiting the proliferation of microorganisms and stabilizing the enzyme matrix, is heat treatment. The blended mixture, or alternatively the macerated fragments, are subjected to heating with temperatures and exposure times that may vary: some processes involve holding the mixture at eighty degrees Celsius for sixty minutes, others require boiling for twenty minutes, while still others opt for preliminary blanching of the cladodes at ninety-five degrees Celsius before grinding (Barco-Tocto et al., 2024).

Once the heat application phase is completed, the mixture must be brought back to room temperature and then enter the phase of physical separation of the liquid fraction from the suspended solids. The operation is carried out by filtration, using tissue strainers, sieves or filters that retain the coarse fibres and residues of the parenchyma tissue. To increase the purity of the extract, decantation can be used, a physical separation process based on the action of gravity: the extracted juice is left to rest in a refrigerated environment for a period that can extend up to three days, thus allowing the heavier solid microparticles to precipitate and settle to the bottom, facilitating the removal of only the clear surface liquid (Barco-Tocto et al., 2024).

In more advanced industrial-scale processing, the goal is to obtain a perfectly clarified juice, free of any solid or mucilaginous residue in suspension for which membrane separation technologies are implemented, specifically microfiltration and ultrafiltration. The membranes used for these processes are able to completely retain suspended solids and larger macromolecules, allowing the permeation of a highly pure clarified liquid (Inglese et al., 2018).

In order to extend the useful life of the extract, the product is subjected to pasteurization, a heat treatment aimed at destroying pathogens, performed for example at seventy-six degrees Celsius for fifteen minutes or at sixty degrees for ten minutes. However, this thermal phase requires strict control, as excessive exposure to heat can lead to degradation of heat-sensitive nutrients or cause side chemical reactions that give the juice a bitter taste (Inglese et al., 2018).

4.3 Tuna seed oil

the extraction of oil from tuna seeds is a process of great agroindustrial interest, motivated by the high value of the compounds present in them. The seeds make up about 10–15% of the weight of the edible portion of the fruit and are characterized by a very rigid outer covering, known in botany as the "head," which protects the inner core. The overall oil content within the seed is relatively low, ranging on average between 7% and 15% of the total weight (Gharby et al., 2015). This intrinsic factor makes the extraction operations particularly delicate and justifies the value of the final product.

The process begins with a phase of separating the seeds from the fruit pulp, an operation that is commonly carried out in conjunction with the primary processing of nopal, using special mechanical separating machinery that isolates the seed from the rest of the sugary and mucilaginous plant matrix. Once obtained, the seeds must be thoroughly cleaned and stabilized to prevent degradation processes, thus preparing them for the actual extraction phases (Inglese et al., 2018).

To obtain oil from seeds, industry and scientific research essentially use two extraction methodologies: chemical extraction with solvents and mechanical extraction by cold pressing.

The extraction with organic solvents is a chemical-physical process in which seeds, previously ground, to maximize the contact surface, are treated with specific liquid chemical compounds. The function of these liquids is to penetrate inside the cellular tissues of the seed and selectively dissolve the lipid fraction. Subsequently, the resulting mixture is subjected to evaporation: the solvent, being highly volatile, evaporates, leaving pure oil as a residue. This method is widely used in research because it guarantees the maximum possible extractive yield, allowing the recovery of a percentage of oil

ranging from 4.4% up to 14.1%. However, the use of chemicals makes this approach less suitable for obtaining products certified as organic or intended for very high-purity cosmetic applications (Inglese et al., 2018).

The most environmentally friendly and qualitatively superior engineering alternative is cold pressing, also known as cold pressing. This is a purely mechanical method that does not use chemical solvents or external heat sources. In this case, the intact seeds are placed in industrial presses that apply high physical pressure, mechanically forcing the oil to escape from the plant cells. The term "cold" indicates that the temperature throughout the process is kept strictly low to avoid thermal degradation of the oil (Inglese et al., 2018).

This thermal control is of crucial importance since tuna seed oil is a concentrate of thermolabile compounds, which are chemicals that are irreparably destroyed or altered when exposed to heat. Among these compounds are tocopherols, the molecules that make up Vitamin E and act as powerful natural antioxidants, and a high concentration of polyunsaturated fatty acids, particularly linoleic acid. Polyunsaturated fatty acids are lipid molecules that possess multiple chemical double bonds in their chain, a characteristic that makes them very fluid but also highly reactive and sensitive to oxidation induced by high temperatures. Although cold pressing ensures a very pure product, free of any chemical residue and intact in its bio-functional properties, its volumetric yield is significantly lower than that of chemical extraction, generally remaining only between 6% and 7% of the seed weight. Precisely because of the low yield and high pressures required to crush such hard seeds, the production of this oil on a large scale is not economically advantageous for simple food use. On the contrary, the extracted oil is almost exclusively destined for sectors with very high added value, such as the cosmetics and pharmaceutical industries (Inglese et al., 2018).

Specific infrastructure and instrumentation are therefore necessary to carry out the entire extraction cycle in the industrial sector. Upstream, pulping machines are needed for the initial separation of the biomass, followed by drying systems for removing residual moisture from the seeds. For the chemical extraction stage, mixers and distillation units are required for solvent recovery, while for cold processing, structurally designed mechanical or hydraulic presses are essential to tolerate the hardness of the seed head. The entire process should be surrounded by an integrated agro-industrial approach, in which oil recovery is part of the overall processing of the nopal plant to optimize resources and fully enhance agricultural by-products.

4.4 Nopal powder

The production of nopal flour, also known as dehydrated nopal, is an agro-industrial transformation process that converts fresh cladodes into a fine, stable powder rich in fiber and minerals. Again, it is important to choose the raw material carefully, as the use of damaged or degrading cladodes will irreparably compromise the final material, making it unsuitable for high-quality industrial or food applications. To obtain a high-quality flour, rich in nutrients, fiber, and minerals, mature cladodes are preferred, usually between one and three years old, or specimens that have reached considerable size and a weight of up to two kilograms. The selected cladodes are washed with water to remove soil and dirt residues, and then stripped of their spines. In many specific procedures, the outer cuticle is also removed. The cuticle, in fact, is the natural barrier that the plant uses to retain water, therefore, its removal not only promotes faster and more homogeneous evaporation during drying, but also makes the dried material much more fragile and easier to grind, simultaneously improving the appearance and color of the final powder. Once cleaned and hulled, the plant tissue is cut into small pieces about two centimeters thick or into thin sheets about five millimeters thick, in order to maximize the surface area exposed to air or heat (Rives-Castillo et al., 2021).

Dehydration is always a critical step since fresh nopal is composed overwhelmingly of water and contains molecules that, in the case of food application, would be compromised in the event of an inadequately controlled thermal exposure, causing all the organoleptic properties of the final product to be lost.

The goal is to inhibit microbial proliferation and allow subsequent shattering. There are several ways to dehydrate cladodes, ranging from perfectly domestic solutions to more ingenious solutions that reduce dehydration times. The

simplest and most economical method is solar or open air drying, in which the fragments are spread in a single layer on clean, ventilated surfaces. However, this process is extremely slow, taking up to 188 hours in humid climates, and exposes the material to the risk of cross-contamination if the area is used for other purposes or simply trafficked (González Gaona et al., 2024).

For faster and more controlled production, thermal methods are used using conventional furnaces or forced air dryers. In this equipment, it is significantly easier to control temperatures, for the reasons above. Generally, you operate at thermal regimes between 60 and 65 degrees Celsius for a period ranging from 10 to 24 hours. Exceeding these temperatures would mean caramelizing the sugars present in the pads or the mucilage itself which would therefore ruin the product (Rives-Castillo et al., 2021).

Another alternative is that of freeze-drying in a manner entirely the same as that previously explained in the paragraph concerning mucilage extraction.

Once the water removal phase is completed, the plant material, now dry and fragile, is subjected to the milling or grinding phase. Industrial blenders or, preferably, blade mills are used for this operation. The blade mill is particularly suitable for plant tissues since its mechanical cutting action can effectively fragment the fibrous structures of the nopal. The use of other types of mills, such as friction or impact mills, is often avoided because they tend to generate excessive overheating and cause apelmazamiento, a technical term that indicates the compaction and agglomeration of the fibers, obtaining lumps and therefore not a fine powder (Ceballos García, 2025).

Immediately after milling, the raw flour is sieved, passing it through wire mesh to separate the fine particles from the residual coarse fibers. Like dehydrated mucilage, Nopal flour is also highly hygroscopic, so to prevent it from absorbing

atmospheric moisture, it is immediately vacuum-packed or sealed in airtight containers.

4.5 Lignocellulosic fiber

Lignocellulosic fiber is the first element of Nopal that is extracted from waste never intended for human consumption: dried and discarded spines and cladodes.

To improve the final yield of subsequent processing, the material - although already dry - is subjected to dehydration processes, as we have already seen previously. This process, although it may seem useless, actually has a dual function of dehydrating and embrittling the rigid structures of the cladodes and spines without chemically degrading them. To do this, the method is similar to what has already been seen: controlled low temperature drying (60°) for a period of up to 24 hours (Trujillo et al., 2010).

Once the fibers have been completely dehydrated, milling is carried out, which, as with Nopal flours, reduces the cladodes and spines to fine, ready-to-use powders.

4.6 Cellulose nanoparticles

Cellulose nanoparticles can also be extracted from Nopal waste alone, mainly from spines that, remember, are composed of parallel cellulose and hemicellulose fibers held together by lignin.

To isolate the spines from the biomass - in case the starting material was a Nopal blade - the latter is subjected to a heat treatment at forty degrees Celsius. This treatment is necessary since mechanical removal of the spines does not aseptically separate the spine itself from the cladodium biomass and this affects the purity of the final product.

The isolation of cellulose from hemicellulose and lignin occurs through a process called “delignification”, in particular, a processing called “Milox method” explained by Marin-Bustamante et al. (2017): a treatment in an acidic environment that oxidizes and degrades the bonds of lignin making it soluble without affecting the polymer chains of the cellulose.

The acid used for separation is formic acid in solution with hydrogen peroxide and distilled water. In the study by Marin-Buustamante et al. (2017) sixty-four milliliters of formic acid, four milliliters of hydrogen peroxide and twelve milliliters of distilled water were used, in a ratio of solid mass (the spines) to liquid solution of one to forty.

The mixture must be heated to a constant temperature of eighty degrees and mixed constantly with a stirrer for one hundred and eighty minutes. Once the cellulose is separated from the other components, the mass is washed with distilled water to remove trace acids and thus stop oxidative processes.

Finally, to obtain cellulose nanoparticles, a final transformation step called “high-energy ball milling” is necessary, that is, using a machine with a rotating chamber made of agate (due to its extreme resistance to abrasion) with free spheres inside that move by inertia thanks to the high rotation of the container.

The kinetic energy of the spheres is sufficient to break up the cellulose mass until it is reduced to a nearly impalpable nanoparticulate powder, whose granules vary in size between twenty-four and one hundred and twenty-two nanometers. Analyzing the powder under x-rays shows how this process is able to generate irregularly shaped particles which, from a chemical-physical point of view, reveal a complex dual structure. In fact, they present both highly crystalline regions, that is, zones in which the cellulose molecules are arranged in a geometrically ordered and compact way ensuring mechanical resistance, and a high percentage of amorphous material, which instead indicates a disordered molecular arrangement, resulting from the intense impacts suffered during grinding in the planetary mill.

4.7 Natural pigments and dyes

In reference to what is explained in Chapter 2, the Spanish colonization of Central America, when addressing the topic of the cochineal and its extraction, refers to what has been an element of wealth, luxury and trade for hundreds of years.

Nowadays, the Nopal system represents a source of natural pigments and dyes, which are experiencing a strong industrial renaissance as a replacement for synthetic alternatives. Obtaining these coloring substances is essentially divided into two macro-categories: the extraction of carminic acid, a precious red pigment of animal origin derived from a parasitic insect that infests plants, and the extraction of betalains, pigments of plant origin obtained directly from the pulp and peel of Nopal fruits.

The extraction of carminic acid has as raw material the carmine cochineal (Dactylopius coccus), a small insect that feeds on the sap of the plant and destroys the possible harvests of nopaleres, motivation for which, in Mexico, there is a variant of Nopal called “cochinillero”. The coloring active compound accumulates in maximum concentrations of between eighteen and twenty-two percent within the body of adult females. The production process begins with the harvesting phase, a less mechanizable operation that must be performed manually, using brushes, brushes, or special spatulas to brush the surface of the nopal and collect insects. This procedure must take place in a very precise time frame, preferably in the days immediately preceding or at the beginning of the time when the insect lays its eggs, to maximize the extractive yield of the pigment and not damage the chemical purity of the product. Once separated from the plant surface, the insects are subjected to a physical screening process using sieves or sieves. This mechanical cleaning step is essential for removing coarse impurities and separating the whitish protective wax that the insect naturally secretes, known as coccicerina,

which is a waste byproduct that can in turn find secondary use, for example in the cosmetics industry (inglese et al., 2018).

The most critical and criticized step in pigment extraction is insect sacrifice: this process, depending on how it is performed, can significantly impact the quality of the product. There are various thermal and physical methods for performing this operation, including rapid immersion in boiling water, suffocation by water vapor, asphyxiation in airtight containers, or the use of hot air currents; all modes that have also triggered reactions from animal rights associations and against animal exploitation.

In any case, freezing at temperatures below freezing is the scientifically and industrially optimal technique, since thermal inhibition guarantees the maximum preservation and the least molecular degradation of carminic acid.

Subsequently, the cochineal - still moist - must undergo immediate dehydration to prevent decomposition. Drying can occur naturally and at low cost, taking advantage of direct solar radiation for several days or slow wilting in the shade for a period that can extend up to a month. Alternatively, artificial systems with forced and controlled hot air between fifty and seventy degrees Celsius can be used for a few hours. The dried material is finally selected based on size, since logically the physically bulkier specimens contain a greater amount of pigment. The product is then finely ground to break up the insect tissues, obtaining a red-purple powder, intended for high-quality textile, cosmetic or food-grade inductors, while it can be equally extracted with hydrochloric acid and heat as demonstrated by Portillo et al. (2021).

By shifting the focus to nopal fruits, the dye extraction process focuses on betalains. From a biochemical point of view, betalains are water-soluble pigments.

They are divided into two main subclasses: betacyanins, which are responsible for the intense red to purple colorations (like betanin), and betaxanthins, which instead give yellow and

orange hues (like indicaxanthins). Compared to other very popular natural dyes such as anthocyanins, betalains have the advantage of being chemically stable over a much wider pH range, making them much more versatile for food use and therefore mixed with other foods with even very different pHs, without undergoing unwanted degradation or color changes, offering antioxidant properties in parallel (Inglese et al., 2018).

The most suitable filtration processes for pigment extraction force the crude juice through the semipermeable membranes having microscopic pores, successively on decreasing size scales. This sieving at the molecular level allows all suspended solids and viscous macromolecules (such as mucilage and heavy polysaccharides) to be retained on the filter, allowing permeation and a clear liquid, in which the betalain pigments are highly concentrated and structurally unchanged. An alternative biotechnological approach employed for the concentration of betalains relies instead on controlled fermentation. By inoculating the fruit juice with specific yeast strains, such as Saccharomyces cerevisiae (the same one used for bread or beer), the microorganisms rapidly metabolize and consume the sugar component present in the liquid, drastically reducing the volumes of sugar and water, thus increasing the concentration of pigments in the solution (Inglese et al., 2018).

4.8 Nopal applications - Case studies

4.8.1 Medicine and cosmetics

In the medical field, nopal has been widely studied for its hypoglycemic properties - the ability to lower blood glucose levels - and lipid-lowering properties - the ability to reduce the concentration of harmful lipids such as cholesterol. These properties are mainly due to the large quantities of dietary fiber contained inside, especially the pads. These fibers can be divided into soluble fibers and insoluble fibers: the former are mostly found dissolved to form mucilage, while the latter, on the other hand, are part of the more rigid tissues of the pads and fruits. When soluble fibers are ingested, they form a viscous layer in the gastrointestinal tract, mechanically acting on the emptying of the stomach, which is slowed down, and trapping sugar and lipid molecules by distributing their absorption over time or inhibiting it altogether (Basurto Santos et al., 2006).

Nopal, in fact, helps prevent blood sugar spikes, offering itself as an excellent natural alternative for the prevention of type 2 diabetes or obesity.

The same viscous layer that forms in the gastrointestinal tract, in addition to its metabolic control function, performs a cytoprotective function, that is, protecting the gastric mucosa, protecting it from excessive acidity or irritants such as alcohol and spicy foods (the latter widely used throughout Mexico), preventing the formation of gastric ulcers.

An additional benefit in the medical field comes from the high content of micronutrients such as calcium and magnesium, present in chemical forms highly bioavailable to the human body. Studies such as that of Hernández-Becerra et al. (2022) or that of Domínguez García et al. (2023) on the properties of the Nopal plant have highlighted that the integration of nopal into the diet promotes the maintenance and increase of bone mineral density, making this plant an excellent adjuvant in the prevention of degenerative skeletal pathologies such as osteoporosis, especially in post-menopausal women. Furthermore, important hepatoprotective properties have been documented, as the nutrients and amino acids present in nopal help detoxify the liver, facilitating the elimination of toxins induced by the environment or unhealthy lifestyles.

What makes Nopal useful for both medical and cosmetic applications is the heritage of natural chemical compounds produced by the plant for its cellular defense, which include polyphenols, flavonoids (such as quercetin and isorhamnetin), vitamins (A, C, E, K), and betalains (Domínguez García et al., 2023).

These betalains are the substances that pigment Nopal fruits, are water-soluble and, together with polyphenols, can act as antioxidants by neutralizing free radicals (chemically unstable and reactive molecules) that are generated by the body from normal metabolism or exposure to agents such as sunlight and air pollution, therefore environmental stresses. Exposure of the skin to these stresses would cause premature aging, damage to DNA, lipids, and cells, but the application of betalains and polyphenols inhibits or slows these phenomena, mitigating inflammation and generating antitumor and protective effects for the cardiovascular system (González Gaona et al. 2024).

In the dermocosmetics industry, nopal is gaining recognition as a valuable ingredient, ideal for replacing synthetic and petroleum-based compounds. Mucilage extracted from cladodes, due to its nature as a hydrophilic polysaccharide, is used in the formulation of lotions, creams, soaps and nanoemulsions as a moisturizing and emollient agent. When applied to the skin, mucilage penetrates deep into the surface layer, increasing its water content and restoring its function as

a natural shield against dehydration. This film-forming effect accelerates the proliferation and repair of epithelial tissues, making nopal extracts extremely effective in the topical treatment of burns, wounds, dermatitis and in promoting rapid skin healing (de Brito Damasceno et al., 2016).

Cold-extracted oil from prickly pear seeds is also becoming a material that can be transformed into products with high added value. This is not only due to the low yield of seed pressing (about 3–5% of the weight, as already analyzed in more depth previously), but above all to its organoleptic properties. Tuna seed oil, in fact, is increasingly being compared to the more famous and sold Argan oil and sometimes judged to be better. Tuna seed oil is characterized by a high presence of polyunsaturated fatty acids, e.g. linoleic acid (approximately 60%), which, as highlighted by Kadda et al. (2026), is a lipid molecule essential for maintaining flexibility, elasticity and structural integrity of skin cells. The lipid content is combined with a high presence of tocopherols - which constitute vitamin E - and phytosterols, which give the oil anti-aging properties. The application of this oil not only reduces the skin's dehydration phenomenon, but stimulates collagen synthesis, reduces wrinkles and strengthens the keratin of fragile hair and nails. Thanks to its combined effect with phenolic compounds, this extract provides natural photoprotection, acting as a sunscreen, preventing damage induced by ultraviolet radiation and accelerating recovery from erythema and sunburn.

4.8.2 Nopal in building

In pre-Columbian times, Nopal extracts were widely used in building construction. Mayan, Aztec, and other peoples used juice and mucilage to stabilize blocks of raw earth-adobe- and to adhere stucco, cement, and mortar and make them waterproof.

Nowadays, these ancestral uses have been confirmed in highly targeted scientific articles, demonstrating the effectiveness of Nopal as a natural solution to everyday problems.

It all starts from the extraction of mucilage, which, as already seen, is a simple process that can be performed in any context; “baba”, from a chemical point of view, is defined as a “hydrocolloid” which, composed mainly of complex polysaccharides that generate hydroxyl and carboxylic bonds, is highly hydrophilic in a more or less dense gelatinous solution.

As explained by Hernández Carrillo et al. (2017), mucilage, already in the newly extracted liquid phase (or in the solid phase, dehydrated), can be added to concrete mixes, acting as a natural plasticizer and viscosity modifier (Fernandez et al., 2024), improving its workability, the kneading phase and improving compaction in cassiforms by preventing its components from separating.

Another function improved by Nopal concerns the installation times, i.e. the drying period of the concrete, which is increased by retaining the water inside the mass: although it may seem like a negative note, in reality, Increased setting time is a sought-after feature - especially in hot, arid climates (such as Mexico) - since drying too quickly would result in cracks and localized performance drops in concrete curing (Ceballos García, 2025). In order to achieve all this, mucilage creates a thin viscoelastic membrane, which, like a hydrogel, seals the surface pores, reducing water evaporation. This improvement

in water evaporation control mitigates one of the most well-known problems of cement, namely plastic shrinkage, which generates internal stresses and causes cracks and fissures, both at the surface and in the internal structure.

Mucilage reduces surface tension and, also considering the retarding effect on water evaporation, minimizes contraction forces within the material.

Once the concrete reaches complete hardening, as analyzed in the study by Mandujano Zavala (2024), the addition of Nopal in quantities between ’1% and 2% with respect to the weight of the cement, increases the resistance to both compression and bending in the medium and long term (with tests conducted at 28, 56 and 90 days of maturation), thus allowing it to withstand greater loads, thanks to its compressive strength and can withstand extraordinary loads such as an earthquake, which in Mexico is a very likely case (Durán-Herrera, 2012).

A further advantage of the use of nopal in the construction sector is the increased durability of reinforced concrete: in the study by Torres-Acosta (2020), mucilage is able to effectively slow the degradation of steel due to corrosion within the concrete thanks to its clogging function. The Nopal extract, after drying, reduces the effective porosity and, therefore, the permeability of the concrete, thus preventing the entry of external agents (for example water, carbon dioxide or chloride ions).

In particular, carbon dioxide is responsible for the phenomenon of carbonation, a chemical process that lowers the natural pH of concrete which, as a result, destroys the protective layers of the internal metal.

Chloride ions (or simply chlorides), on the other hand, are present in marine environments and trigger rapid corrosion of the metal.

Mucilage, when used within reinforced concrete, minimizes oxygen permeability and thus corrosion and extends the

passivation period of steel, i.e., the long period during which the metal is protected from corrosion, in an environmentally friendly, economical, highly available solution without the use of harmful solvents, making Nopal useful for construction in rural areas (Martínez-Barrios et al. 2025).

In addition to its use in the cement construction sector, Nopal has also found use in the production of natural paints: by mixing mucilage with other traditional ingredients such as lime, alum stone and (sometimes) soap or salt, paints are obtained that can be applied as usual, sealing microporosities by lowering the surface's water absorption capacity to values competitive for the market (Castelán-Urquiza, 2022).

Furthermore, the presence of mucilage makes the paint repellent to some types of insects, replacing synthetic resins derived from petroleum and other aggressive and polluting products to obtain a competitive result (Castelán Urquiza et al., 2023).

4.8.3 Nopal for bio-polymers

Having been in the media spotlight for years due to its massive use of petroleum and low biodegradability, plastics are seeing rapid developments in the creation of similar materials, with comparable characteristics but in an eco-friendly version.

Research on Nopal has also produced scientific studies on the production of biopolymers from mucilage with promising results, both on mechanical and chemical performance, and on the high capacity to be digested by bacteria and fungi (Liberato Portillo et al., 2021).

Plastic production from Nopal starts from two structural elements of the plant itself: lignocellulosic fibres (often derived from agricultural waste) and, to a greater extent, mucilage extracted from cladodes (Garcìa Salcedo, 2025).

Mucilage is certainly the center of the entire process: the hydrocolloid is made up of chains of simple sugars (such as arabinose, galactose, rhamnose, xylose and galacturonic acid), which allow it to form three-dimensional networks that, when appropriately transformed, produce materials completely similar to plastic (Rodríguez Barbosa et al., 2023).

To obtain a film of plastic material from Nopal it is necessary to add glycerol, which functions as an agent “plasticizer”, that is, a low molecular weight molecule that fits between the chains of the main polymer (in this case the sugars), reducing the intermolecular attractive forces, increasing the mobility of the chains, reducing the rigidity and fragility of the material and giving it the flexibility and elasticity necessary to avoid breaking during deformation (Quispe Solìs, 2022).

If you want to increase the mechanical properties of the resulting polymer, you can add potato starch or proteins such as gelatin or soy protein to the compound: gelatinization of these substances in the presence of heat and water creates

a structure that acts as mechanical reinforcement, improving the mechanical behavior of the polymer.

Bioplasty, in this case, is particularly hydrophilic. This condition allows it to bind easily to water, thus degrading; but if you want to reduce this phenomenon to extend the life of the material, you can add natural waxes, such as bee wax (Garcìa Salcedo, 2025).

The most widespread method so far - at least in the laboratory - is the “casting” technique (in Spanish vaciado en placa), which involves the preparation of an aqueous solution in which the mucilage is mixed with the plasticizer and, possibly, with the reinforcing agents and then subjected to a gradual and controlled heating process, generally between 70 and 80 degrees Celsius. During this heating process, the solution must be constantly stirred, thus facilitating the dissolution and homogenization of all components, avoiding the need to increase temperatures and avoiding breaking the thermolabile structure. The resulting fluid should be thick and lump-free, ready to be poured into suitable molds as needed and left to dry at temperatures of approximately 35–45 degrees Celsius until the water has completely evaporated (Orozco Silvas, 2017).

The result obtained will be a thin, transparent or slightly translucent film that is flexible and completely biodegradable.

In the event that a harder substance is to be obtained, it is necessary to include the lignocellulosic fibers obtained from Nopal and use injection molding or extrusion techniques, so as to melt the material and compact it into its final shape.

Biopolymers obtained from Nopal have so far only laboratory applications, but have actually been tested in multiple fields: already in the food industry, a sector particularly sensitive to the use of inappropriate materials, all the films used to cover fresh food, such as fruit, vegetables, meat and fish, could be replaced, as the film obtained from Nopal has better semi-permeability properties, which regulate the presence

of gases inside the package, slowing down moisture loss, oxidation and bacterial or fungal proliferation (Liberato Portillo et al., 2021).

Nopal-derived biopolymers can also be used in liquid-phase agriculture to improve pesticide adhesion to plants, while also decreasing the quantities used of the pesticides themselves (Rodríguez Barbosa et al., 2023).

In the medical field, Nopal films can be used both to create soft capsules for controlled drug release and to produce active-acting wound films, thanks to their hydrating and re-epithelializing properties capable of aiding the regeneration of dermal tissue.

4.8.4 Nopal as a water filter

In relatively recent times, nopal has received attention for the filtration and purification of turbid water, a topic of importance especially in rural areas of Mexico, where the shortage of drinking water is a daily and perennial problem, due both to the scarcity of natural water and the difficulty in finding the resources to purify it and the consequent disposal of the wastewater sludge produced by it, both the lack of infrastructure typical of rural areas.

Waste sludge from water purification is one of the most common problems worldwide, as conventional treatments rely on the use of inorganic coagulants such as aluminum sulfate or ferric chloride. Although effective, these chemical compounds produce toxic sludge that is difficult to dispose of as waste and can release aluminum residues into the water, associated with the development of neurodegenerative diseases (Otálora et al., 2022).

From this, Nopal stands out for being a totally natural, non-toxic, biodegradable and low-cost bio-coagulant and bio-flocculant, also obtainable from agricultural and production waste of the plant.

Also for this process, the fundamental material is the mucilage extracted from the Nopal pads.

The coagulation process is a chemical process that cancels the repulsive electric charges of the polluting particles forming part of the initial compound that is intended to be purified, causing them to aggregate together in a single mass. Flocculation, on the other hand, is the next phase, where these particles form larger and heavier masses called, precisely, “floccules”, which fall to the bottom by the action of gravity, leaving the rest of the water clear (Wan et al., 2018).

The mucilage of Nopal allows both processes to be carried out, as it is an anionic polyelectrolyte, that is, a negatively charged molecule, whose chemical interaction with turbid or heavy metal-containing water activates the hydroxyl (OH) and carboxyl (COO-) functional groups present on its polysaccharide chains (Choudharya et al., 2018).

These functional groups form hydrogen bonds and electrostatic attractions with the contaminating particles called “inter-particle bridges”, binding all the contaminants into a single network.

Observations from the study by Wan et al. (2018) demonstrated how the chains signed by Nopal mucilage floccules together with pollutants have larger and denser morphologies than those obtainable with chemical coagulants.

This increase in density allows a sedimentation rate up to 50% higher (Wan et al., 2018), thus optimizing the treatment processes.

If it only considers the turbidity removal treatment of suspended solids, nopal showed solid performance, reducing turbidity at scales from 90% to 99% (Wan et al., 2018) in river waters.

Otálora et al. (2022) observed how the efficiency of this process is closely related to the pH of the treated water and, with high degrees of efficiency in a pH range between 5 and 10 with higher performance in values between 10 and 13, since the increase in alkalinity favors the process of “deprotonation”, that is, the process of proton loss by mucilage in order to multiply the sites of absorption of impurities.

In addition to visual water purification, nopal has good aggregation capabilities with heavy metals and industrial contaminants. Studies conducted by Ovando Franco (2012) have confirmed how mucilage is able to reduce the amount of heavy metals by 83% for lead, 80% for iron and with good efficacy also for zinc and cadmium.

In addition to heavy metals, an effective action against arsenic

has been recorded, equal to 64%, particularly present in the aquifers of many areas of the world, including Mexico.

With these results, Nopal has proven versatile not only for the purification of drinking water, but also for complex waters such as industrial ones, such as those in the textile, paint, and waste water from tar sands tailings ponds for oil extraction.

With reference to the studies of Lugo-Arias et al. (2020), the research is also evaluating the combined use of Nopal mucilage with cassava starch, which acts as a flocculation aid, i.e. increasing the efficiency in reducing turbidity.

In addition to the increased efficiency, this mix does not significantly alter the pH of the treated water, thus avoiding the need to use other chemicals to modify it, thus also reducing purification costs.

The use of Nopal in water purification, therefore, has been assessed as mature to ensure safe, circular, and low-impact access to drinking water.

4.8.5 Nopal for energy production

The use of Nopal as a source for bioenergy production has already received strong interest from the scientific community, starting from the assumption that it is an easy-to-grow, resilient plant requiring low amounts of water.

These qualities allow Nopal to obtain high quantities of biomass in arid lands, thus avoiding competition for land use compared to other types of crops, which require more care and attention.

The most widely tested route for energy production today is anaerobic digestion and the subsequent production of biogas, a biochemical process in which Nopal biomass is degraded by bacterial and microorganism loads in the absence of oxygen.

The exclusive use of cladodes presents a technical limitation: the lowering of the pH (therefore very acidic values), observed especially in young pads, could compromise the correct functioning of the biodigester. Ramírez-Arpide et al. (2019) demonstrated how the solution to this problem is to add waste such as pig or cattle manure to Nopal biomass. The combination with manure provides a balance on the carbon-nitrogen ratio and helps maintain the pH at neutral or slightly acidic values, while nopal functions as a source of carbon and energy, thanks to the rapid battery production favored.

Bacteria degrade biomass by producing a new type of battery charge called "methanogenic", accelerating the process.

The high presence of water within Nopal (approximately 90–92%) allows the biomass to be introduced into biodigesters without the addition of additional water, also considering that, in the case of water addition, it would be necessary to use fresh water, which is generally limited in contexts such as Mexico (Comparetti et al., 2017).

The biogas obtained from this battery fermentation is a combustible mixture of 50–60% methane and 40–50% methane with traces of hydrogen sulfide and water vapor.

The methane potential of pure nopal is approximately 0.360 cubic meters of biogas per kilo, with a calorific value of 7058 kilocalories per cubic meter. This allows it to be exploited through two main energy valorization processes: direct combustion in boilers, and use in micro turbines for energy production.

Eventually, the biogas can be subjected to a carbon dioxide removal process to obtain pure methane, which can be used as an environmentally friendly fuel to replace fossil fuels (Ramírez-Arpide et al., 2019).

Ramírez-Arpide et al. (2017) demonstrated how biomethane produced from Nopal has high EROI values, i.e. the energy return on investment, with values between 8.1 and 12.4 confirming good energy efficiency.

Ramírez-Arpide et al. (2019) also observed that, in addition to biogas, the biodigestion process produces a biological residue called stabilized digestate, a by-product and high agronomic value that can be used as a fertilizer, thus circularly closing the product use cycle, leaving a zero amount of waste. The implementation of a farm-scale biodigester may require careful economic evaluation, as the price of biogas would still be linked to typical global economic dynamics, but if used in a purely agricultural context it could have high margins on internal rates of return, managing to amortize costs both through energy production and through the use of digestate as fertilizer on site, having no need for transportation costs, giving an additional economic possibility to rural communities.

In addition to anaerobic digestion in biodigesters, the bioenergy sector has explored the valorization of older, lignified cladode portions that, if properly sun-dried and shredded, can be thermally valorized or used in biomass plants for thermoelectric power generation. This material also

functions as firewood, with a direct calorific value between 3850 and 4200 kilocalories per kilogram (Inglese et al., 2018).

Finally, a cutting-edge research area explored by Shoukat et al. (2023) is studying bioelectrochemical cell (biobattery) technology, compact devices for converting biomass-derived chemical energy into actual electrical energy in real time, exploiting the metabolic activity of microorganisms that develop within it, which oxidize Nopal juices by converting them into continuous electrical flows.

4.8.6 Nopal in cultural heritage

Pre-Columbian civilizations, such as the Maya, Aztecs, and Toltecs, already used nopal juices and mucilage to protect their buildings, stabilize the stucco, and fix the colors of wall paintings. Today, the conservation properties of Nopal are being rediscovered, in order to pave the way for the replacement of artificial substances used in restoration, so as not to expose operators to the toxicity of these products, which in the long term can cause serious damage to the organism (Rodriguez-Navarro et al., 2017).

In the field of architectural restoration and cultural heritage, the use of mucilage as a hydrocolloid produces positive effects at the microstructural level, facilitating the orderly growth of calcium crystals contained in the matrices often used, making them flat and more compact.

At the architectural conservation level, its use on adobe makes it more resistant to the erosive action of water, consolidating it and making it waterproof. By penetrating the microporosities of the structure, the mucilage fills the internal voids without completely blocking the permeability of the material, preventing internal moisture from stagnating, thus allowing it to exit without allowing it to enter further (Ruiz et al., 2009).

A study on Lecce stone - which includes some monuments in the Salento area - conducted by Rizzo et al. (2020) demonstrated how mucilage allows a strengthening of the calcium oxalate patina already present on the stone naturally, that is, a pinkish-coloured patina that protects the material.

To increase the water-repellent effect of mucilage, it can be mixed with lime, soap, and alum stone (as already seen for cement treatment), which creates a barrier to water absorption, inhibiting the production of saltpeter, outcropping crystals that cover the stones and modify their aesthetics (Castelán-Urquiza, 2022).

Nopal can also be used for the preservation of pictorial works of art, especially wall paintings and tempera paintings on paper or plaster. Historically, mucilage was already used to preserve the color by making it adhere more effectively to the walls. Studies carried out on Mesoamerican archaeological sites, such as Mount Alban, have found that the preservation of the original pigments is due precisely to the use of nopal as a binder, as it allows the colors to be chemically protected from the secret caused by ultraviolet rays and exposure to climatic events (D'Agostino et al., 2023).

Another possible use of Nopal mucilage involves the restoration and preservation of metal tools made of copper, bronze, iron, and steel, such as coins, weapons, armor, and various tools. Current polymers are based on synthetic resins, such as Paraloid b-72, substances that are derived from petroleum and can be toxic, with long-term irreversible effects. Furthermore, these substances can modify the aesthetics of the artifact by changing its color. Application of Nopal compounds accumulates on metal surfaces, isolating the material from water, oxygen, polluting particles, and microbial and bacterial charges (such as Pseudomomas aeruginosa), limiting any corrosion and biocorrosion events (Abdel-kareem et al., 2017).

Nopal Production

Politecnico di Torino

Planting

1 Cutting Nopal pad

2 Artificial Planting

2 Natural dispersion

Cultivating

3 Fertilization & irrigation

4 Use of pesticides

5 Plant height control (Pruning)

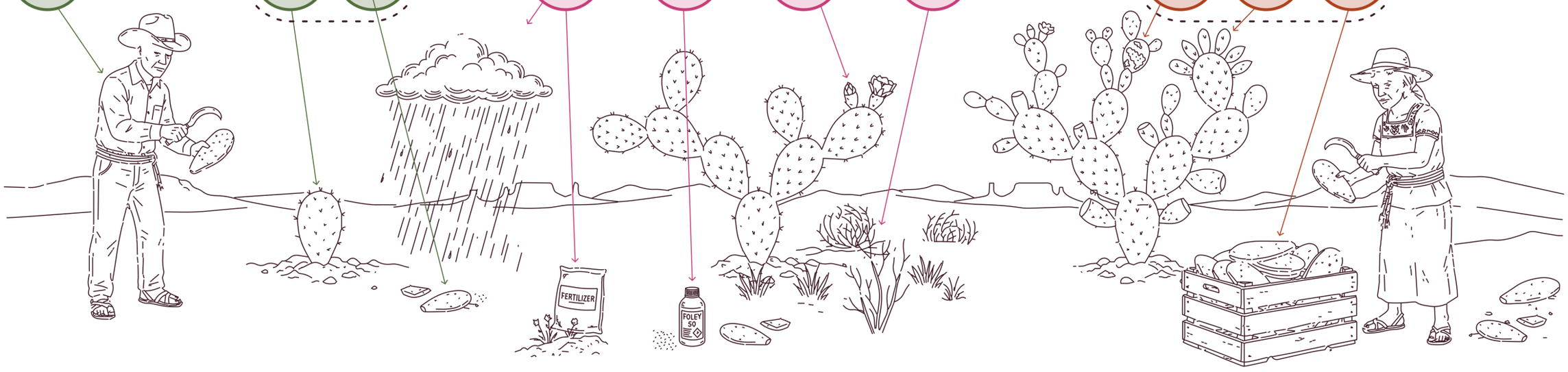
6 Weed Control

Harvesting

7 Collecting cochineal

7 Collecting Tunas

7 Collecting Nopal Pads



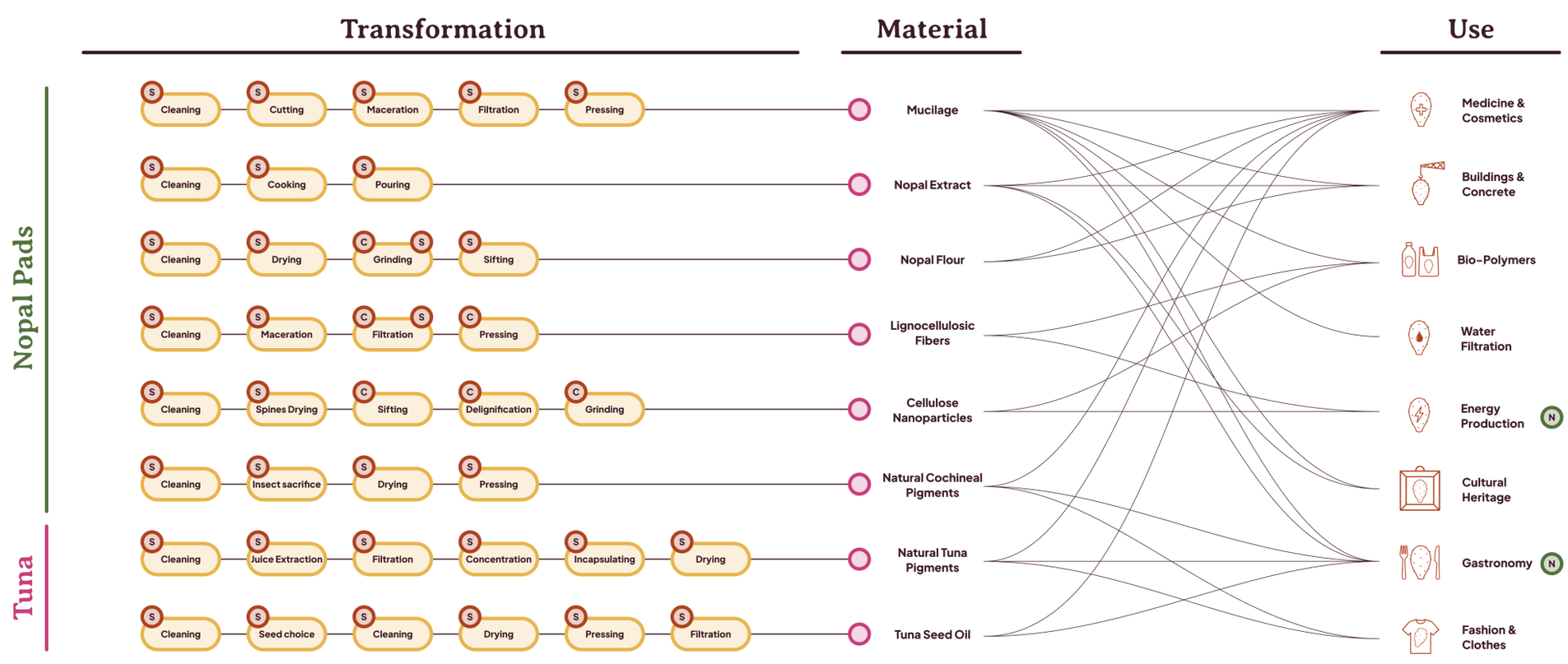
Description

The Production Map shows a short sequence of actions necessary to the planting, growing and harvesting of Nopal.
Later shows the potential uses of Nopal, with the procedure to obtain the extracted materials from the plant.
As showed in the map, the procedures for the material extraction in most cases doesn't require heavy or complex machinery, making Nopal based materials a good and reliable option in low-tech applications.

Legend

Alternative Processes: Identifies a branching node where system pathways or operations are mutually exclusive alternatives.

- S Simple action: the action or the process **doesn't require** complex or heavy machinery.
- C Complex action: the action or the process **requires** complex or heavy machinery.
- C S Both present: the action or the process is strictly **related with quantities** of material to transform.
- N Nopal Mark: It is possibile to use the raw Nopal Biomass for the application



Systemic Analysis

5



5.1 Milpa Alta

Milpa Alta is one of the sixteen Alcaldías of Mexico City, located south of the town and Xochimilco, delimiting part of the southern border of the city via the Ajusco-Chichinautzin mountain range with the state of Morelos, and the eastern border with the state of Mexico.

The district is divided into twelve “pueblos originalios”, small villages whose most important center and administrative seat are Villa Milpa Alta, from which Alcaldía itself takes its name.

Milpa Alta is the Alcaldía of Mexico’s least populated city: in 2020, according to the Mexican National Institute of Statistics and Geography (INEGI), the population was 152,685. At the same time, Milpa Alta has the highest percentage of people who speak Nahuatl (one of the most important pre-Hispanic languages) in the entire city, which stands at 4%. In fact, much of Milpaltense culture is the result of the preservation of indigenous identity, from religion to agriculture and gastronomy.

To discuss the current system built around Nopal in Milpa Alta, it is important to consider that-since it is a perfectly traditional cultivation rooted in pre-Hispanic culture-a separation cannot be made between the material sphere in the strict sense, and therefore the set of material objects that are part of the flow, and between the immaterial sphere, such as traditional, technical, and experimental knowledge.

The local governance regime is based on the use of shared communal lands called “Ejidos”. These lands are provided for by the Mexican Agrarian Law and are divided among the heads of peasant families in the form of “Tierras Parceladas” and are managed democratically and autonomously with respect to ordinary authorities, such as the government.

The highest decision-making body is the “Asamblea General

de Ejidatarios”, which meets periodically for the approval of external projects, economic budgets and changes of regulations. Next there is the “Comisariado Ejidal”, or the legal representation of the ejido delegated to communicate with the state or third parties, which is made up of a Commissioner’s President, a secretary and a treasurer.

Finally, there is the “Consejo de Vigilancia”, the body responsible for independent checks on the police station to ensure compliance with the Agrarian Law and the wishes of the assembly.

The individual social actors present within the ejidatarian structure are mainly three: the Ejidatarios, that is, the holders of agricultural law who cultivate a parcel and exercise the right to vote, the Poseisonarios, who cultivate a parcel recognized by the assembly but do not have full decision-making powers in it and, finally, the Avecindados, resident citizens of urban settlements who do not directly own land to be cultivated or voting rights, for example non-heir children of the Ejidatarios or Poseionarios or unstabilized immigrants.

Milpa Alta is characterized by the presence of Ejidos, but above all by the presence of lands called “Bienes Comunales” [6], that is, portions of territory assigned to indivisible collective use and possession on the basis of the recognition of land ownership by indigenous communities, of which Milpa Alta

[6] The substancial difference between the Ejidos and the Bienes Comunales present in Milpa Alta is strongly connected with the fact that almost the entire Alcadia of Milpa Alta is considered a “Suelo de Conservacion” due to the presence of green areas totally not urbanized that allows the production of oxygen and water for Mexico City. The legal difference between Ejidos and Bienes Comunales is explained in the Ley Agraria, readable at the link: https://www.gob.mx/pa/documentos/descarga-tu-ley-agraria

is densely populated. This type of land is considered an inalienable asset, inseparable from the community sphere, which demonstrates how the Alcaldía and its inhabitants are unwilling to give in to real estate speculation.

Over the years, Nopal cultivation has certainly undergone a hierarchical transformation, going from being a domestic subsistence crop or, in some cases, purely wild, to becoming a production crop so widespread that it has transformed into a type of market called Oligopsony: demand is concentrated in a few but large buyers (intermediaries), while supply is fragmented among many small producers.

The first sale of Nopal in Milpa Alta, that is, the direct one between the producer and the first buyers or intermediaries takes place at the Centro de Acopio located in Villa Milpa Alta, a facility that allows many producers to gather in one place, even if only physically, and sell their products without the need for long travel.

5.1.1 Territory

Milpa Alta's land area is approximately 228 square kilometers, making it one of the largest Alcaldías in Mexico City. The territory is predominantly mountainous and is made up of a volcanic system whose eight cones form the highest peaks of Milpa Alta: from the Teuthli volcano, 2710 metres above sea level, to the Tlàloc volcano, 3690 metres above sea level.

The hydrography of the territory is peculiar: although the entire surface is divided between the beds of two ancient rivers, the shortage of drinking water strongly characterizes the region. Only during torrential rains can small streams emerge from the slopes of its hills.

Of the entire territory of Milpa Alta, 7,500 hectares are dedicated to the production of Nopal, producing approximately '80% of all Nopal consumed in Mexico City. These territories, as well as the inhabited areas, are all located in the more temperate areas, which have slightly higher temperatures and rainy summers.

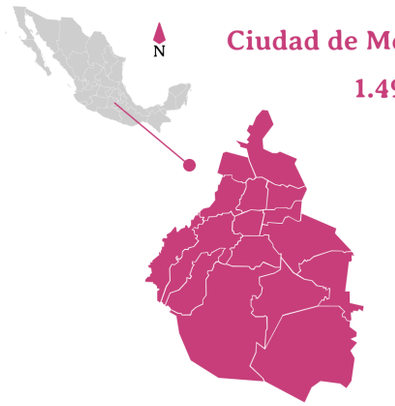
Other crops present, although almost negligible in economic weight compared to Nopal, are forage oats and corn. The rest of the territory is almost entirely subject to ecological protection constraints, and the rural population appears to be the only human presence that can prevent the city's urbanization from progressing. In addition to the opposition encountered by the population, Milpa Alta benefits from being covered for approximately 90% of its area by the "Suelo de Conservación" regime, meaning it is legally perceived as a protected, non-urbanizable area, since any waterproofing of the land would burden the water situation of the entire capital. More precisely, Milpa Alta, thanks to the permeability of its volcanic soil, functions as a recharge zone for underground aquifers, which then feed part of Mexico City's water system.

Territory Map

CDMX — Nopal

Politecnico di Torino

Ciudad de México



1.494,3 km²

16 Districts 1.812 Colonies

9.209.944 inhabitants

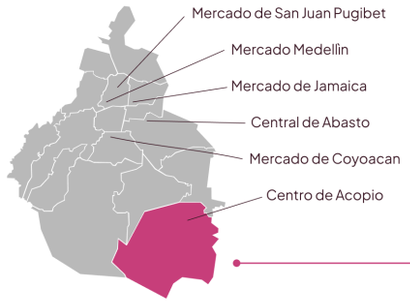
35y average age

6.163,3 in/km²

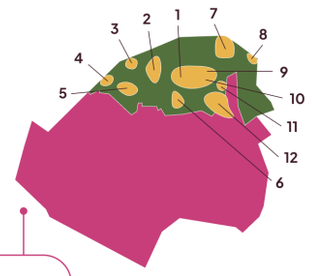
57 Indigenous languages

52,2% 47,8%

Places of interest of Agriculture



Cultivation surfaces - Milpa Alta



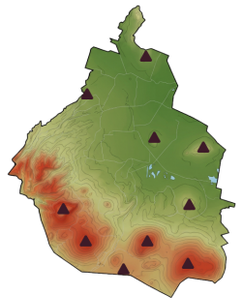
- Urban Areas
- Cultivated Areas
- Forests and Vegetation

1 Villa Milpa Alta
2 San Pedro Atocpan
3 San Bartolomé Xicomulco
4 San Salvador Cuauhtenco
5 San Pablo Oztotepec
6 San Lorenzo Tlacoyucan
7 San Antonio Tecòmitl
8 San Agustìn Ohtenco
9 San Francisco Tecoxpa
10 San Jerònimo Miacatlàn
11 San Juan Tepenàhuac
12 Santa Ana Tlacotenco

Milpa Alta - Cultivated areas

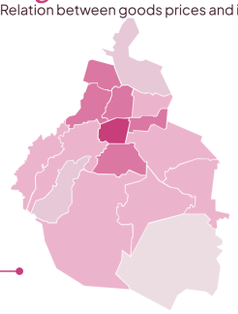


Morphology



Engels Index

Relation between goods prices and incomes



Agriculture

People involved

16%

84%

Milpa Alta is the main producer of Nopal in CDMX

228,41 km²

12 Pueblos Originarios

152.685 inhabitants

30y average age

511,9 in/km²

4% of population speaks indigenous languages in Milpa Alta

Main Nopal Events



Feria del Nopal



Nopalera en el corazòn

Nopal in the Escudo Mexicano





The mith of the foundation of Tenochtitlan (now Mexico City)

Nopal species



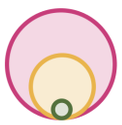
- Worldwide Nopal species (220)
- Endemic mexican species (61)

Hidrography



- Rivers
- Lakes

Productive sectors



- Third Sector 64,3%
- Second Sector 32,2%
- First Sector 3,5%

4.669.730 Millions MXN

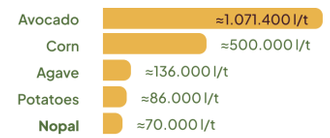
CDMX GDP

Religions

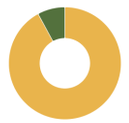


- Catholic 75,87%
- Protestant/Evangelist 7,26%
- Atheist 10,97%
- Other religions 5,9%

Water consumption

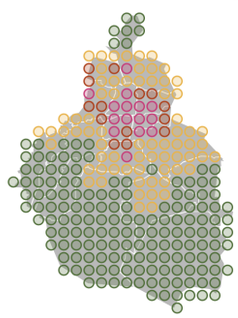


Nopal Production in America



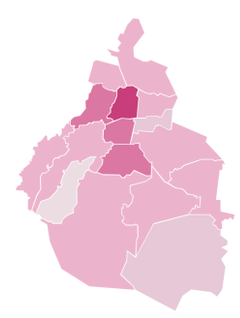
- Mexico
- American Continent

Pollutants - PM 2.5, PM 10, SO2



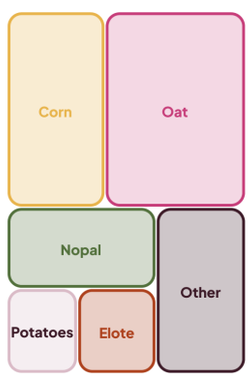
- Acceptable
- Tolerable
- Annoying
- Unacceptable

197 Museums located in CDMX

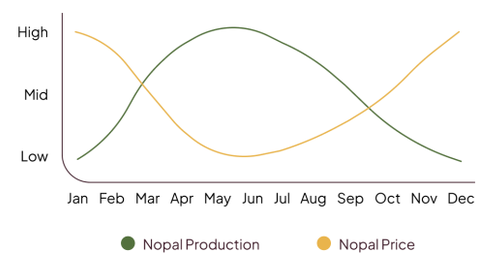


14.771,88 ha

cultivated surface in CDMX



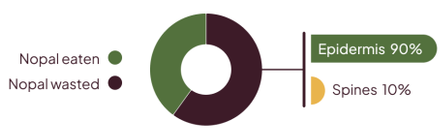
Nopal prices and level of production



Nopal Waste



~40.000 t of Nopal yearly waste produced in Milpa Alta



Main Nopal Stakeholders in Mexico

Instituto Politécnico Nacional

RED IIINOCA

DELEGACIÓN MILPA ALTA

Gobierno de México

MORELOS PODER EJECUTIVO

5.1.2 History

Before the arrival of the Spanish, the territory of Milpa Alta was a system of villages called “Malacachtepec Momoxco”. The name “Milpa Alta” derives from the Nahuatl language of the Native Americans who inhabited it and from its interaction with the new Spanish arrival: Milpa, in fact, was the term used to refer to the agricultural systems of simultaneous cultivation of corn, beans, chili peppers and nopal, a technique that allowed the soil to be preserved and, at the same time, have as complete an agricultural output as possible (Gomez Cèsar, 2009).

Following the arrival of the Spanish, the territory was first renamed Milpas de Xochimilco and only later was it completed with “Alta” to differentiate it from the other Milpas on the lake shores of the Valle de Mexico. With the Mexican Revolution, the territory of Milpa Alta was invaded by the forces of Emiliano Zapata, a peasant leader of the Southern Liberation Army, who transformed it into a stronghold, thanks to its territorial morphology. It was precisely during the Mexican Revolution that the problem of the division of agricultural lands was addressed, creating and defining what would become the municipal territories for community benefit that still exist in Milpa Alta (Gomez César, 2009; Dìaz & Curiel, 2019).

In 1992, Article 27 of the Mexican Constitution was reformed: in a strong liberal current, President Carlos Salinas de Gortari [7] put an end to the redistribution of agricultural dowries, registered part of the Ejidos on a land registry, and granted the Asamblea Ejidale the powers to convert community lands into fully-fledged private property (Williams, 1999).

[7] President Carlos Salinas de Gortari has been the last president to radically modify the Ley Agraria, also if the last modifications were made in 2024. The name of the ex-president is still present on the document of the Ley Agraria.

The consequence of all this was the beginning of land speculation on the outskirts of cities, whose land began to be sold to entrepreneurs and real estate developers in order to urbanize the areas and expand the population centers, expropriating the peasants from their rights to cultivate the land. Fortunately, Milpa Alta suffered relatively little from the consequences of this reform, as most of the land was part of the benefit of the communal lands, therefore of absolute communal dominion. Since then, Milpa Alta’s internal governance has not undergone any particular changes, continuing to experience issues such as gender inequality, which still excludes women from the right to vote in Ejidos (Paz Navarro, 2021).

5.2 Inputs

To correctly and systemically evaluate the input present within the Nopal world, it is not enough to evaluate only the input of materials but we must consider both material and immaterial elements at the same time. On a material level, certainly the first fundamental factor is the input raw material that allows the plant or the entire nopalera to be generated, therefore the seeds or cladodes prepared for planting. Subsequently, although CAM metabolism makes Nopal an extremely optimized plant in water management, it is necessary to consider the water supply required, especially in intensive plants, to increase production yield. To this input, one must also add nutritional inputs, therefore, soil improvers such as manure, compost and chemical fertilizers and medicines necessary to prevent or eradicate diseases and pests of the plant. To conclude with material resources, we must also include the input of energy necessary for the cultivation and transport of the material such as tractors, trucks and other agricultural machinery in general.

In the immaterial sphere, however, one fundamental aspect must be considered: physical and scientific human labor. Without this, not all the collection, cleaning and transport phases on which the Nopal supply chain is permanently based would take place. A highly important detail is the gender division of labor; in fact, physical effort is often borne by women within rural communities, who, however, are not included in the management sphere of the Ejidos. Last on the list but of fundamental importance is the academic and scientific approach of the institutions: UNAM, the Universidad Autónoma de Chapingo, the Politecnico Nacional, and global networks such as CactusNet and IIINOCA all contribute to the growth and dissemination of traditional and innovative knowledge related to Nopal. This experimental know-how allows for the development of innovation in the cultivation, collection, and reuse of agricultural waste, but unfortunately, this information often fails to reach those directly involved-such as producers-who remain unaware of the innovation present, using only their traditional culture regarding Nopal cultivation, which, while equally fundamental, cannot exist isolated from the rest of the knowledge.

5.3 Outputs

On the output side of Nopal cultivation, here too we are aware of the coexistence of tangible and intangible outputs, the management of which could have important repercussions both at the agricultural and socio-economic levels.

On the material side, as already explored in Chapter 4, Nopal has a high quantity of extractable materials and therefore possible by-products, which can generate high added value if managed correctly. From the Tuna - which is already an output in itself - you can extract juices, seed oil and some food colourings. From the rest of the plant, however, nopalitos can be obtained, which is possible intended for human or forage consumption. From these, other by-products can be extracted, first and foremost mucilage, already used in numerous different types of applications which, as equally explored in Chapter 4, range from the production of bioplastics, to its use in concrete and even to the production of energy.

From an intangible point of view, there is certainly an economic output that fuels the entire supply chain, despite the strong imbalances in earnings between producers, intermediaries and the industry linked to Nopal. From an economic point of view, therefore, it is possible to observe the oligopsony phenomenon as one of the intangible outputs generated by the Nopal supply chain, as the numerous small producers are unable to exercise bargaining power for the sale of their products to the few large buyers (cajeros and coyotes).

Socially and politically, the sharp inequalities between the urban and rural populations are generating many challenges for producers, between ever-higher living costs and stagnant earnings. In some areas outside Milpa Alta-which, we recall, are managed through the presence of municipal, communal, and inalienable land-other areas of Mexico have seen misappropriations of land, through political maneuvers and the imposition of physical barriers such as barbed wire fences, which have separated the Ejidos from the producers, selling the land to wealthy landowners, industrialists, and developers. Women also suffer from one of the intangible outputs unfortunately generated by the mismanagement of social life within the Ejidos, since, despite being the main workers within the camps, they have never obtained the veto power that is instead given to men as heads of households.

Added to all this is the strong social stigma that labels both rural populations, forced into poverty and marginalization from city life, and the consumption of Nopal itself, historically known for being a poor food and, although being reevaluated, still cut off from high-end cuisine. Effect closely related to what has just been described is the flight of young people from rural communities in search of a better economic and social condition. This entails, at the end of the chain of effects, the risk that the traditional know-how and local culture of rural populations will gradually disappear, so that world culture can potentially lose pieces of history passed down verbally and never shown on the outside.

5.4 Waste and By-products

The Nopal production system inevitably generates production waste and by-products which, in the case of Nopal, have demonstrated a good capacity for valorization and, consequently, that a circular production system is possible.

During the cultivation phase, large quantities of biomass are generated due to pruning, remediation and rejuvenation operations of the plant. Traditionally speaking, all this waste is instantly reintegrated into the soil-already demonstrating a circular system-but these procedures are not the most efficient and could, if poorly managed, pose health problems within the nopalera.

Between cultivation and cleaning processes, it is estimated that in Mexico City alone, approximately forty thousand tons of waste are produced, 10% of which consists of thorns and the remaining 90% of epidermis and moist tissue. If the sales chain is added, the percentage of waste produced increases significantly, reaching 60% of the total product, which, however, outside the fields, ends up in landfill and is not valorized.

As previously analyzed based on existing scientific studies and realities, upcycling of waste materials is possible. Starting from the spines, for example, it is possible to extract cellulose nanoparticles, useful for reinforcing plastic materials and creating composite hand materials. Waste cladodes, on the other hand, can still be used for the extraction of mucilage, a material with dozens of possible uses in the industrial and domestic fields ranging from the production of bioplastics, use inside concrete, water purification and more.

The general biomass produced (i.e. all the waste components of Nopal combined) can be used for biogas production through biodigestion, not only producing energy, but also an additional waste material that is very effective as a stabilized fertilizer.

The transformation of Tuna also generates reusable waste: after pressing the fruit, the waste produced is seed pomace, from which it is possible to extract Tuna seed oil, which can be used in cosmetics and medicines following other processes to obtain pure compounds.

Case studies on Nopal Biomass Reuse

Nopalimex

Country: Mexico
Year: 2009
Source: https://nopalimex.mx/

Nopalimex is a bioenergy and renewable biofuel production company located in Zitácuaro, Michoacán state.
The company aims to **create energy from Nopal and integrate the plant into a circular economy circuit with a zero-waste** perspective.
As described on the company's own website, Nopalimex began planting Nopal in 2009, coinciding with the design and construction of the industrial plant, which began use in 2014.
Since then, the company has perfected its patented method for producing biogas from Nopal biomass, arriving, in 2016, at Bio-GNC (Biomethane) for the fuel replacement of internal combustion engine vehicles, which since 2019 has been used by the Zitácuaro municipal and public transport vehicle fleet and is preparing to become a pioneer of private use, with the installation of the world's first Nopal-derived biogas station already underway.
The residual biomass, called "digestate", after the extraction of biogas, is **used as a stabilized fertilizer** in the Nopalere, after studies in this regard have confirmed the excellent performance of the biomass.
Nopalimex is currently expanding its bioenergy production business in the state of Quintana Roo, where the problem of the presence of Sargasso (an extremely widespread weed in the area) is turning into a possibility for eco-sustainable development.



NopaliMex

Biodigestor SUEMA in Milpa Alta

Country: Mexico

Year: 2017

Source: https://suema.com.mx/

SUEMA (Sustentabilidad en Energía y Medio Ambiente SA de CV) is a company operating in the cleantech that has installed a Biodigester in Milpa Alta, Mexico City in collaboration with the Secretariat of Education, Science, Technology and Innovation of the Capital.
The goal was to intercept Nopal waste at a busy point: the Centro de Acopio de Nopal, a wholesale market where producers sell Nopal to intermediaries, which then generates waste from cleaning and unsold goods.
The project was designed to handle between **3 and 10 tons of waste per day** and aimed to supply gas and digest rural populations.
Nowadays, in reality, the activity of the biodigester has been scaled down and the plant has been converted into a research center for the production of eco-friendly and low-impact fertilizers, while the produced gas is used for self-sustainment of the plant.
The reasons for the partial failure of the project were due to a poor communication campaign towards the rural population, who saw the Biodigester as a threat to their health, with strong concern about the technological risk. All this, combined with the disproportionate size of the biodigester, not only contributed to fueling the feeling of threat from the population, but also "betrayed" the prospects of studies by the Autonomous University of Chapingo, skeptical of the full-scale scalability of such a plant. Another issue concerns the very inclusion of the **rural population,** who were **unaware of how the biodigester worked** or of the benefits it would bring, from biogas production to fertilizer production, making the community a participant only for the delivery of biomass, which, among other things, was delivered with preponderant disaffection or lack of co-responsibility. The final key issue was the centralization of the plant in a historically community-based environment, which demonstrated that **the presence of a private company**, even if in collaboration with a ministry, cannot have the same engagement in a community-based environment composed of 12 Pueblos Originarios with **strong cultural identities, accustomed to self-management**.



DESSERTO

Country: Mexico
Year: 2017
Source: https://desserto.com.mx/

Desserto is a registered trademark for a prickly pear material: Nopal leather. It all started in Guadalajara from an idea by Adrián López Velarde and Marte Cázarez (now owned by Adriano Di Marti SA de CV), who, after two years of research and experimentation, synthesized a stable polymer from Nopal waste, presented in 2019 as a plant-based alternative to animal skin.
Despite the critical and media outcry over a product that **was supposed to be revolutionary** (up to 90% bio-based components), studies conducted by Meyer et al., (2021) and Sardroudi et al., (2024) have highlighted a composition very similar to that of common synthetic leathers, with a supporting polyester structure, an intermediate layer of polyurethane loaded with ground Nopal particles and a thin surface layer of PUR.
If the tensile strength capacity is a figure in which Nopal skin has recorded high values compared to other solutions, there remains the **total absence of biodegradability** (which untreated animal skin possesses), the presence of **dangerous substances** such as butanoxime, toluene, isocyanate, diisobutyl phthalate and folpet.
Furthermore, Nopal leather is characterized by **poor levels of breathability and long-lasting durability**, breaking at 30,000 flexion cycles - compared to the minimum 80,000 required by the footwear industry (Meyer et al., 2021).







Ohoskin

Country: Italy
Year: 2019
Source: https://ohoskin.com/

A Southern Italian company, more specifically Sicilian, that produces an alternative to l**eather from orange and Nopal waste**, both of which the island is rich in. The company has an e-shop, but you can only purchase samples ranging in size from 1 to 5 m by 1.4 m. These samples cannot be used commercially. Together with Moebeus - an Italian startup dedicated to making other companies regenerative through ESG projects - Ohoskin has moved closer to the United Nations 2030 agenda, embracing some of its points. Corporate communication focuses heavily on sustainability from various perspectives: on the one hand, environmental sustainability, with data on the reduction of CO2, SO2, and NOx emissions, is certainly a priority; on the other, social sustainability is being discussed, so **Ohoskin claims to help local farmers increase their profits**.
The company communicates as a promoter of a more equitable economy, which re-uses 1.3 million orange and nopal waste annually produced by the food and cosmetics industries-which therefore does not use water to produce the raw material-and exploits a former petrochemical plant in an economically depressed area of the region.
The first composition released on the market for Ohoskin vegan leather was composed of 30% polymer synthesized from organic orange and Nopal waste and 70% virgin PVC. An article dedicated to transparency-present on the company blog-explains how, initially, the 70% PVC present in the polymer compound was necessary for the product's durability, since the company claims that PVC can last up to 100 years and does not release microplastics, as is the case with PU commonly used for faux leather.

Subsequently, Ohoskin changed the compound and although the chemical composition is not explicitly stated, **the company boasts a 90% reduction in emissions** while maintaining mechanical and temporal resistance characteristics equal to those of PVC. The mix currently used is **32% polymer made from orange and nopal waste and 68% PVC from recycled, non-fossil and circular sources**.
Nowadays, the company has collaborations with fashion and luxury brands and appears to be active from both a production and communications perspective.
Anyway, the material is still not biodegradable, such as Desserto piel.







Sikalindi

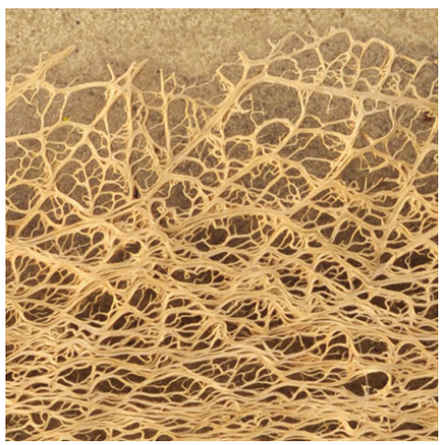
Country: Italy

Year: 2011

Source: https://www.sikalindi.it/it/

SIkalindi is a Salento-based company that **produces furniture with veneers made from Nopal fiber**. It all starts with sourcing the raw material, which is readily available in the area where the company operates. Subsequently, the material is mechanically processed to extract only the fiber that will be used, which is dried before actual use, i.e. application to a multilayer panel. The **Nopal fiber is glued onto the panels** and then sanded and impregnated, thus providing greater mechanical, chemical, and wear resistance.
Sikalindi sells its products as cutting-edge design objects but specifies how its furnishing elements should be used like any other, as the company gives its products such resistance that they can suffer daily accidents - such as bumps or falls of liquids such as water or wine - and absolutely ordinary cleaning processes, for which no compromises should be made for the longevity of the product.
Trials are currently underway regarding the use of plant-based impregnating bioresins, and the company promises to use them as soon as the technology makes them sufficiently resistant in the long term.
Additionally, **semi-finished products** can be purchased from the company to produce custom furniture from third parties such as carpenters; the semi-finished products can be purchased directly from the company and can be viewed in the “panels” section of the website.
The main problematique of this product is that the Nopal utilized needs to be in perfect conditions: **it is not possibile utilize damaged Nopal Pads or Nopal waste.**
The name Sikalindi means “prickly pear” in Griko, a Salento variant of Greek, which arrived in Puglia with Magna Graecia and is still spoken in some small communities in Salento. The company has also decided to give some of its products names in Griko, to reinforce the meaning of the tradition strongly desired in branding.







Case studies on Community Museums

Kakaw - Museo del Cacao y Chocolateria Cultural

Country: Mexico
Year: 2010
Source: https://www.kakawmuseo.com/

The Kakaw Museum is located in San Cristóbal de las Casas, Chiapas, and was founded in 2010 as a private initiative dedicated to the **history and culture of cocoa**, a subject of cultural significance because it was once considered the food of the gods. The museum contains a typical museum exhibition, with agricultural equipment for growing cocoa, biological explanations of the plant, and, in addition, an experiential tour with guided tours and workshops dedicated to production and sensory tasting accompanied by master chocolatiers. The combined effect between the **museum and experiential journeys** allows visitors to better metabolize the concepts to which they are exposed, thus making them more engaged. Kakaw also owns an area dedicated to the sale of artisanal cocoa products, and **all revenues**, despite being a private initiative, are **distributed externally among producers** and to its farming community.





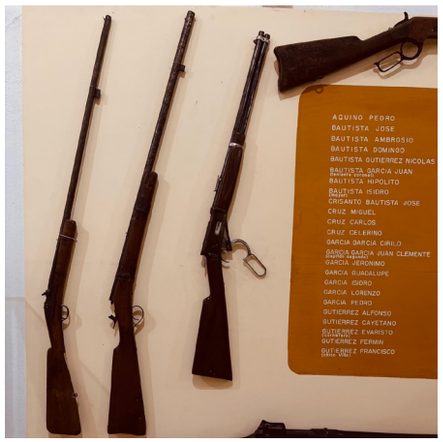
Museo Comunitario de Shan-Dany

Country: Mexico
Year: 1986
Source: https://museosantaana.netlify.app/

The Shan-Dany Community Museum in Santa Ana del Valle, Oaxaca, represents a concrete example of a community museum, as it was founded by the **Zapotec community** in collaboration with the Istituto Nacional de Antropolgìa y historia (INAH) in 1986 following the accidental discovery of an area dedicated to the burial of the dead in the city's main square. The museum houses an **archaeological area and sections dedicated to historical events and culture**, such as the sections on the Mexican Revolution, feather dancing, and wool harvesting-a product still handcrafted and traditionally made by the community. Shan-Dany is fully community-controlled throughout the management chain, making it a useful example and **benchmark case study for the development of other community museums** around the world. Its importance is also due to the fact that Shan-Dany hosted the first national meeting of community museums in Mexico (1994), an event that led to the birth of the Union Nacional de Museos Comunitarios y Ecomuseos (National Union of Community Museums and Ecomuseums) and the first meeting of Community Museums of America (2000), which saw the participation of ten nations. Actually, among the various networks of which it is a part, the museum is one of the members of the network of community museums of oaxaca, which includes eighteen members.







Museo Yuku ITt

Country: Mexico
Year: 1990
Source: https://sic.cultura.gob.mx/ficha.php?table=-museo&table_id=563

The Yuku ITt Community Museum (Cerro de Ocote) in Santa Maria Yucuhiti, Oaxaca, is one of the museums within the aforementioned network of Oaxacan community museums. It was founded in 1990 by the local rural community **inside a colonial-era building from the 1700s**, which was renovated in 2010. The museum places particular interest in the pure history of the Mixteca community through **documents, photographs, and oral testimonies from the village's elderly members**, also displaying artifacts and maps of the delusions of the common land to which the community is particularly attached. One section, in particular, is dedicated to **textile production, an ancestral practice still practiced by communities** and allows the culture belonging to the history of the place to continue and not be forgotten, also through the ecological conservation of the land and food.





Museo del Maguey y el Pulque

Country: Mexico
Year: 2009
Source: https://www.museumsmexico.com/museum/museo-del-maguey-y-el-pulque-hidalgo

The maguey and pulque museum was founded in 2009 and later moved to the Casa de Cortés in Tepeapulco, Hidalgo state, in 2016. The museum is **managed by the association "Amigos del Museo del Maguey e del Pulque"** with a museum itinerary that traces the internal cultivation and production process of Maguey, from the harvesting of Aguamiel to its fermentation and transformation into Pulque, thus placing the plant as **a central element of the culture of the place nowadays marginalized by urban networks**. This museum is an important example of **how a botanical element can become of great importance** if enhanced on the basis of the cultural experience of the community.



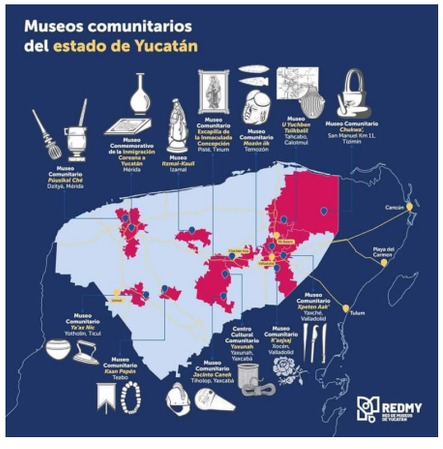


Red de Museos de Yucatán

Country: Mexico
Year: 1996
Source: https://museosyucatan.com/

The Yucatan museum network was founded in 1996, when a training course for museum promoters held in Tahdziù led to the conception and formal establishment of the Unión de Museos Comunitarios en Yucatán (Union of Community Museums in Yucatán) under the guidance of anthropologist Juan Fermín Santos Cortés. The first Yucatecan community museum (Hunucmá) had already been operational since 1992 and featured an exhibition **on ancestral shoe production**, a traditional activity of the place. Today, the museum network includes **twelve museums** located in the municipalities of Tizimín, Yaxcabá, Calotmul, Teabo, Ticul, and Izamal. All the museums in the network are **entirely managed by local communities**, which entirely manage what to show the public and, through a sort of council, elect a **self-determination methodology** explicit with the museum's content and journey.







Museo Comunitario de La Trinidad Tenexyecac

Country: Mexico
Year: -
Source: https://culturacomunitaria.cultura.gob.mx/blogs/detalle/convite-trinidad-tenexyecac

The community museum of La Trinidad Tenexyecac is a museum entirely dedicated to the **local tradition of ceramics**, an activity that is still important for the area with more than **150 workshops scattered around the town**. The museum is located in Tlaxcala and is the fruit of the "Convites Culturales", a federal program of the Mexican Ministry of Culture that for five years has brought together local artisans and young people in weekly meetings on cultural exchange. The La Trinidad Tenexyecac Museum **has become a hub for the town**, transforming a local tradition such as the production of ceramic artifacts into a **meeting point for the local network**, enhancing all processes such as smoking and lead into visible and recognized cultural value, establishing itself as an **institution capable of communicating with other Mexican government and local institutions.**





Museo Hitalulu

Country: Mexico
Year: 1991
Source: https://www.museoscomunitarios.org/galerias/imagenes/7-salas/detail/73-94

The Hitalulu Community Museum (Flor Bonita) is located in San Martín Huamelúlpam, Oaxaca. It was inaugurated in November 1991 with the aim of **tracing and documenting local archaeological finds and preserving traditional knowledge**. The museum features two rooms: the first is **a space dedicated to the archaeological site**-about 500 meters from the city-and features stone tools and ceramic artifacts; the second is **dedicated to traditional medicine**, displaying medicinal plants and evidence of ancestral practices for treating conditions such as empacho and mal de aire. The museum organizes **excursions and tours** within the archaeological site, workshops, and theatrical performances that have transformed a rural and marginalized municipality of just over a thousand inhabitants-with an important but nationally unknown archaeological site-into a sponsored area with growing visibility.







Red de Museos Comunitarios de América

Continent: America
Year: 2000
Source: https://www.museoscomunitarios.org/

In 2000, when representatives of various communities from Bolivia, Venezuela, Panama, Costa Rica, Nicaragua, El Salvador, Guatemala and Mexico came together to **find a solution to the marginalization of rural American communities**, the Network of Community Museums of the Americas was born. In the following years, the network also saw the participation of some rural communities from Brazil, Colombia, Chile, and Peru, proving to be a growing network with a strong internal structure. Between 2000 and 2014, seven traveling meetings were organized (in Mexico, Guatemala, El Salvador, Nicaragua, Venezuela, Costa Rica, and Bolivia) and dozens of **workshops for the creation of museums and training of museum facilitators** in nine countries on the American continent. The stated goal of the network is to **strengthen the identity, autonomy and self-determination capacity of indigenous communities through fully self-managed museum networks.** To do this, at the central level, the network has developed shared guidelines and characteristics, primarily the need for initiatives to always arise from within the communities themselves, always remaining their property.







Museu de Favela

Country: Brazil
Year: 2008
Source: https://museudefavela.org/

The Favela Museum (MUF) in Rio de Janeiro was founded on November 5, 2008, by a group of community leaders living in the favelas of Pavão, Pavãozinho, and Cantagalo, in the southern part of the city. The MUF calls itself a **"territorial" museum, which is therefore not housed in a building: the exhibition itself is the neighborhood.** The approximately twenty thousand inhabitants that make up it are the museum's "living collection" and the museum itinerary is created through the narration of the "Circuito das Casas-Tela, **dozens of murals painted on the facades of the houses** by local artists that represent moments of the collective memory of the place. Following the creation of the open-air museum, some places became meeting points for groups of individuals from the communities, for example, a decorated public fountain became a **meeting point for samba musicians.** The museum collects **oral testimonies from older residents: the "Mulheres Guerreiras"** (Women Warriors) project was created from the testimonies of older women in the community and demonstrates that a museum does not necessarily require a building to contain it. In this case, it is the territory that is the museum and the narrative of the inhabitants becomes the exhibition.





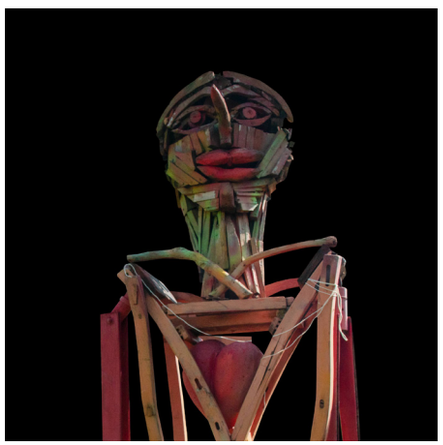
MOSS - Ecomuseo Urbano Diffuso

Country: Italy
Year: 2023
Source: https://www.mossecomuseo.it/

The Diffused Urban Ecomuseum of Scampia, Naples, is the city's first ecomuseum, founded in 2021 by the cultural association "Chi Rom e... Chi No", which has been present in the area since 2022. Networking with other local organizations, the museum opened to the public in May 2023 and is now one of four Campanian ecomuseums recognized by a law enacted by the Campania Region specifically dedicated to ecomuseums. The museum offers a **walking tour** lasting approximately three or four hours, passing through symbolic places in the neighborhood, redeveloped from below, then from the communities through community centers, **urban gardens, and murals dedicated to the Scampia Carnival.** The tour then concludes at the ecomuseum, located on the upper floor of an intercultural restaurant run by a social enterprise called Chikù. The guides who accompany visitors along the route deliberately use an ironic and joking tone, with the intention of **removing the criminal stigma present** within Scampia, placing themselves directly in opposition to the so-called "Gomorrah Tour", which focused on the symbolic places of local crime.



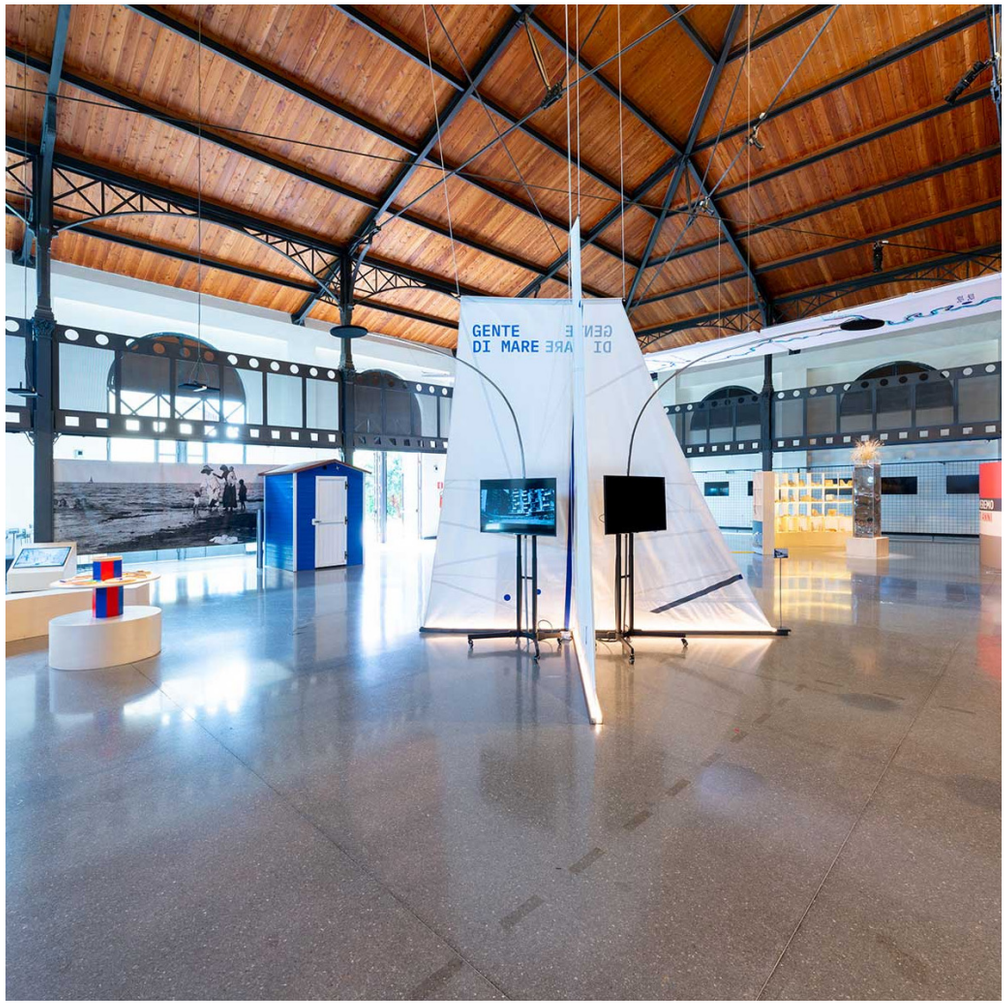




MMV - Mare Memoria Viva

Country: Italy
Year: 2014
Source: https://www.marememoriaviva.it/

The MMV Ecomuseum in Palermo is located in the former Sant'Erasmo Locomotive Depot, a late 19th-century building restored by the municipality in 2004. The museum was born from local research conducted by the CLAC cultural association, starting with an audiovisual archive launched in 2012 consisting of **photographs, videos, interviews, documents, and maps**. Enriched with the works of **local artists**, it has created a journey that oscillates between the sea and the mainland, from the Gulf of Palermo to the Conca d'Oro, with stories of fishermen and families from seaside villages. The Museum also **deals with environmental injustices, illegal construction, and the protection of the Oreto River**: MMV has committed to safeguarding the latter.
On the occasion of its tenth anniversary, the museum invested €335,000–from PNRR funds-renovating the exhibits, making them accessible to the deaf and blind.





Ecomuseo delle Erbe Palustri

Country: Italy
Year: 1985
Source: https://ecomuseoerbepalustri.it/

The Ecomuseum of Marsh Herbs of Villanova di Bagnacavallo in the province of Ravenna was founded in 1985 from a collection by Maria Rosa Bagnari who, having moved into her husband's family home, began **collecting hand-woven curtains** (found in an ancient farmhouse) from the marsh herbs typical of Villanova, such as tancia, lake rush, sedge, reed and pointed stipa, From here a **recovery process** was born which later transformed into today's museum. The museum is currently managed by the Civiltà delle Erbe Palustri Cultural Association, based in CEAS Bassa Romagna, and has a four-story layout featuring a house-workshop where **local artisans perform live demonstrations of ancient marsh herb weaving techniques.** The collection includes more than three thousand artifacts and its narrative is explicitly linked to **the work of the women of the community,** to whom a specific section is dedicated.







Ecomuseo della Pastorizia

Country: Italy
Year: 1995
Source: https://www.ecomuseopastorizia.it/

Located in the hamlet of Pontebernardo in the province of Cuneo, the Ecomuseum of Pastoralism was founded in 1995 and its reference territory extends over five municipalities: Aisone, Demonte, Pietraporzio, Sambuco and Vinadio. The project was born from the recovery of the Sambucana sheep, a native sheep breed at risk of extinction in the 1980s, the **rediscovery of local pastoral culture**, and the transhumance processes that have long characterized the region. The museum is divided into two buildings: **a small cheese factory run by various resident herding families** for cheese production-which also houses a tasting area-and a building dedicated to **rams and Sanbucana wool artifacts**, with a museum itinerary called “Na Draio per Vlours”. Today the project has expanded to include a sheepmeat processing workshop and the “Felt School”, **dedicated entirely to wool processing**. The value of the initiative lies in having managed to systematize all the various production chains dedicated to the sheep breed, increasing the added value of products and artisanal processes.







Ecomuseo della Collina e del Vino

Country: Italy
Year: -
Source: https://www.frb.valsamoggia.bo.it/musei/eco-museo-della-collina-del-vino-new/

The Hill and Wine Ecomuseum is located in Serravalle Castle in Valsamoggia, in the province of Bologna, and is housed in the House of the Captain of the Mountain, a building dating back to 1235, formerly constructed for civil and military control of the territory by the Bolognese Senate. The building retains institutional importance since between 1800 and 1900 it was the seat of the municipality. The exhibition is organized into **nine themes ranging from archaeology to local architecture, from fieldwork to the landscape of the badlands,** combining all the themes with a color to facilitate the tour. The intention is for a minimalist layout that will **entice visitors to be outdoors,** featuring itineraries of history and archaeology, nature, agriculture, society, and folklore. This outdoor route is a 35-kilometer loop and **can be explored on foot, by bike, or by car.** There are **tasting areas** where you can stop to sample **local wines.** This **open-air exhibition model,** where the museum as a building is only the starting and/or ending point, has been extended to another project called "Valsamoggia Museum Outdoor", which extends across the entire Valsamoggia area and allows visitors to discover the cultural elements of the entire area.







5.6 Challenges

Territory

Cochineal presence

The presence of the Nopal parasite has always been a problem for those who produce nopalitos and tunas. The stabilization of the insect on the pads of the plant completes the total loss of the cladode (consequently also of the fruits) which dries out, blocking the production of the plant, causing the total loss of the product.

Climate change

Climate change poses a challenge to all crops, not just Nopal. Although cacti can tolerate heat and dry soils well, in an intensive production system, this substantially slows their production. Furthermore, metereological instability-which causes muggy days in cold seasons and violent hailstorms in hot seasons-impairs the plant's health and productivity, forcing farmers to make increasingly low profits.

Illegal pesticides use

Illegal use of pesticides on plants has often been recorded in nopaleres. The event was discovered with the discovery of bottles of illegal pesticides inside the Ejidos and municipal estates. This heavily affects both the quality and - above all - the food safety of the final product. Although there are precise rules on pesticide use methodologies and timelines

in Nopal cultivation, the use of illegal pesticides would render the entire process process futile, even if appropriate timelines are met.

Water shortage in Mexico

A major problem that has historically afflicted the Mexican territory is the lack of water. Central America has always been known for the aridity of its regions, a region for which crops that require little water like Nopal have been favored in Mexican ecosystems and gastronomy for millennia.

Governance

Women exclusion

Women, due to a persistent patriarchal view of the system, have been excluded from decision-making powers within the Ejidos and municipal property. Despite the communal meaning that should characterize this type of land, there have not yet been reforms that allow women to take part in community decisions, which still fall "democratically" to the heads of families of the communities.

Traditional know-how loss

One of the trends induced by globalization is the loss of traditional knowledge and indigenous culture that strongly characterizes Mexico. Many Mexican myths, legends, and history are based directly or indirectly on the presence of Nopal or other fundamental elements of the Mexican context,

from the founding of Tenochtitlán to the Escudo de México in the center of the flag.

Lack of technical knowledge

The fact that Nopal remained for years an understudied plant and confined to the production of rural communities did not allow the diffusion of technical and cutting-edge knowledge regarding the cultivation, processing and possible alternative uses of the plant.

Market

Oligopsony

The fragmentation of Nopal production within rural communities must face a reduced number of large buyers who have bargaining power in their hands every day and the possibility of manipulating the market and its prices.

Seasonality of Nopal

About 60% of Nopal produced in Mexico becomes waste. This is not mainly due to product cleaning processes or plant pruning, but to the seasonality of the plant which concentrates a strong availability of product in a relatively short part of the year. This means that a significant fraction of the product becomes unsold along the supply chain and, therefore, thrown away.

Perception

Internal social stigma

In Mexico, being part of a rural community like those that formed in Milpa Alta around Nopal is often associated with a negative stigma. Poverty, ignorance and illiteracy are some of these characteristics that are often mistakenly subjected to rural communities in Nopal.

Nopal just as poor food

Due to its lack of publicity, consistently low price, and low circulation outside Mexico, Nopal has always been categorized as “the bread of the poor”. Recently, following discoveries about the plant’s potential in gastronomic and other fields, a reevaluation of Nopal is underway in Mexico, which is now referred to by the name “green gold”, but the negative characterization is well rooted in public opinion.

Low worldwide Nopal knowledge

Outside Mexico and a few other countries such as Italy, Tunisia and some African or South American countries, Nopal is an unknown plant. In many countries around the world, such as those furthest from the equator, Nopal is considered a tropical plant, difficult to encounter, and therefore not considered from all points of view. Even in countries like Italy, in reality, a culture of production limited to the fruit has established itself, which neglects all the potential of the rest of the plant, which will never be exploited.

5.7 Opportunities

Legend

A Active

M Mid Term

S Short Term

L Long Term

Attributes

Tecnological

To realize, analyze, improve or update a technology or a methodology.

Community

Grouping, activating, or connecting people and cultures for the creation or identification of networks.

Development

Human, social, or economic development from the application or acceptance of nopal as a resource.

Communication

Translate, spread, or exchange knowledge and narratives to align stakeholders, build awareness, and bridge systemic gaps between communities.

Territory

To contextualize, adapt, or locate systemic solutions within specific environmental, spatial, geopolitical and social boundaries.

Tolerant Nopal varieties

L

During the agricultural history of Nopal, since the Mesoamerican period, the cactus has undergone important selection and adaptation processes that have led to the cultivated species we know today. The Opuntia species grown for the production of nopalitos, and therefore for shovels intended for direct human consumption, were selected to reduce the spines on the cladodes until they were completely eliminated, thus facilitating the collection and cleaning process, which are traditionally and commonly carried out by hand. Similarly, plants used for other purposes, such as tuna harvesting, may have thorns on the cladodes, but a significantly lower quantity on the fruits which, again thanks to the selection processes mentioned above, have become larger and meatier, maximizing final production.

The exact same selection process is already carried out to improve the plant's resistance in more extreme environments, both for heat and cold, allowing farmers better stability over agricultural production.

Integrated Biological Control

L

Integrated Biological Control refers to the use of natural predators, pests, and pathogens to control or eliminate weeds within a crop or farm. For the cultivation of Nopal, the main threat is represented by the cochineal (referred to in Chapter 3), which can be countered through the use of other insect species, such as some types of ladybugs, beetles and flies or the use of fungi or botanical extracts, such as D-Limonene.

Micro-climatic Management



Many nopalere systems see the mixed and simultaneous cultivation of multiple plants in the same field in microtunnel conformations dug into the earth. This allows the microclimate within the field to be controlled over temperatures and atmospheric events, which can thus place less burden on the existence of crops. As previously stated, Nopal and its cultivation certainly enjoy great traditional know-how but lack innovative agricultural technologies due to the delay in applied studies on the Opuntia genus. Their deepening by the scientific community would allow for more systemic exploitation of crops in order to facilitate yield and allow the cultivation of other cultivars in unfavorable environments, while still obtaining reasonable results.

Material extraction from Nopal



As analyzed in Chapter 4, prickly pear allows the extraction of various materials present within it, first and foremost mucilage in terms of number of applications. The extraction of these materials not only allows for the creation of other products with high added value, but also allows for the use of production residues and waste, unsold products from producers and markets, and non-edible materials. This could allow for additional revenue for Nopal producers, a reduction in general waste along the supply chain, and an extension of the useful life of Nopal by-products.

Bio-energy production from Nopal



The production of biogas from Nopal biomass is one of the most studied and in-depth sectors relating to cacti. Companies such as Nopalimex and SUEMA have already built their biodigesters and confirmed the potential previously mentioned in laboratory tests. Biodigestion, in rural settings such as those in Nopal communities, would allow a reuse of waste material or unsold material that can not only be transformed into biogas for self-consumption, but could also be resold to energy management companies or third parties in order to generate real economic gain. Studies on the economic feasibility of a farm-scale biodigester - therefore on a large scale and large quantities of biomass - have highlighted how the main problems are on the cost of building the plant if not financed by third parties, the direct purchase of biomass or land for the subsequent cultivation of Nopal, the purchase of manure used to balance internal acidity and the recruitment of staff to control the operation of the plant.

Once biomass becomes digestate, and therefore subsequent to biogas production, the digestate itself has proven to have superior performance to manure alone or chemical fertilizers for agricultural use, establishing itself as a valid and reusable production output and closing the Nopal life cycle by returning part of the energy removed from it to the land for cultivation.

Low emission Concrete with Nopal

The history of the production of concrete added with Nopal dates back to pre-Columbian times. Over the years it has been forgotten and rediscovered only recently by some scientific papers. Nopal's additive low-emission concrete production would enable the construction of safer and more robust structures over time at a competitive price, allowing even the poorest communities to improve their home solutions.

Nopal based paints

The production, or self-production, of Nopal-based paints is another of Opuntia's frontiers of alternative use. It is produced using Nopal mucilage as part of the ingredients and has water-repellent and insect-repellent properties. The conversion of part of Nopal's waste, even at a domestic level, allows for its valorization and the production of an easy-to-make, economical, and green product.

CactusNET

CactusNET is an international research network on cactus plants created by the Food and Agriculture Organization of Finite Nations (FAO) and the International Centre for Agricultural Research in Dry Areas (ICARDA) in 1993. It is concerned with promoting the ecological and social benefits of cactus crops, such as Nopal, developing new food and industrial uses derived from the same plants and improving the technical capacities of the acceding countries

High-added value market for Nopal

The use of Nopal within the high-value-added market has almost always seen the use of virgin or directly grown Nopal by the companies that process it. These industries are generally part of the fashion and accessories industries or of medicine and cosmetics. The use of Nopal waste coming directly from producers would allow industries to receive raw materials at a lower price and encourage the production of Nopal by rural communities without qualitatively affecting their products.

Adding Nopal in animals diet

For years, livestock farming has been at the center of a global problem: water consumption. Traditional feeds, such as cereals, corn, sorghum, although well optimized, have significant water needs. Nopal, on the other hand, often has "rainfed" crops, so it does not require additional water to irrigate the fields and contains high doses of liquids inside. Using Nopal as fodder would also reduce direct water consumption by animal hydration.

Nopal community museums



Many rural communities, especially in Mexico, have relied on Community Museums for the protection of their culture. Community Museums allow individual citizens within communities to tell their stories and culture from their own perspective, also representing a source of pride in intangible culture, such as popular music, rituals, and traditional gastronomy. In the distinctly agricultural environments, the Museums represent the profound bond that has been created throughout history between the population and the surrounding nature, generating tourism in a responsible form that maintains the authenticity of the place and its traditions while at the same time allowing for social and infrastructural redevelopment. The museum, as a physical space within rural environments, allows for the creation of meeting points that foster social interaction, countering the isolation or feeling typical of less urbanized environments. It also allows for interaction in daily life among young people in the communities, strengthening the shared sense of belonging while respecting the needs of the new generations.

Feria del Nopal



The Feria del Nopal is one of the most characteristic events regarding cacti. There have been several editions throughout Mexico, the last two of which took place in 2025 in the Alcadia of Milpa Alta and the 2026 one at the Monumento a la Revolución in Mexico City. During these events, small producers can sell directly without intermediaries. In addition to selling nopalitos and tunas, they also prepare dishes and showcase common uses, such as cosmetics and medicine, to showcase the plant's potential.

EXPO Nopal



EXPO Nopal is an annual event promoting gastronomy, culture, and economics generated by Opuntia. It is held in Valtierrilla, in the state of Guanajuato, and showcases various Nopal gastronomic possibilities to the public, drawing not only on traditional gastronomy but also on culinary and industrial experimentation. The EXPO also sees the participation of part of the community of the city of Kasugai, a small Japanese village where a strong Nopal culture is equally present, making the event international. There is also a social theme related to cultivation, with the exhibition and promotion within the Pink Pavilion (in Spanish "Pabellón Rosa") of entrepreneurial projects not launched by women.

Nopalera en el corazón



Nopalera en el corazón was an art exhibition on Nopal held in January 2026 in the Zócalo of Mexico City. The exhibition, promoted by the Secretaria de Cultura de la Ciudad de México, aimed to promote the artistic promotion of Nopal as a national, mythological, and resistance symbol. Over 200 sculptures were displayed in the main square of the Mexican capital, all works by independent artists, artisans, and local collectives, with themes ranging from the relationship with pre-Hispanic culture to current issues, both social and cultural.

UACh knowledge spreading

S

Universidad Autonoma Chapingo is one of the most important agricultural universities in Mexico and Latin America. Initially, the name under which it was founded in 1854 was “Escuela Nacional de Agricultura” and its slogan is “teach the exploitation of the land, not of man” (in Spanish “Enseñar la exploitación de la tierra, no la del hombre”). Over the years, the UACh has developed specialized expertise in agriculture and has also developed scientific research on Nopal, its cultivation, and alternative uses. Collaboration between rural communities dedicated to growing Nopal and the University’s experience in agricultural science innovation can increase crop yields and improve the social and economic situation of communities.

Nopal Workshops and Hackathons

L

Collaboration between rural communities and universities can also extend to the design of workshops for rural communities themselves to disseminate skills related to the uses of Nopal outside the agricultural and gastronomic sphere. Hackathons can be created with the aim of finding solutions to the daily or specific problems of Nopal cultivation, while workshops can be used both to disseminate design derived from Hackathons developments and to disseminate existing expertise on the alternative use of Nopal, such as water purification, home biogas production, and other design solutions.

IIINOCA

A

The International Research Network is Innovation of Nopal and Other Cactaceae (in Spanish “Red de Investigación y Innovación de Nopal y otras Cactáceas“) is a network dedicated to the valorization and development of prickly pear cactus that brings together experts, researchers and producers in the sharing of scientific knowledge and agricultural practices. The network’s Mission is to be a space of excellence in research and innovation of Nopal and other cacti for human development. The network involves three universities: the Universidad Michoacana de San Nicolás de Hidalgo, the Universidad de Guadalajara, and the Universidad Nacional de Santiago del Estero, and an executive council composed of researchers in animal nutrition, human nutrition, materials derived from product processing, and agronomists.

Water purification with Nopal

M

The ability to remove heavy metals, arsenic, and turbidity from waters in an area with low drinking water availability makes growing Nopal perfect for arid Mexican areas, which suffer from this very problem. The simplicity of the operations, combined with the ability to carry out all the procedures without the use of machinery, makes water purification through Nopal mucilage a concrete choice for rural populations far from the infrastructure of large population centers.

Circular organic Nopal fertilization

S

Many Nopal farmers add pruning-derived Nopal waste to the cycle of common organic and chemical fertilizers. Addition can be done either with freshly pruned Nopal or by burning it and distributing the ashes, as they are particularly rich in potassium, which aids the growth and production of the plant.

Expanding the “scozzolatura” technique

S

For decades, Italy, more precisely Sicily, has been characterized by a large production of prickly pears. Over time, cultivation techniques such as “scozzolatura” have developed, which consists of removing the flowers during the budding phase and then forcing a new generation of flowers. The delay caused by this technique allows the ripening of the fruits to be moved to the period of September-November, which are called in slang “bastardoni” (in Sicilian “bastadduni”).

DOP mark for Nopal

M

Given the production history of prickly pear cactus in Italy, with DOP brands for fruits grown on the slopes of Mount Etna, one possibility of de-stigmatizing Nopal lies in the comparison of Mexican cacti with quality awards similar to those found in the boot.

Improved production of Nopal Bio-polymers

L

The production of biopolymers from Nopal is one of the fields that has received the most attention from the scientific community. Although the current state of the art has not yet surpassed the scale of laboratory synthesizations or home use, it has demonstrated significant potential, especially in its use as biodegradable food packaging.

Universidad Itinerante Internacional del Nopal

A

It is a traveling academic and scientific event, initially developed in Morocco from the idea of Moroccan engineer Aithamou Abderrahmane, which saw its first edition held in 2006. The aim of the travelling university is to create a scientific sharing network for the exchange of agricultural and processing know-how and to increase the focus on sustainable development.

Challenges and Opportunities

Politecnico di Torino

Description

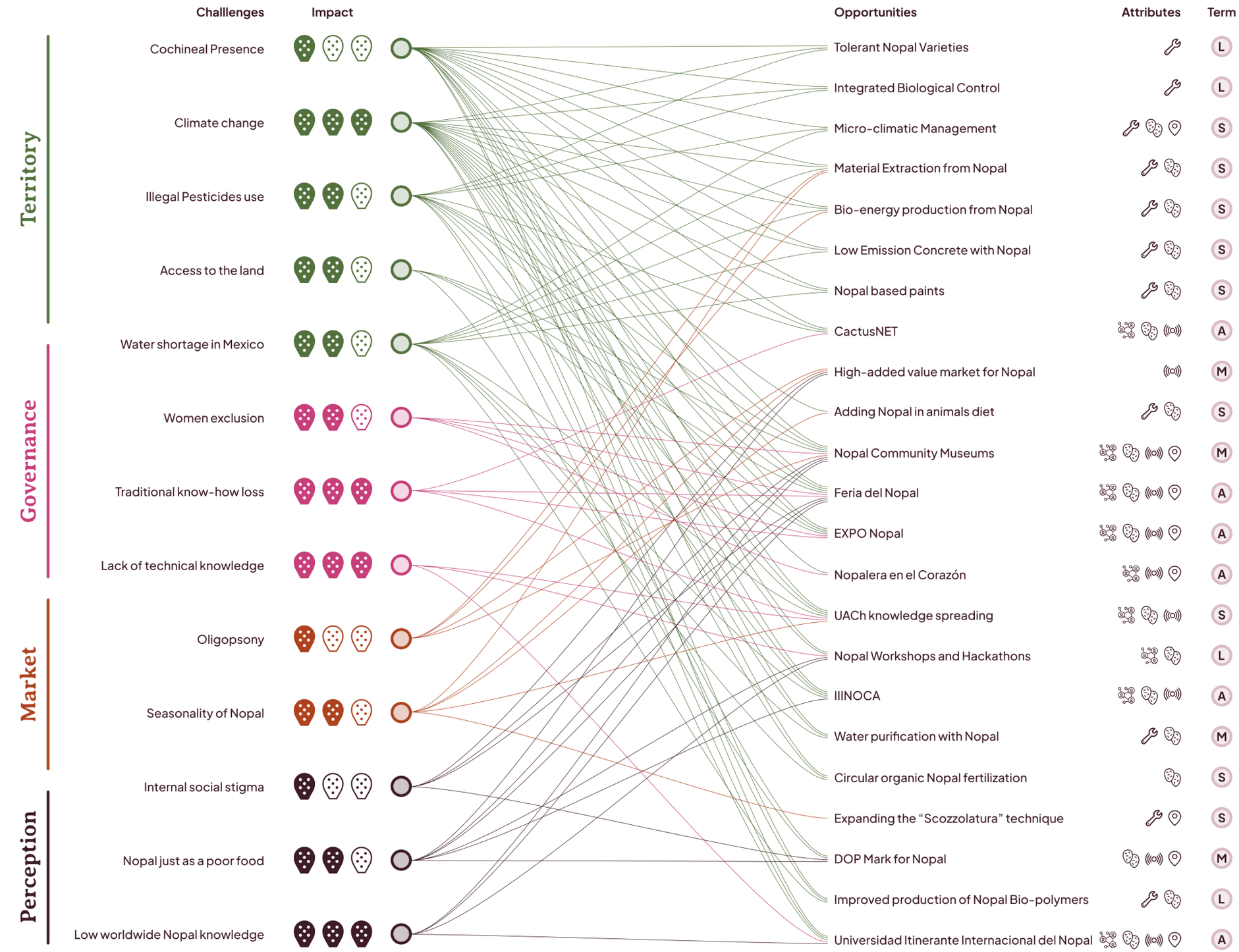
The Challenges and Opportunities map translates the critical points identified in the Holistic Diagnosis into a structured field of possible interventions. Fifteen documented challenges are grouped into four systemic categories, each challenge is linked to one or more opportunities. These opportunities, already active initiatives within the nopal ecosystem or original interventions proposed by already existent studies or this thesis, first among them the Ruta del Nopal. This distinction between existing and proposed opportunities allows to build a communication strategy that extends real precedents rather than inventing solutions in isolation.

Legend

- (A) Active
- (S) Short Term
- (M) Mid Term
- (L) Long Term

Attributes

- Technological: to realize, analyze, improve or update a technology or a methodology.
- Community: grouping, activating, or connecting people and cultures for the creation or identification of networks.
- Development: human, social, or economic development from the application or acceptance of nopal as a resource.
- Communication: translate, spread, or exchange knowledge and narratives to align stakeholders, build awareness, and bridge systemic gaps between communities.
- Territory: to contextualize, adapt, or locate systemic solutions within specific environmental, spatial, geopolitical and social boundaries.



Systemic Approach

6



6.1 Strategy

The project strategy, based on several systemic project proposals, aims to operate on three different sides: economic, social and environmental.

From an economic point of view, as already examined, the population of Milpa Alta lives thanks to the cultivation of Nopal in an oligopsony regime that does not allow it to have bargaining power in the selling prices of the raw material. Furthermore, the strong seasonality of the product means that there is a large supply in a limited period of time, which results in a significant loss of product and therefore economic loss.

The social problem, given the stigma that the Nopal community carries with it, is that of poverty, of a society that seems unable to organize itself to improve its social situation. This is a false fact, since the communities of Nopal have been living in a situation of almost total self-management for decades, thanks to the municipal demesnes. These rural communities are already perfectly and consistently educated in self-management processes and therefore already ready for a next step.

The environmental problem is certainly based on the quantities of unsold Nopal that necessarily becomes waste, and therefore on waste, but also on the need to find a solution to energy production that allows the renewable use of material that already exists. Although actual studies on Nopal are almost in their infancy, it has already been demonstrated how cactus has the potential to become an even more important resource than it already is.

In addition to the numerous uses that were analyzed in Chapter 4, there is another factor to consider such as the ability of Nopal to grow in environments where other plants would have no chance.

Extending Nopal cultivation-unlike what often happens to other plantations when they become intensive or industrial-does not threaten the removal of land for other purposes necessary for human sustenance, making it a highly potential choice for communities seeking rebirth, redemption, or a better quality of life.

The solution representing the best strategy sees a system where the community remains at the center, together with Nopal itself: the culture, history, myth and legend that were created behind the cultivation of Nopal should not be set aside or received as if they were of lower value than the economic return, but rather, they are part of the same thing.

The establishment of a community museum in the Alcadia of Milpa Alta, directly managed by the community, can revive the value of pre-Hispanic rural culture and generate a responsible tourist flow that does not undermine the authenticity of rural life or the quality of the gastronomic product. Museum exhibitions can take place in the central squares of Ciasun Pueblo Originario, as, on municipal land, squares are explicitly created as social and sharing places, with the contribution of funds allocated by the Mexican government to rural communities.

The 12 Pueblos Originarios have stories and cultures that have certainly met several times, but which remain in their own right, which cannot all be summed up together to form a single common history.

For this reason, a subsequent extension of the community museums to all 12 Pueblos Originarios is planned, so that 12 different stories can be told, with their cultivation techniques, tools, and the pride of being part of such a community. The emergence of new, more limited community spaces allows self-managed communities to feel more part of the community itself, highlighting social issues and creating macro groups of people who, through the same social interactions, can find solutions that benefit the entire community.

The waste of Nopal that we are witnessing in the present cannot be made good by a simple reduction in production, as it would be an unjustifiable strategy for families who base their economic possibilities on Nopal production. For this reason, it is needed to identify a path through which waste finds new life and generates a new flow of possibilities: a network of domestic biodigesters that exploit the full potential of biodigestion, that are self-managed by the communities themselves and that return to their benefit.

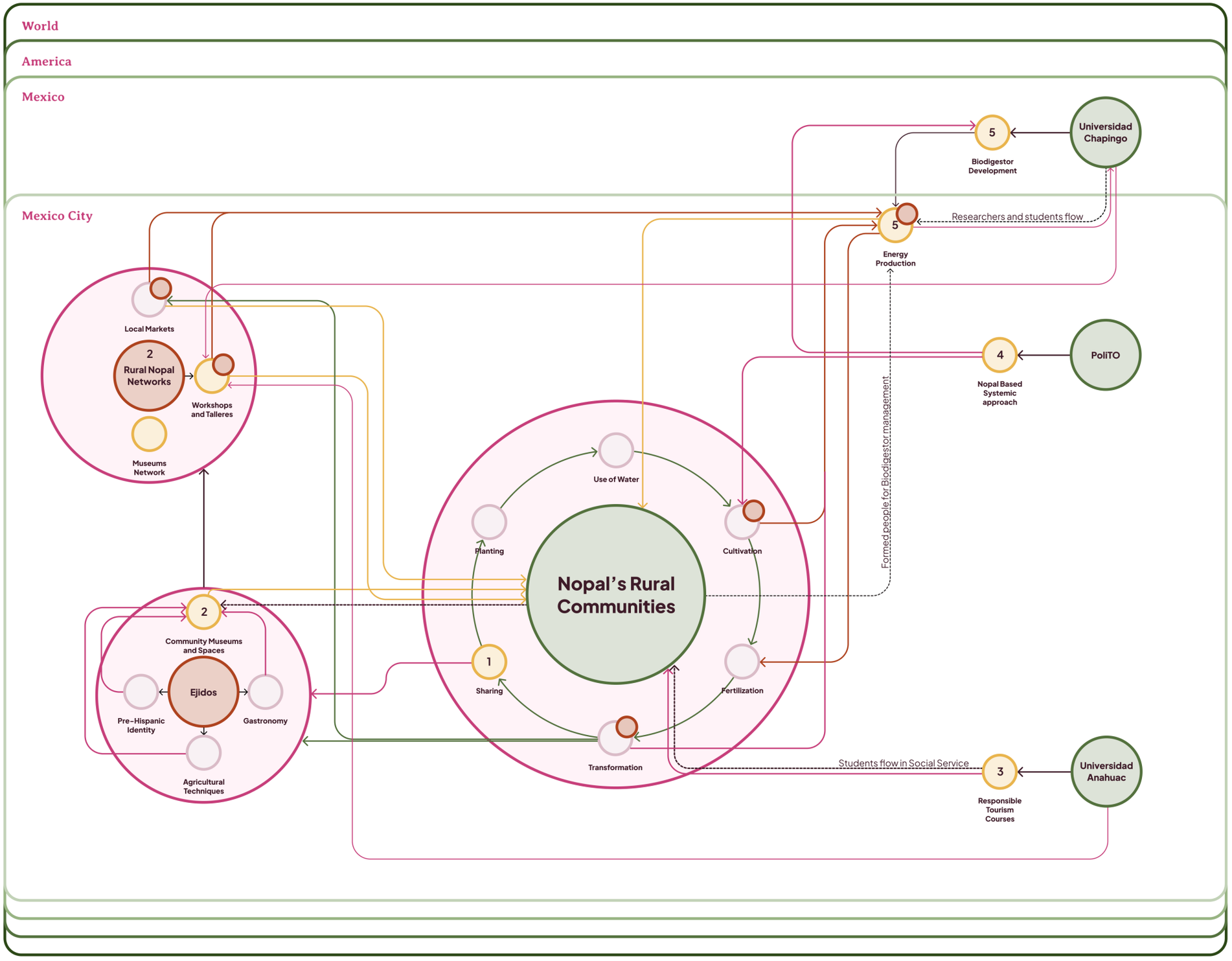
A Nopal and manure-based biodigester[8] would never be a cost-effective choice for a company, as it would have to cover the cost of building the plant, hire staff to use it, and purchase the biomass needed for its operation.

For the communities of Milpa Alta, however, the requirements are already ready: there are funds for rural areas from the Mexican government, there is the potential for media attention from universities (first and foremost the autonomous university of Chapingo, UNAM and the Politecnico Nacional), the communities are already independently responsible as they are accustomed to the self-management of assets, they already produce the biomass of nopal and already purchase the manure necessary for the proper functioning of the biodigester.

[8] Note. Despite an attempt to build a biodigester was already made, the hierarchy behind the project changes completely. It is a known fact around the topic that a technocratic approach in Milpa Alta will surely fail, due to the population tendency to live in a constant self-managing social structure. A new strategy based both on bioenergy production and self management has much more probabilities to be succesful.

System Map

Politecnico di Torino



Legend

- Project Core
- Partners & Stakeholders
- Places and Hosts
- Existent Phases
- Project Phases
- Nopal Waste

Connection · Knowledge Flow
Waste Flow · Economic Flow
People Flow · Resource Flow

Description

This System Map is based on the existance of a rural community which most important resource is Nopal. That is the rural community of Milpa Alta.

1. Sharing

To build the strenght of the community, people need to start sharing knowledge, techniques and resources as a real network: some rural communities built a real intranet to share digital data with a real closed circuit network.

2. Community and Network

In order to share, the Ejido (already a community space) becomes a space to build Network between rural families and farmers.
The thesis research has highlighted that other rural communities built community museums to preserve ancestral culture and techniques, enhancing the economical situation in rural areas and getting a higher social relevance. Later, building a network between community museums will lead to the creation of a cultural path allowing people to know more about Nopal, thanks to nopal based workshops and giving farmers a new income with local markets.

3. Responsible Tourism Course

An Italian case study (AITR - Associazione Italiana Turismo Responsabile) showed how a responsible tourism enhance the added value of the resources from rural areas and allows them to be part of a turistic path without compromise nature and ancestral knowledge.

4. Nopal Based Systemic Approach

Systemic Design allows to build a system for rural areas where waste and by-products becomes resources. Nopal can be used as a stable fertilizant after the biogas porduction.

5. Energy Production

The development of a Biodigestor usable in rural context and by farmers allows rural communities to be less conditioned by economical crisis. The Project will be executed by UACh in collaboration with PoliTO and U.Anahuac.

6.2 Road-map

Nopal community museum

Desk & Field Research

The first ever phase for the conception of community museums is a research phase that is based on the current state of Nopal's production. Desk-type research can be carried out, therefore through the study of documentation on the subject, or Field, with visits to the nopalere and interviews with the producers in order to fully understand the predisposition for a possible application of the project.

Mapping community museums & Mapping the state of the art of community museums

These phases, carried out at the same time, serve to understand the current state of the art of community museums in Mexico and around the world, obtaining useful information for generating subsequent phases.





Defining guidelines

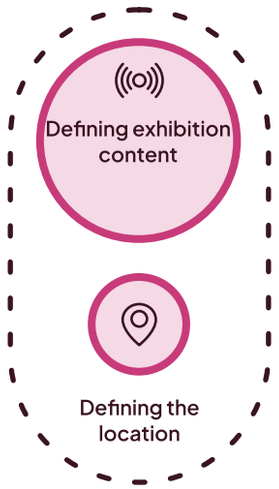
With the data collected from the mapping of community museums, especially Mexican ones, guidelines must be generated that match the possibilities offered by the territory, the preparation of the community and its preservation, including protections for individuals and protected areas.

Analisys for possible location & Defining case studies

In this phase, the physical context of the project is analyzed. Starting from the previously mapped case studies, possibilities are drawn up for defining the location intended for the project

Defining exhibition content & defining the location

In the case of the rural communities of Nopal, the nopalera and the Pueblo become the very theatre of the exhibition. The content of the exhibition must be decided closely with the community, which knows what is right to promote and how to do so. The academic part, in this case, has the function of facilitator, supporting the possibilities offered by the community.



Tourism Training to Rural Community Manager

At this stage, the population is educated in responsible tourism through courses offered by universities. The central theme is the coexistence of tourism with the aim of preserving the territory and the community's identity and culture.



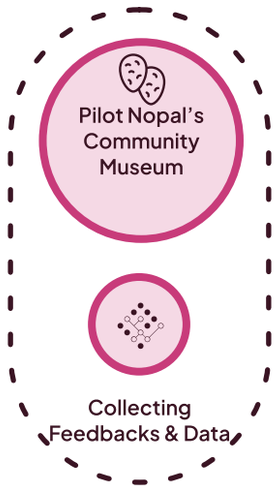
Co-design the location

Universities, together with individuals from the community, design the flow and layout of the museum exhibition, based on previously chosen content.



Pilot nopal community museum & collecting feedbacks & data

The first community museum in the Nopal community is opened to the public. To carry out the exhibition activity, the collection of data and feedback, both from visitors and the community, is added, so as to begin creating a database that allows for the gradual improvement of the exhibition level and the existence of the museum itself.



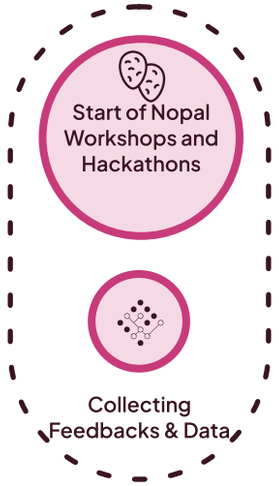
Evaluating socio cultural effects & evaluating political effects

After a medium-long period of museum activity, the broad effect of the museum and its related activities is evaluated. This is done so that the social, cultural and political situation of the community is monitored, with a view to facilitating its existence.



Start of Nopal Workshops and Hackathons & Collecting Feedbacks and Data

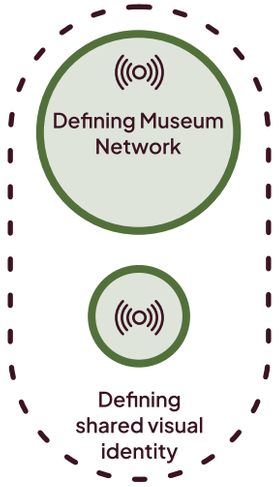
The first workshops and Hackathons start, based on daily problems of the communities and basing the outcomes of the projects on the innovative use of Nopal's resources. At the same time, it will start the collection of feedbacks and datas made for the optimization of the projects and the collection of project request by the community itself.



Network of Nopal Museums

Defining museum network & defining shared visual identity

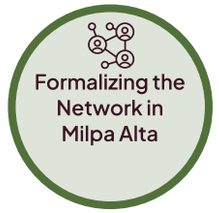
In this parallel phase, stakeholders prepare to network. The first step is to define a common visual identity that leaves room for individual communities to express their personal identity.





Developing a shared channel for museums

A web channel is developed that encompasses the entire museum system with pages dedicated to individual museums and communities, giving visitors the opportunity to learn about the local reality from a distance.



Formalizing the network in Milpa Alta

It is necessary to formalize the social network that is being created through the creation of a common association that allows for direct dialogue with local institutions to protect communities. At the same time, the web channel for sponsoring the museum network is opened to the public.

Opening two new community museums & collecting feedbacks and data

In the long term, two more community museum locations are planned to open, allowing for exhibitions by other rural communities in two more of the Pueblos Originarios. At the same time, the same data and feedback collection carried out in the pilot museum is carried out.



Expanding museums in all twelve towns

In the future, a community museum is planned to open in all twelve Pueblos Originarios, expanding the museum network and participation in the network.

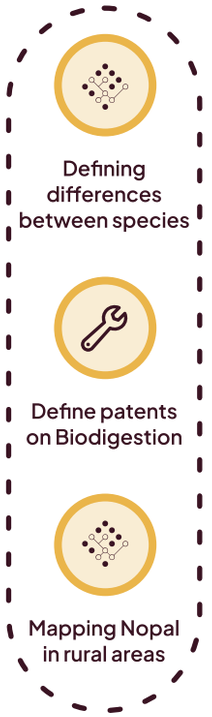


Nopal Biodigestor for energy production



Research on the state of the art of Nopal use

Research is needed into the possible current uses of Nopal. The aim is to weave a network of information that allows us to explore the functions of the materials extracted from the cactus



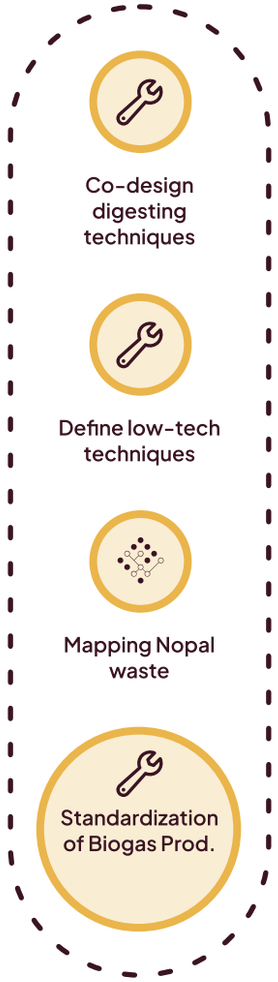
Nopal mapping in rural areas, define patents on biodigestion & defining differences between species

In order to obtain a database useful for the continuation of the project, the entire availability of Nopal within the Alcaldía of Milpa Alta is mapped and patents on the production of biogas from Nopal cladodes (for example that of Nopalimex) are searched. Furthermore, research is carried out on the possible performance difference between the various Opuntia species, in order to attest to the possible use of individual species within biodigesters.

Interview with rural Nopal Producers

Interviews are conducted to assess the producers' willingness to participate in the project. In the long term, it is appropriate to map the entire population of the entire Nopal-producing population of Milpa Alta, also in order to explain its functioning, direct benefits and ensure its participation.



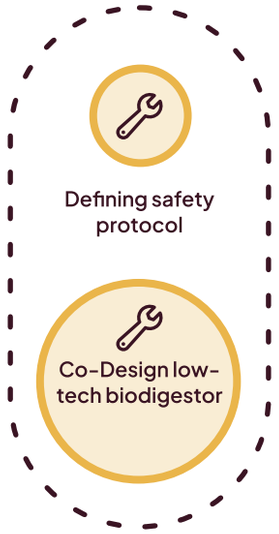


Standardization of biogas production, mapping Nopal waste, define low tech techniques & co-design digesting techniques

At this technologically crucial stage, potential biodigestion methods are evaluated and the waste production chain is mapped to identify critical points. Subsequently, low-tech biomass collection and cleaning techniques and digestion techniques must be defined, so that a common methodology beneficial to rural communities can be applied.

Co-design low tech Biodigestor & defining safety protocol

Universities, together with rural communities, are designing a biodigester, regulated by the quantities of biomass available and the logistics of the collection chain. Furthermore, a protocol is defined in case of danger due to the hypothesis of biodigester malfunction, also defining the safety personnel.



Defining Nopal circular economy, LCA impact evaluation & define supply logistics

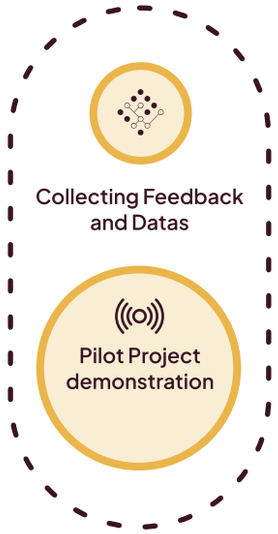
Starting from the results of the interviews, universities plan the circularity of Nopal's resources, from biomass collection to the redistribution of energy and digestate usable as fertilizer. The life cycle impact of nopal biomass and the achievable benefits are also evaluated.





Biomass optimization, test on different mixes, comparison with competitors

Tests aimed at optimizing the biomass used in the biodigester are being carried out, with the financial support of Mexican federal programs, testing different mixes of Nopal biomass, manure, and water. Finally, the difference in energy production compared to other types of biomass is evaluated.



Pilot project demonstration & collecting data and feedbacks

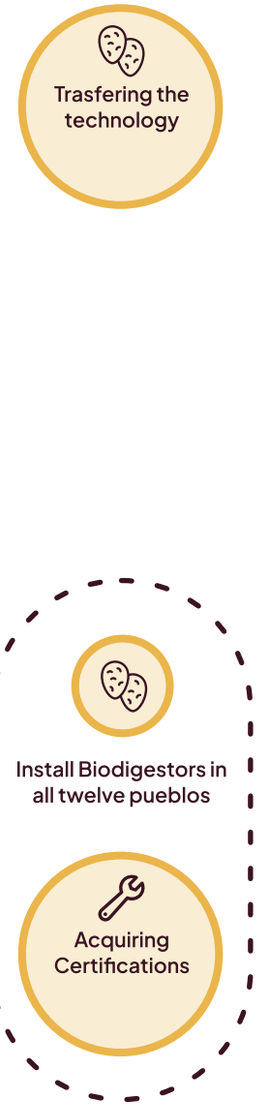
The first biodigester from the Milpa Alta community is created and its potential in the field is evaluated. At the same time, data and feedback are collected aimed at improving the relationship between the community, universities, and local sustainable development.

Transfering the technology

Training courses aimed at the direct management of the biodigester by the community are carried out. Following training, the technology is left in the hands of the community, which will be the sole beneficiary. Subsequently, experts, researchers, and students will be sent to scientifically evaluate biodigestion, apply corrections, and maintain the plant.

Acquiring certifications & expanding the network of biodigesters

In the future, once biodigestion technology has improved, universities, the government, and the rural population will be able to proceed with the acquisition of green and eco-friendly certifications. Furthermore, the expansion of the plants within Milpa Alta is planned in order to create a network aimed at completely eliminating the waste biomass thrown into landfill.



Roadmap

Politecnico di Torino

Opportunities

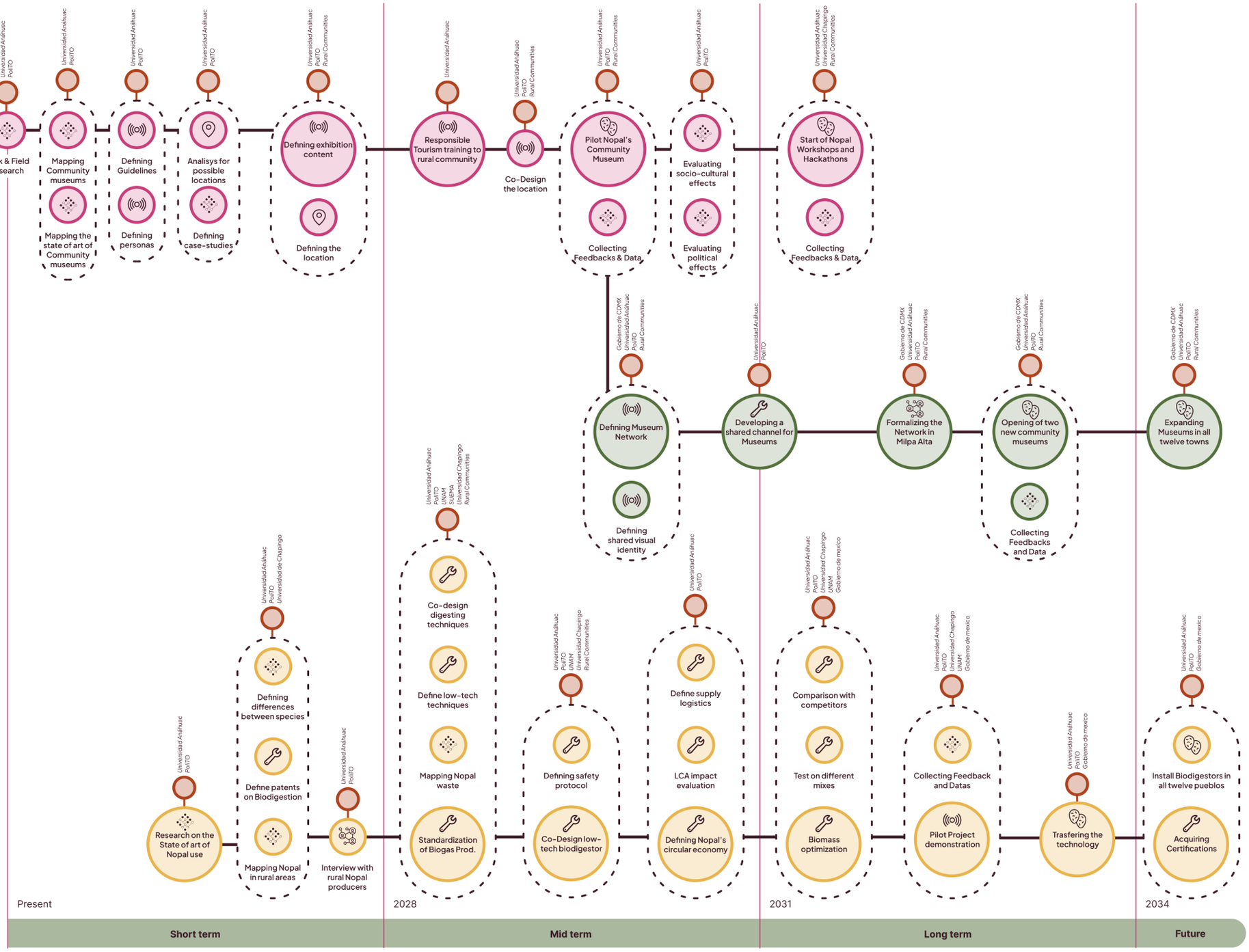
- Nopal Community Museum
- Network of Nopal Museums
- Nopal Biodigestor for energy prod.

Legend

- Primary Action
- Secondary Action
- Groups of actions (To make at the same time)
- Stakeholder

Attributes

- Technological: to realize, analyze, improve or update a technology or a methodology.
- Community: grouping, activating, or connecting people and cultures for the creation or identification of networks.
- Development: human, social, or economic development from the application or acceptance of nopal as a resource.
- Communication: translate, spread, or exchange knowledge and narratives to align stakeholders, build awareness, and bridge systemic gaps between communities.
- Mapping: collect, visually represent, or analyze spatial and quantitative data regarding material flows, resources, waste volumes, and system boundaries.
- Territory: to contextualize, adapt, or locate systemic solutions within specific environmental, spatial, geopolitical and social boundaries.



6.3 Circular Design and economy

The solutions presented have the additional objective of minimizing the quantity of Nopal that ends up definitively in landfill with circular solutions. The goal is to get as close as possible to the model presented by Gunter Pauli (2010) in the book “Blue Economy”.

Nopal waste, which accounts for approximately 60% of the entire product share, is currently not used for any purpose, negatively impacting the carbon footprint of the entire Nopal production chain without generating any value or resources. Within the solutions evaluated during the thesis, biogas production from biomass represents the most profitable and reproducible solution, independently managed by an already well-established network of producers. The presence of small biodigester plants within the individual Pueblos Originarios allows producers to deliver their waste at any stage of production, from cultivation to sale, including pruning and cleaning. If one of the initial problems of the Villa Milpa Alta biodigester was the possibility of delivery by producers, the widespread and decentralized presence of individual plants makes delivery easier. This allows producers, starting from Nopal biomass, to produce biogas and also receive stabilized biomass to use as fertilizer, restoring the energy used to produce waste to the earth.

6.4 Museum's governance

The governance of the pilot rural museum and subsequent expansions to the remaining Pueblos Originarios is intended to be entirely entrusted to rural communities, ensuring that each Pueblo has its own community space to manage, given the cultural differences within Milpa Alta, which must be valued and protected rather than mixed, risking distorting its identity.

The governance model aims to draw on what was already seen during the analysis of the case studies, with examples mainly concerning the Museu de Favela, the Diffused Urban Ecomuseum and the Yucatan Community Museum Network. The rural population applies its decision-making power through the Assembly of Pueblo and Common Goods, already institutionally present in the territory.

The main reason driving towards this type of fully self-managed governance is the rejection, by the local community, of any form of centralization and privatization (which, among other things, conditioned the failure of the SUEMA project), since it has been demonized by the processes of land expropriation and privatization to the detriment of farmers.

In order to better and more controlled internal management of the museum, it is proposed to establish the Community Museum Committee for each Original Pueblo in the area, consisting of a section dedicated to the History and Know-How of the population and another section dedicated to the Exhibition Project.

The Population History and Know-How section was designed to be composed of older members of the communities, able to collect testimonies on the oldest Nopal harvesting techniques, community history, and pre-Hispanic history, generally passed down verbally.

The Exhibition Project section, on the other hand, was designed to be entrusted to young people aged between 18 and 30, which allows them to be actively included in the project and to experiment through Exhibit Design techniques, designing the museum's path and visual identity, which aims to be an outdoor experience.

To do all this, a training activity carried out by Universidad Anahuac is planned for individuals belonging to the Community Museum Committee. The goal is to train the population in a responsible tourism experience, as already seen in the example of the AITR (Associazione Italiana Turismo Responsabile), which allows the valorization of indigenous culture and the cultivation of local Nopal without compromising.

To this end, students from the University of the Department of Tourism are directed to Milpa Alta for part of the Social Work projects, required by law in Mexico, and the University will organize Responsible Tourism workshops, providing guidelines useful for the proper functioning of the museum.

These guidelines are listed in the next pages:

Community Museum Free

The museum must allow access to anyone without the obligation to pay a ticket. The museum's financial income must be characterized solely by tips and donations made by visitors, the organizations involved in the project, and related associations.

Respect for the Suelo de Conservacion

Tourist flows must in no way affect the integrity of the territory. To do this, flow planning is necessary that does not disturb the ecosystem and tranquility of the Pueblos Originarios.

Sovereignty of the Community Museum Committee

No project can be undertaken without the approval of the Committee and, consequently, of the local population as the sole custodian of the common good.

Rejection of the Folklorization of culture

Technical knowledge, the history of the people, ancient languages and the general culture of the people must not be reduced to spectacle for external consumption alone but must remain under the ethical and narrative control of the community.

Transparent management of the Reserve Fund

Any revenue generated by the Community Museum must be recorded within a transparent common fund, accessible at any time to each community member and intended to be used only for the maintenance of common assets.

Ecological responsibility education

The museum and the rural community must educate visitors to be aware of the role of agriculture within society and to respect plant and animal species.

Academic training and horizontal dialogue

The participation of universities in the training of rural communities must never take a form of vertical education. For the museum to function properly, a co-design process based on equal respect between academic knowledge and rural knowledge is necessary.

Internal solidarity

For the ethically correct functioning of the network of museums that will be generated by the project, the absolute absence of competition between the proposals of the twelve Pueblos Originarios is necessary, which must act synergistically in order to preserve the visibility of all the communities present in the area.

Within the museum sphere, in this case seen as a community space dedicated directly to the communities themselves, workshop and hackaton events will be held to develop project solutions dedicated to issues exposed by the population. To do this, in addition to students from the Universidad Anahuac, students from the Universidad Autonoma Chapingo (UACh) are also involved, drawing on the academic and agricultural experience of the scientific center.

These workshops will focus on using Nopal as a raw material, developing solutions to empirical issues such as water scarcity or the construction of domestic infrastructure. To define the issues, individual citizens can contact the Community Museum Committee by formally submitting a request for intervention. Subsequently, the Committee will act as an intermediary with academic institutions, arranging common spaces for events and communicating with universities.

6.4.1 Museum expected effects

The expected effects of the museum's presence mainly concern the well-being of the community and their recognition at the social level.

In particular, an increase in tourism flows in the area is expected, with a consequent economic revenue derived from tips and donations made explicit in the guidelines.

In the social sphere, however, the museum can strengthen the identity of the community and the common good, increasing direct protections for the Suelo de Conservacion, making possible land speculation less likely. Furthermore, the presence of an institution like the Community Museum Committee could put a damper on the youth depopulation of rural areas, providing opportunities for active participation for young people, also connecting them with the academic environment and the opportunities that can exist by combining university and agricultural careers.

Greater attention is also expected to community issues, both social and material, through the development of highly feasible domestic methodologies and technologies such as turbid water purification, concrete waterproofing, and the production of natural paints, all technologies feasible starting from Nopal.

One example of this process is based on the design of a flyer to distribute to the population with the instructions on how to purify water. The flyer is supposed to be designed by the academic istitutions included in the project, starting from the needs of the rural communities developed inside of the community spaces.

For the feasibility of the project, it is supposed that a request for that kind of issue is submitted by some people part of the community. After that collection of request, made inside of

the community spaces of the museum, a Hackathon event is supposed to be planned to put the community and the universities in communication.

During the Hakcathons, the participants (mostly students and people from the community) will focus on the problematique and develop a design solution with the facilitation of the university professors and other students.

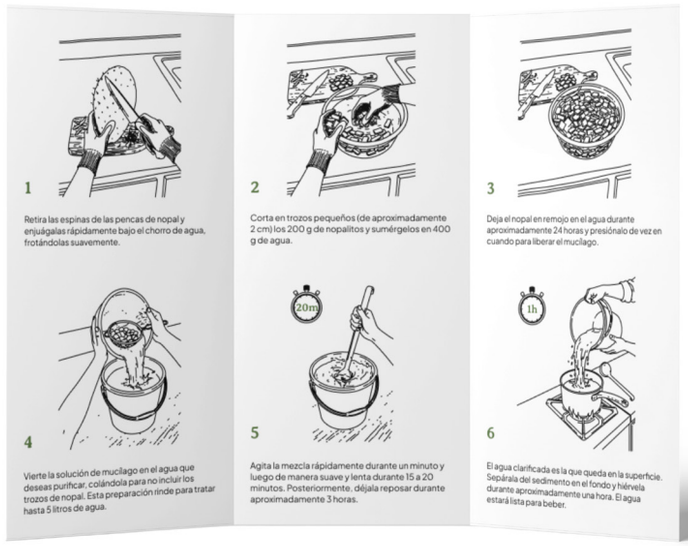


Image 17: An example of a flyer designed in the Hackathons

6.5 Biodigestor's technical support

The construction of the pilot biodigester and its subsequent extension to the various Pueblos Originarios relies on the numerous non-repayable government programs that both the Mexican Government of Mexico and the Mexican state are making available, which will be explored in more detail in a dedicated section.

Technical training is entrusted to the Universidad Autonoma Chapingo, which has already undertaken extensive research and publications on biodigestion starting from Nopal cladodes. The university in this case would play a twofold role: on the one hand, the training of staff from the local community through specialized training courses, and on the other, the periodic inspection of the facilities to evaluate their proper functioning and collect data useful for scientific research and the further affirmation of the university center as an authority on the topic. By doing so, the university's research division would provide a place to evaluate the long-term effects of biodigestion through the periodic referral of field researchers and students specializing in social work, thus collecting data and simultaneously expanding their expertise in academic research.

In addition to the University, the role of technical facilitator is given to the Gobierno de Mexico, which, as already demonstrated in the case study of the SUEMA biodigester, can provide both financial funds and technical expertise to train local individuals.

The role of technical training and university and government oversight to protect the biodigester, its operation, and rural communities is necessary to control values that, if altered, could lead to inefficiencies within the plant. For example, it is necessary to monitor the Carbon/Nitrogen ratio inside the chamber, to avoid excessive acidification of the biomass or the internal temperature which, if not controlled for a long time, could cause the internal pressure to increase with the risk of explosion of the plant.

At the end of the training periods for individuals from rural communities, a training certificate may be issued (by the university or the government), recognizing their professional competence.

Furthermore, within community spaces, manuals can be written in collaboration with universities that allow future generations of biodigester staff to facilitate their training in this regard, using accessible and non-academic language.

6.5.1 Biodigestor expected effects

Considering what scientific studies have previously stated, approximately 40,000 tons of Nopal waste are produced annually in the Milpa Alta nopaleres, which can be used entirely within the biodigester. To these quantities could be added biomass derived from unsold throughout the supply chain, but this is a consideration that is left to future developments.

All calculations on the possible biogas production, starting from the ratios between Nopal biomass, manure and water and the production of biogas and digestate, were made in close reference to the study by Ramírez-Arpide et al. (2019), in such a way as to have a clear and truthful approximation of the potential of biodigesters.

As explained in the table, considering the hypothetical case that all waste material is delivered to the various biodigesters in the network, the input materials would be 40 thousand tons of Nopal waste, approximately 13 thousand tons of manure (which producers already purchase in abundance) and water to dilute the compound, for a total of approximately 124 thousand tons of total input material. With these values, production capacity amounts to more than 1.6 million cubic meters of biogas and more than 120 thousand tons of digestate directly usable as stabilized fertilizer. This fertilizer turns out to be the replacement equivalent of about 240 t of urea, 95.5 t of triple superphosphate, and 280 t of potassium chloride, all chemical fertilizers that are already integrated into the plant's nutrition and can be replaced.

In detail, the operating values of the biodigester network are illustrated in the following table.

Estimated Production from the Milpa Alta biodigester network		
Typology	Day	Year
Input		
Nopal Waste	*~110 t*	*~40.000 t*
Manure	*~65,5 t*	*~13.340 t*
Water	*~194 t*	*~70.830 t*
Output		
Biogas	*~ 4.550 m³*	*~ 1.660.400 m³*
Digestate	*~ 338 t*	*~ 123.460 t*

Table 1: Energy production for Nopal Biomass

Among the effects achievable by this biogas production, it is certainly possible to mention the reuse of waste, which currently ends up in landfill without any valorization. Furthermore, it is possible that the biogas produced can be resold to third parties, generating an economic income directly proportional to the price of the biogas, which will only be converted later into biomethane (approximately 996,200 m³ can be produced in a year).

A secondary effect could be a slight increase in the bargaining power of Nopal producers, resulting in a (albeit slight) increase in the selling price of the raw material, as there would be a slight trend towards using Nopal for the benefit of individual producers (biogas production and fertilization), causing a slight decrease in supply.

6.6 Economical Feasibility

The construction of the pilot biodigester and subsequent ones requires financial support from local and national institutions rather than the creation of museum itineraries, without which it would be impossible to build such infrastructure.

As with the calculation of biodigester production in the previous paragraph, the cost calculation is also done in reference to the plant cited in the research by Ramírez-Arpide et al. (2019), with a view to obtaining a more truthful result despite the different production volumes.

All the equipment needed to build a plant capable of producing only biogas, without transforming it, would consist of: a biodigester, a blade shredder, a loading pump, a recirculation pump, and a mixer. This set, would require an initial investment ranging between 40 and 50 thousand euros (800 thousand - 1 million pesos).

If you wanted to produce energy on site, you would need to add an electricity generation turbine and a system for connecting to homes, bringing the cost of the entire system to around 70–80 thousand euros (1.4–1.6 million pesos).

Surely, in the event that the plants were to be extended to benefit as many people as possible, the total cost would be lowered due to scale factors.

Fortunately, Mexico presents various programs to finance these projects, allowing the use of non-repayable funds to protect indigenous communities, promote the social development of rural communities, and develop eco-sustainable technological solutions.

The opportunities offered by the institutions are set out in the next page.

Altépetl Bienestar - Secreteria de Medio Ambiente SEDEMA CDMX

“Altépetl Bienestar” is a project born explicitly for rural development and to help individual agricultural producers or entire communities through non-repayable economic provision and technical support for technological and social development projects in the common lands. The project is constantly growing, in fact, if in 2018 250 million pesos (about 12 million euros) were allocated, nowadays 1100 million pesos (about 55 million euros) are allocated.

PROCODES - Programa de conservación para el Desarrollo Sostenible

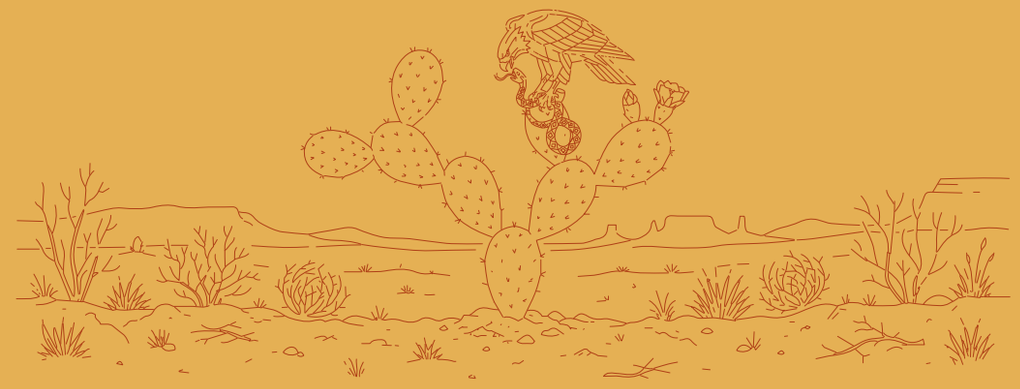
PROCODES is a federal program of the Secretaria de Medio Ambiente y Recursos Naturales that provides direct economic support to local communities to implement projects for the conservation and sustainable use of natural resources in protected natural areas, such as Milpa Alta. The aim is to promote the social well-being and ecological exploitation of entire communities, making innovative actions involving groups of individuals easier.

PROBIPI – Programa para il Bienestar Integral de los Pueblos Indígenas

The programme for the integral well-being of indigenous peoples has been allocated by the INPI (Instituto Nacional de los Pueblos Indígenas) and has as its objective the promotion of collective development, autonomy and the exercise of the rights of indigenous peoples. The programme finances Community and regional production projects covering sustainable activities to conserve natural resources.

Future Developments

7



Future developments regarding the project are intended to imply that the project itself is not an end in itself, but an integral part of a methodology. Such an approach can be scalable or translatable to other places and other types of contexts.

Staying within the context analyzed, there may be interesting prospects for the future, which can improve the conditions of the Milpa Alta community and enrich human knowledge.

It is desirable to raise awareness of the properties of Nopal and the materials that can be extracted from it, which can lead to further optimization of production processes and an increase in cases of application of the use of Nopal as a bio- and eco-sustainable solution. The replacement of substances that can only be obtained by synthesizing them or that require a lot of energy for extraction or solvents and other harmful components can lead to the creation of equivalent products with low environmental impact and perhaps replicable at home.

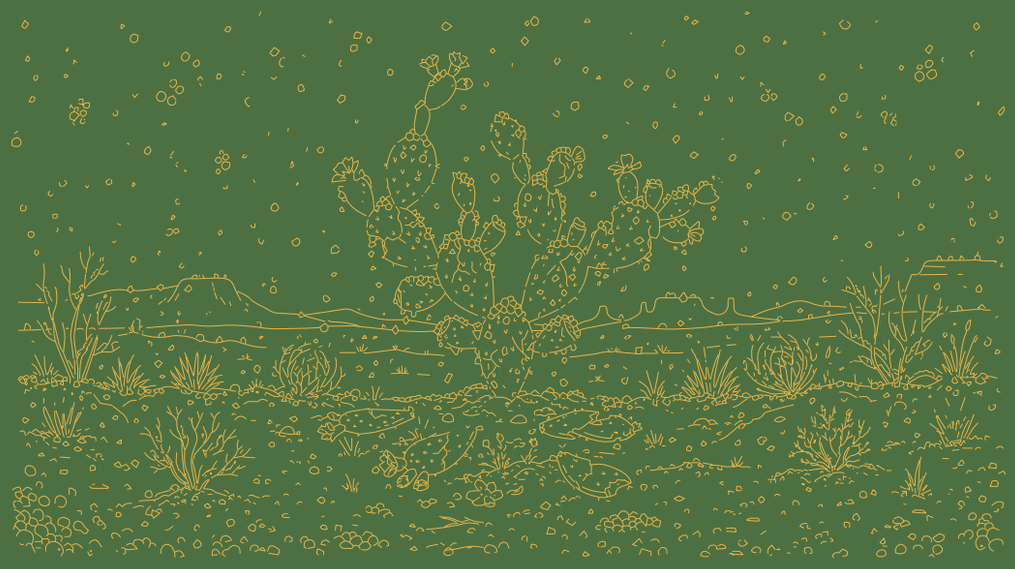
As far as community museums are concerned, one can hope for a greater diffusion of these solutions. A nation like Mexico, which has a particularly complex pre-Hispanic history and is strongly characterized by fragmentation resulting from the presence of multiple populations with completely different cultures, can only treasure its historical and cultural heritage. Community museums allow the expression and affirmation of populations who, alternatively, would find it difficult to gain recognition, ending up losing their traces altogether. An expansion of community museums allows for the preservation of indigenous heritage and the possibility of others learning about it.

In Italy, however, it is desirable to absorb Mexican expertise in Nopal, certainly because the boot is the second largest producer in the world and a wider use option, both gastronomically and scientifically, is a condition that can be used strategically, given the sudden climate change we are witnessing.

Biodigestion, on the other hand, can lead to improved plant efficiency and their potential spread, as they allow for the possible and future production of carbon credits, which can be purchased from other third-party companies and therefore entirely for the benefit of the community that uses them.

Conclusions

8



This thesis project started from the study of Nopal as a planting and cultivation plant, and then evolved into a systemic study on the plant's potential. The crassulacea, as such, demonstrates excellent performance in arid environments and has historically supported the most marginalized populations of Central America. From this, a historical study was conducted, highlighting how the prickly pear cactus is actually a fundamental cultural element: starting with its domestication thousands of years ago, its presence within the Mendoza Code, and, finally, its presence on the Escudo Mexicano and therefore on the Mexican flag.

Despite its strong cultural significance, Nopal cultivation has continued to exist as rural cultivation, in a fragmented context in which there are a multitude of small producers and a small number of strong buyers. This condition is called Oligopsony and results in low, if not non-existent, bargaining power on the part of producers, who are forced to sell agricultural products at too low a price, sometimes failing to cover costs.

To this must be added an alarming figure: approximately 60% of the Nopal present along the entire supply chain (from cultivation to consumption) becomes waste. This condition is dictated by the strong seasonality of prickly pear, which has a high production in short periods and therefore a strong supply in the face of homogeneous demand throughout the year.

To delve deeper into the socioeconomic issue of Nopal, the case study of Milpa Alta, Alcadia of Città, Mexico, and the second largest national producer after the state of Morelos, was used. The Milpa Alta area is considered a common good, and here, farmers have forms of self-regulation that allow them to cultivate the land and raise livestock despite not personally owning any large estates. The conception of the common good, in the Alcadia of Mexico City, is particularly strong and cannot undermine the self-management nature of the territory and its communities.

It is no coincidence that, despite an attempt to reuse Nopal biomass through the construction of a biodigester, a strong rejection and revulsion of the technocracy and private nature of the project was noted, which soon failed, in turn highlighting the failed nature of the vertical and centralized approaches of private projects in Milpa Alta.

Other attempts to use Nopal as an alternative have been made-though not in Milpa Alta-through the production of fake leathers, which, however, have proven to be fully green-washing-focused approaches, proving neither eco-friendly nor biodegradable.

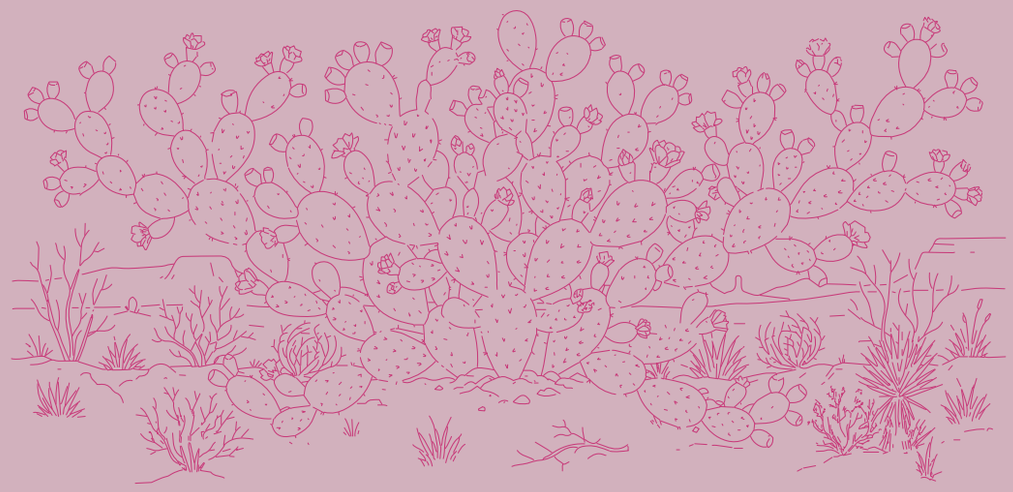
The project proposal is based on the two key points that emerged during the research: the communal nature of the lands and the ability to produce energy from Nopal biomass, and therefore from the approximately 40,000 tons of waste produced in Mexico City each year.

The project includes the establishment of a pilot community museum and a community, self-managed biodigester, which would then expand to all 12 Pueblos Originarios in Milpa Alta, directly benefiting the rural communities themselves.

Following existing case studies, the museum is not conceived as an enclosed space within walls, but as a field, a place of daily life, and an immersion in the activities and history of rural communities. With the collaboration of academic institutions, they develop a museum itinerary that allows for the generation of controlled tourist flows within rural areas.

At the same time, biodigesters would not only allow energy production from Nopal biomass, but would also return a material called digestate: a stabilized fertilizer more effective than manure or chemical fertilizers alone.

In this scenario, Nopal, like rural communities, are brought back to the center of attention, allowing greater knowledge from the outside world, both about the plant's potential and the marginalized conditions of rural populations.



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Consulted the day 14 of April 2026

Sikalindi, italian porducer of furnitures decorated with Nopal:

https://www.sikalindi.it/it/index.php

Consulted the day 14 of April 2026

Ohoskin, italian producers of Nopal and Orange fake leather:

https://ohoskin.com

Consulted the day 14 of April 2026

POLA POLA, Mexican fashion brand of Nopal leather:

https://polapola.mx/

Consulted the day 14 of April 2026

OKA Mexico, fashion brand of Nopal leather:

https://okamexico.com/

Consulted the day 14 of April 2026

Karl Lagerfeld, fashion styilist that used Nopal leather:

https://www.vegolosi.it/moda/karl-lagerfeld-ecco-borse-e-portafogli-in-cactus-per-la-nuova-collezione-sostenibile/

Consulted the day 14 of April 2026

DESSERTO, the most important Nopal leather producer:

https://desserto.com.mx

Consulted the day 14 of April 2026

Handcrafted furnitures made with Nopal leather:

https://www.luteca.mx/shop/p/alacran-chaise-strapping-indoor-6bllghttps://www.luteca.mx/shop/p/alacran-chaise-strapping-indoor-6bllg

Consulted the day 14 of April 2026

Biodegradability of DESSERTO leather:

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Consulted the day 14 of April 2026

DESSERTO - Vegan leather isn't what you think it is:

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https://desserto.com.mx/news/f/%E2%80%9Cif-we-stop-using-leather-240-million-hides-would-be-wasted%E2%80%A6%E2%80%9

Consulted the day 14 of April 2026

SEDEMA - Programa Altepetls Bienestar

https://sedema.cdmx.gob.mx/programas/programa/altepetl

Consulted the day 20 of July 2026

Gobierno de Mexico - PROCODES

https://www.gob.mx/conanp/acciones-y-programas/programa-de-conservacion-para-el-desarrollo-sostenible-procodes-57997

Consulted the day 20 of July 2026

Ecologic Evaluation of the Program Altepetl Bienestar:

https://cedua.colmex.mx/proyecto/evaluacion-socio-ecologica-del-programa-altepetl-bienestar-2019–2024/area-de-estudio

Consulted the day 20 of July 2026

Gobierno de Mexico - PROBIPI

https://www.gob.mx/inpi/acciones-y-programas/programa-para-el-bienestar-integral-de-los-pueblos-indigenas-probipi

Consulted the day 20 of July 2026

Gobierno de Mexico - SEMARNAT

https://www.gob.mx/semarnat

Consulted the day 20 of July 2026

Nopalimex - Energy production from Nopal

https://nopalimex.mx/

Consulted the day 20 of July 2026

SUEMA - Milpa Alta Biodigestor

https://suema.com.mx/

Consulted the day 20 of July 2026

KAKAW - Museo del Cacao y Chocolateria Cultural

https://www.kakawmuseo.com/

Consulted the day 20 of July 2026

Museo de Santa Ana

https://museosantaana.netlify.app/

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Milpa Alta - Zona arquelogica secreta

https://cdmxsecreta.com/zona-arqueologica-de-milpa-alta-secreta

Consulted the day 20 of July 2026

AITR - Associazione Italiana Turismo Responsabile

https://www.aitr.org/

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Consulted the day 20 of July 2026

Red de Museos de Yucatan

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Museo Comunitario Hitalulu

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Red de Museos Comunitarios de Mexico

https://www.museoscomunitarios.org/

Consulted the day 04 of August 2026

Museu de Favela

https://museudefavela.org/

Consulted the day 04 of August 2026

MOSS - Ecomuseo Urbano Diffuso

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Consulted the day 04 of August 2026

MMV - Museo Mare Memoria Viva

https://www.marememoriaviva.it/

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Ecomuseo delle Erbe Palustri

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Consulted the day 04 of August 2026

Ecomuseo della Collina e del Vino

https://www.frb.valsamoggia.bo.it/musei/ecomuseo-della-collina-del-vino-new/

Consulted the day 04 of August 2026

CactusNET

https://www.cactusnetwork.org/

Consulted the day 04 of August 2026

Feria del Nopal - CDMX

https://conoceciudaddemexico.com/en/eventos/feria-del-nopal/1d81a912-1de5-4a60-a2b4-cd6739a12097

Consulted the day 04 of August 2026

EXPO Nopal

https://boletines.guanajuato.gob.mx/2022/05/12/inauguran-la-edicion-xvii-de-la-expo-nopal/

Consulted the day 04 of August 2026

Nopalera en el Corazon - CDMX

https://www.mexicodesconocido.com.mx/nopalera-en-el-corazon.html

Consulted the day 04 of August 2026

Red IIINOCA

http://iiinoca.org/

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Tuna Poblana como desarrollo sustentable

https://www.puebla.gob.mx/index.php/noticias/item/20574–uth-posiciona-a-la-tuna-poblana-como-desarrollo-sustentable-en-foro-internacional

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