Opuntia as a Perennial Food, Bioenergy, and Carbon Capture Crop for Profitable U.S. Arid Zone Development – A Review

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Introduction

The utilization of Opuntia cactus (Opuntia ficus-indica, cactus pear) for arid zone agricultural production and carbon capture has created increased global and U.S interest and research (Neupane, et al, 2021, Debeux, et al, 2022).

Diminishing water resources, food scarcity, and need for atmospheric CO2 removal are currently the most pressing global environmental issues. Opuntia's efficient water utilization, climate resilience, high rate of long term carbon sequestration, and commercially viable multiple product stream, including several foods and bioenergy, provides an ideal crop for mitigation and remediation (Blair, et al, 2021). In addition, cultivation takes place on inexpensive underutilized marginal lands, crucial since 40% of the Earth's area with a population two billion are considered arid zone where water resources and food production are limited. (Dubeux, et al, 2022). Opuntia has the potential to mitigate drought and reverse desertification (Nefzaoui, A., 2014).

Large scale commercial Opuntia plantings are successfully implemented in Mexico, South America, Africa, the Middle East and several other areas, comprising an area of 6.5 million acres (Neupane, et al, 2021). Agricultural development in the United States has been neglected, though no significant physical or financial limiting factors exist, and an existing product market is available. The reasons for this paradox lie in a historical and ongoing lack of knowledge based educational/extension and development activities regarding this outstanding species and its commercial applications.

Opuntia holds high potential for arid zone development, environmental solutions including carbon storage and community enhancement.

A Confirmed Multipurpose Low Input Perennial Crop

Opuntia provides a larger and more diverse fresh and processed product stream than perhaps any other perennial specie, including high water use crops. This creates a favorable economic scenario for growers and processors, providing a wide choice of end products.

Fresh Produce

Due to the large and growing U.S. Hispanic community, sizable markets currently exist for both young vegetable cladodes (*Nopalitos*), and Opuntia cactus pears (*Tunas*), found commonly on store shelves, imported from Mexico and of poor quality. Fresh local Nopalitos and cactus pears from selected and improved varieties have significant advantage, economically viable at current price points.

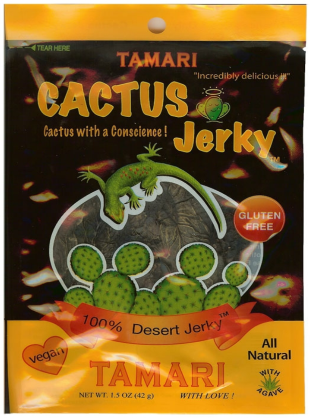
Fruit production ranges from 17,000 to 30,000 lbs/acre. (Neupane, et al, 2021, FAO, 2013). A conservative wholesale price of $1/lb for 17,000 lbs, provides a gross revenue of $17,000/ac/yr, significantly higher than most crops. Almonds are considered a high value crop with a gross revenue per acre of $5500 at the high range. High density Nopalito production yields 40,000 to 80,000 lbs/ac (Hernandez, 2004, FAO 2017), providing profitable margins and opportunities for small holders with five to ten acres.

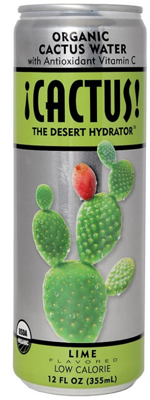


Biofuel and Biogas
Bioenergy crops such as maize and sugar cane are irrigation intensive, consuming 80% more water resources than Opuntia (Nobel, P., 2001). Opuntia field biomass potential averages 135 tons/ac/yr, (Neupane, et al, 2021), highly suitable as feedstock use for bioenergy production (Hussein, A., 2021). Research has been completed identifying a consortium of microbe species suitable for converting Opuntia biomass into biofuel and biogas (Blair, et al, 2021). Opuntia produces biomass with a specific composition proviiding for high production rates of methane (3717 m3 ha-1 yr-1), comparable to traditional high water use energy crops (Taciana, et al, 2016).

Carbon Capture
Opuntia absorbs and stores significant quantities of CO_2 and soil carbon as compared to other annual and perennial crops, as well as the fastest growing trees, detailed below. It is a viable option for sustainable crop production while providing socioeconomic development in rural areas of the South West. The significant level of carbon sequestration opens the possibility for carbon credits and similar mechanisms to assist in building a new agricultural industry on marginal dry lands (Bautista-Cruz, et al, 2018)

Food Processing
Fruit products include beverages, water soluble powder for instant use, puree, jam, sauces and syrup, cactus pear leather, ground seed products and liqueur. Nopalitos may be dehydrated for non refrigerated applications, and are also used in the production of cactus jerky and other vegan products (Dubeux, et al, 2022).



Neutracuticals and Medicinal
Opuntia contains a significant amount of biologically active compounds, containing vitamins, antioxidants, and various flavonoids such as quercetin-3-methyl ether that can lower cholesterol and act as anti-inflammatory and anti-ulcer agents (El-Mostafa et al., 2014). Numerous supplements are found in the natural product marketplace, including beverages, tea, cosmetics, essential oil, capsules and powders derived the fruit, cladodes, and seeds. High volume wholesale distribution of bulk ingredients to manufacturers is a strong possibility.

Industrial
Opuntia produces multiple polysaccharide compounds and gums, useful in various manufacturing processes including textile, fuel, bioplastic,wastewater treatment, pharmaceutical, medical, cosmeceutical, agrochemical, and pollution control industries (Kudanga, T., Aruwa, C.E. (2021). Biomaterials produced from *Opuntia* species showed high potential for paper and other manufacturing processes. (Hussein, A, et al, 2015). Utilization of agricultural and processing waste streams is possible in this capacity.

Fodder
Mature cladodes are exclusively utilized for nutritious animal feed in many parts of the world (FAO, 2013).

Environmental Remediation
Opuntia cultivation results in several environmental benefits including reduction of desertification and

soil erosion of arid lands, and sustaining a variety of wildlife. It is an excellent option for dry land development and improving the livelihood of rural communities (Dubeux, 2022).

During the initial period for identification of suitable partners for food/supplement/industrial processing and biofuel/biogas production, the existing sizable fresh market may be utilized for the initial income stream. This provides sufficient cash flow to initialize the industry, enhanced with potential carbon credits.

Metabolic Strategies for Water Efficiency, High biomass, and Carbon Storage

Opuntia is endowed with numerous physiologic enhancement mechanisms providing an ideal crop to assist in solving the three pressing environmental issues that humanity now faces – water scarcity, food production on marginal arid zone lands, and carbon capture.

Several solutions providing high water use efficiency are employed. The Opuntia cactus is composed of thick stems known as cladodes, consisting mostly of parenchymal tissue providing a reservoir of enhanced water storage capacity. Cladodes are covered in a thick wax layer preventing most transpirational evaporation, plus an extensive and tuberous root system for water storage. Opuntia cladodes have a lower frequency of stomata than most plants (Nobel, 2001), and roots remain close to the surface for absorption of water from light rainfall.

Opuntia utilizes a highly evolved metabolic strategy enabling minimal water use while simultaneously increasing quantities of carbon fixation and biomass production (Nobel, P., 1998). This process is known as Crassulacean Acid Metabolism, or CAM. Stomatal openings on the cladode surface enables the exchange of carbon dioxide and oxygen needed for photosynthesis and respiration. Typically stomata remain open during daylight hours to absorb carbon dioxide required for photosynthetic production of carbon compounds upon which life depends. Open stomata during daylight hours also necessitates that the plant will transpire water through the same openings, resulting in a significant daily water deficit for most desert and dry land species.

CAM physiology reverses this cycle, with stomata closed during the day and open during night time hours, resulting in high reduction in transpirational losses. With cooler nocturnal temperatures, the stomata open and carbon dioxide is absorbed and stored as organic acids. During daylight hours when photosynthesis is active, carbon dioxide is released from the organic acids, without the need for gaseous exchange via open stomata. Combined with other storage and anti-transpiration measures, Opuntia's water use efficiency (WUE) three times higher than the most highly productive C4 carbon pathway grasses such as maize and sugarcane, and five times higher than other C3 arid zone crops such as alfalfa or cotton (Nobel, 2001).

Cladode organic acid content is evident by the somewhat sour taste of young cladodes (*Nopalitos*) that have not been adequately prepared for consumption. Acid content diminishes throughout the day as it is consumed in the photosynthetic cascade.

CAM is a highly efficient enzymatic process which significantly increases carbon capture and biomass production as compared to non CAM C3 and C4 plants, providing Opuntia with an additional enhancements compared to other perennial crops (Osmond, et al, 2008).

Aside from promoting soil carbon sequestration, Opuntia has been found to increase soil microbial biomass and activity (Bautista-Cruz, et al, 2018). The soil microbiome is essential to plant health, and an important aspect in sustainable agriculture systems.

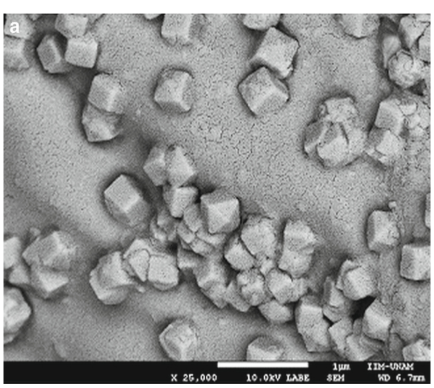
Multiple Carbon Storage Mechanisms with Long Term Sequestration

Medium density Opuntia fields sequester as much carbon as a typical temperate forest, producing fresh biomass of at least 135 tons/ac/yr on average (Neupane, et al, 2021). Most importantly, this takes place on marginal arid lands, with 20% of the water usage consumed by the most productive water intensive bioenergy crops such as sugarcane, maize and switchgrass (Neupane, et al, 2021). In terms of dry mass production, Opuntia can produce up to 50 tons/ha/yr compared to 41 tons/ha/yr for the four fastest growing tree species (Nobel, 2001).

Several strategies are employed for biomass carbon storage, including a high volume of organic acids within the plant, the fibrous endoskeleton, and an extensive tuberous root system. Succulence allows carbon fixation to continue under conditions of severe water stress (Pimienta-Barrios et al, 2012), a mechanism enabling climate resilience.

Inherent in the family Cactaceae, Opuntia has the rare ability for long term carbon storage as the insoluble mineral calcium carbonate (limestone) (Contreras-Padilla, et al, 2015) Calcium carbonate is stored within cactus tissues in micro-crystalline form, becoming evident upon plant decomposition. In addition, roots have the ability to reduce soil organic carbon (SOC) transforming it into insoluble calcium carbonate (Blair, et al, 2021). This is crucial, as SOC will oxidize over time, cycling carbon dioxide back to the atmosphere.

Evidence of significant calcium carbonate storage in stem and roots of two CAM cactus species. (Ariz, Geol., 2021)



Calcium carbonate crystals inside Opuntia cladode tussue

Single closed stomate with surrounding wax scales on Opuntia cladode surface

Opuntia fields have a distinct advantage over forest silviculture where almost all carbon is stored only in organic plant material and SOC, both undergoing rapid fungal decomposition and cycling with subsequent CO_2 release. Coupled with high biomass production, Opuntia thus maintains several strategies insuring a high rate of long term carbon sequestration compared to other species

Agave americana is a dry land specie grown for agave syrup and tequila production and has been considered for arid zone development. Research has shown that Opuntia produces significantly more biomass, captures more carbon, and is more water use efficient with higher climate resilience than agave, plus having a more diverse product stream (de Cortazar et al., 1998).

Atmospheric and Soil Carbon Capture Data

Cladodes of a mature *Opuntia ficus-indica* plant are capable of absorbing and storing 10 lbs of CO_2 per year (Liguori, et al, 2013a). At 700 plants per acre, this equals 7000 lbs CO_2 per acre per year, comparable to an average forest or woodlot (Lal, 2018). Thus to capture one million pounds CO_2 per year would take 140 acres. For 10,000 acres the figure becomes 35,000 tons CO_2/ac/yr. In terms of commercial production, 10,000 acres is an insignificant quantity, for example compared to the current California almond acreage of 1.64 million acres (USDA-NASS, 2021-22). The same area of Opuntia would capture 5.74 million tons CO_2/ac/yr.

A separate study examined CO_2 capture under extreme drought and water stress, with less than 2% soil water content, the point at which typical plants would enter a state of severe wilt. Under these extreme conditions, a one acre Opuntia field was still able to absorb 432 lbs CO_2 in only the three warmest months of June, July and August (Liguori, et al, 2013b).

As atmospheric CO_2 levels increase, dry weight biomass can increase by 23% (Cui, et al, 1994, de Cortazar, V, et al, 1991), a significant factor as CO_2 levels rise.

In terms of soil carbon removal, a single mature Opuntia plant has the ability to remove 6 grams Total Organic Carbon (TOC) per 100 grams of soil per year, which is 9.5 lbs carbon/acre/year per plant (De Leon-Gonzales, et al, 2018), resulting in significant reduction in both C and CO_2 soil emissions.   Most importantly, Opuntia fields maintain SOC at similar levels to forest soils (Bautista-Cruz, et al, 2018).

It is more complex to ascertain total yearly CO_2 removal from C fixation in cladodes plus SOC removal by roots. The figure cited above of 6 grams Total Organic Carbon (TOC) per 100 grams of soil per year, is rather high since most desert soils will have significantly less SOC content. 9.5 lbs of carbon/acre/year per plant would be the equivalent of 34 lbs CO_2 if the soil carbon was oxidized and released into the atmosphere, and a more conservative estimate would be 25% of 34 lbs, approximately 8.5 lbs CO_2 equivalent captured from SOC. That amount plus 9.5 lbs CO_2 per plant per year from cladode fixation provides an approximation of 18 lbs total CO_2 per plant per year.

Carbon dioxide fixation also takes place in actively growing root tips, estimated to be 57 micro litres CO_2 per gram root per hour (Ting, et at, 1966). This is three times greater than what was found in cladodes of the same species. It is apparent that Opuntia has evolved several efficient strategies for CO_2 fixation and storage compared to other species, while using a fraction of water input.

U.S. Data For Cladode Biomass, Fruit Production, and Water Use

A five year Opuntia field trial regarding these parameters was conducted by UNR and published in 2021 (Neupane, et al, 2021). The results demonstrate:

1. Total cladode weight at five years was 675 lbs/plant. At 2000 plants/acre this equals 675 tons/acre over five years, or an average of 135 tons/ac/yr.
2. Total fruit weight at year four and five averaged 17.5 lbs per plant. At 1000 plants/acre this equals 17,500 lbs/acre, a relatively low yield compared to other studies (FAO, 2013).
3. Highest yield of cladodes and fruit was obtained with 700 mm/yr total water input, including rainfall. However, water use efficiency (WUE) peaked near 400 mm.
4. Of the three species evaluated, Opuntia ficus-indica had the highest cladode count, claode dry weight, and fresh fruit weight, and fruit quality (Cushman, J., 2021).

Under favorable conditions, dry mass per hectare was found to be 50 tons/yr, equivalent to 40,000 lbs/acre dry matter per year (de Cortazar, et al, 1992). This compares to 38 tons/ha/yr for the most productive typical crops, and 41tons/ha/yr for the fastest growing trees (de Cortazar, et al, 1992). Opuntia produces significantly higher biomass per acre than other forage crops under water stressed conditions, (Nobel, 2001).

Relevant U.S. data is of thus type is highly useful to mitigate risk and demonstrate the potential of this new crop to stakeholders and growers.

Agronomic Parameters

Cultivation is possible on most desert and dry land soil series found in the U.S. South West, preferably at an elevation between 1800 to 3200 ft. Plant growth and proper ripening of Opuntia ficus-indica fruit is inhibited in the low desert where temperatures commonly reach 110 to 124 F coupled with warm nights (LBCAS 2022). The high deserts of California, southern Nevada, and Arizona present a suitable environment, similar to the native range in Mexican mountain regions. Minimum temperatures should not fall below -5C (23F) (Park, 2001)

Areas with significant South West summer monsoonal activity are preferable for supplemental irrigation, and the majority of the yearly water requirement derives from summer monsoonal rainfall in indigenous areas. Excess soil salinity inhibits Opuntia growth.

Planting distances and densities are dependent on four factors – the nature of land and soil, quantity of irrigation water plus yearly rainfall available, size of field machinery, and planned use of the crop. Opuntia is a low input perennial crop requiring low labor and materials compared to annuals.

Cultivation systems range from wide orchard spacing for fruit production as practiced in Italy at 150-200 plants/acre, to high density hedgerows for biomass/biofuel using mechanical harvesting at 700-1500 plants/acre. Nopalito production necessitates that plants remain at two to three feet in height, and are planted in super high density (SHD) configuration within narrow rows at 2000 to 5000 plants per acre, harvested two to four times/year (FAO, 2013).

Hybrid configurations are possible with management of multi use fields, such as fruit plus nopalito production, or fresh fruit combined with biofuel and cladode processing.


Medium density Opntia hedgerows


Fruit production on a select improved variety


Super high density (SHD) planting for young cladode (Nopalitos) production, at low height

Limitations and Current Needs

The primary limiting factor to implementation of large scale U.S. Opuntia operations remains the lack of developmental, educational and extension activities for growers, processors and other stakeholders. Sufficient propagation of select and improved Opuntia plant material can be produced by large scale micropropagation.

Opuntia lacks major pest or disease issues that limit expansion. The primary pest is the coccineal insect which requires routine monitoring, easily controlled by OMRI (USDA approved organic) pesticides or pressurized plain water. Opuntia requires far fewer inputs and maintenance activities than other crops, a clear advantage.

Aside from identifying suitable partners, investors, and growers, the next step requires a demonstration field of 20-100 acres where results will be clear to all potential stakeholders. Small scale pilot bioenergy and processing lines are needed for proof of concept leading to investment procurement.

Historical Perspective

The U.S. remains the only area of the globe lacking in large scale Opuntia agriculture. This is attributed to the inability to provide education/information flow, identify appropriate stakeholders, and lack of improved and select variety propagation.

In the early 1900s, Luther Burbank developed spineless Opuntia cultivars focusing on several improved fruiting and forage types. Due to his national fame and publicity surrounding the project, much excitement was generated among South West ranchers for use in forage production. Unfortunately, since micropropagation was not available, planting material became a serious limiting factor.

During the past fifty years, various universities and researchers have been involved in collecting and hybridizing Opuntia, mostly fruit and forage utilization. This includes TAMU (Texas A & M University) (Felker, P, 2019), UCR (University of California, Riverside), and CSUC (California State University, Chico) (Nobel, P., 2019), all of which had extensive collections, now defunct.

Private organizations, grants, and capital ventures are needed to bridge the next level.

Conclusion

Opuntia has the rare combination of a true multi purpose, low input, water efficient, profitable carbon capture crop suitable for marginal arid zone lands. Aside from its diversity of products and economic appeal, special relevance is now apparent due an acute need for:

1. Climate resilient crops adapted to increasing water scarcity and elevated temperatures
2. New bioenergy crops for marginal lands
3. Increased long term carbon sequestration
4. Socioeconomic revitalization of the rural arid zone

Opuntia agriculture has the unique ability to assist in simultaneously solving several crucial climate related issues while introducing a profitable industry. With U.S. research data available, it is now reliant upon the private sector to manifest this vision.

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