Colegio de Postgraduados

Sustainable alternative: A forage prickly pear cactus (*Opuntia ficus-indica* L. Mill.) production system for cattle fattening

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ABSTRACT

Objective: In arid regions such as south-central Chihuahua, Mexico, water scarcity and soil degradation affect agricultural sustainability. The forage cactus (*Opuntia ficus-indica*) has proven to be a viable option under these conditions due to its resilience and low water requirements. This study established a cactus production system in a 500 m^2 experimental plot to evaluate soil improvement, water-use efficiency, and economic investment associated with the planting method.

Design/Methodology/Approach: Comparative soil analyses were conducted before and after planting, improved irrigation practices were implemented, and the Baca Urbina methodology was applied for the economic analysis.

Results: Organic matter increased from 0.5% to 2.36%, and essential nutrients such as nitrates, phosphorus, and potassium also improved, while calcium carbonate levels decreased. Drip irrigation supplied 1.5 L over 4.5 h per month, with an initial investment of $50,000 MXN. The economic analysis yielded a net present value (NPV) of $42,075.89 MXN, an internal rate of return (IRR) of 39.48%, and a cost–benefit ratio (CBR) of 2.03.

Findings/Conclusions: The production system reduced potential cattle feed costs and improved water-use efficiency, demonstrating that forage cactus is profitable and sustainable for small producers in arid and semi-arid areas. Seasonal variability and plot size could influence the results, so it is recommended to expand the trials to different scales and climatic conditions.

Keywords: forage cactus, soil restoration, soil improvement, sustainable agriculture, arid regions.

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INTRODUCTION

In northern Mexico, cattle fattening systems face significant challenges due to the limited availability and high cost of forage resources, conditions that are further exacerbated by recurrent drought and soil degradation (Gutiérrez-Luna *et al.*, 2012). These factors have forced producers, particularly small- and medium-scale farmers, to adopt intensive production systems to compensate for pasture deficiencies; however, such systems require increasing investments that hinder their economic viability (Lara-Pulido *et al.*, 2020).

Overgrazing, resulting from excessive stocking rates, intensifies forage scarcity and compromises animal nutrition and welfare (Flores-Ortiz & Reveles-Hernández, 2010). Consequently, traditional forages such as alfalfa, sorghum, wheat, and maize are commonly used; nevertheless, their high costs have driven the search for affordable alternatives adapted to local conditions, among which forage cactus stands out (SADER, 2018). This forage cactus (*Opuntia ficus-indica*) is widely distributed across the country's semi-arid and arid regions, where climatic and edaphic constraints limit the development of conventional crops (López-González, 2008).

This cactus has transcended its historical use in human and animal food to become a sustainable option in agriculture and livestock production, thanks to its drought resistance, its ability to grow in degraded soils, and its contribution to improving soil structure and water retention (SEMARNAT, 2020). Due to its nutritional composition rich in fiber, water, carbohydrates, proteins, vitamins, and minerals, forage prickly pear cactus has become a valuable feed supplement for cattle, goats, and sheep, especially in regions with limited water and pasture (SADER, 2022).

Historically, in Mexico, forage cactus has been used as livestock feed since the colonial period, particularly in arid areas where the scarcity of conventional pastures encouraged its use to sustain cattle during dry seasons (Cervantes de Salazar, 1991). This tradition has persisted and evolved through the promotion of its cultivation to support animal feeding in arid regions, recognizing its capacity to meet part of the water requirements of livestock in hot climates and to contribute to cattle food security (Anaya-Pérez & Bautizta-Zane, 2008). In Chihuahua, particularly in the south-central region, extensive cattle production is fundamental to the local economy; however, it faces increasing challenges associated with drought, soil degradation, and rising feed costs. These factors negatively affect the sustainability and competitiveness of the sector (Lagos-Gómez *et al.*, 2014).

National forage cactus production reflects its strategic importance: in 2022, approximately 12,081 hectares were cultivated, yielding close to 130,000 tons with an average productivity of 10.8 tons per hectare. This generated a significant economic value of around 62 million pesos, with the state of Coahuila as the main producer (SIAP, 2023). These figures highlight the relevance of this crop as a feed resource in arid and semi-arid regions. From an economic perspective, the use of forage cactus can reduce feed costs in livestock production by 40-60%, given that feeding accounts for up to 70% of the total cost of this activity (Salazar, 2021). Furthermore, its simple management and low technological requirements make its production accessible to small-scale producers, encouraging adoption in rural communities with limited resources (Pedraza-Reyes *et al.*, 2023).

Therefore, considering the climatic and economic challenges affecting cattle fattening systems, it is pertinent to develop productive strategies that promote forage cactus as a sustainable forage alternative. This crop would not only improve the availability and quality of feed for livestock, but also contribute to water conservation and the rehabilitation of degraded soils, offering an integrated solution for producers seeking to enhance the resilience and economic viability of their production systems. In this context, the present study aimed to establish a forage cactus (*Opuntia ficus-indica*) production system adapted to local conditions, providing a replicable model that supports agricultural sustainability and the socioeconomic well-being of small- and medium-scale producers in the study region.

MATERIALS AND METHODS

Study site location

The study was conducted in Delicias, Chihuahua, Mexico (28° 09″46”′ N and 105° 27”03” W). The dominant vegetation in the region includes semi-arid grasslands and native species such as mesquite (*Prosopis* spp.) and huisache (*Acacia farnesiana*) (Jurado-Guerra *et al.*, 2021). The prevailing soils are sandy, with low organic matter content (0.58% initial average) and a sandy clay loam texture in some areas (Cantú-Silva *et al.*, 2018).

The state of Chihuahua exhibits diverse climatic conditions: warm and dry in 40% of the territory, temperate semi-dry in 33%, and semi-cold subhumid in 24%. Temperatures range from 45 °C to −23 °C, with an annual mean of 17 °C. Rainfall is scarce, averaging 510 mm per year (Corrales-Suastegui *et al.*, 2025).

Biological material and crop establishment

The Copena variety of *Opuntia ficus-indica* was used as the biological material. Physiologically mature cladodes were established in a 500 m^2 area using a triangular (three-bolillo) planting pattern, with a spacing of 1 m between cladodes. Each cladode was inserted into the soil up to half its length to facilitate rooting and minimize the risk of dehydration. A drip irrigation system was implemented using perforated tapes designed to deliver 1.5 L h^{-1} during monthly sessions of 4.5 h, ensuring efficient water use. Manual weeding was performed to prevent competition for resources, formative pruning was carried out to promote uniform growth, and phytosanitary management was applied to prevent pest outbreaks, following the guidelines of the forage cactus technological package from INIFAP (2024).

Soil evaluation

Between April and November 2024, comparative soil analyses were conducted to assess soil evolution throughout the study period. In the initial analysis, key indicators such as organic matter, pH, texture, and available nutrients were determined. Subsequently, the same parameters were evaluated in the final analysis to identify changes attributable to the crop.

These physicochemical soil analyses were performed at the Soil Laboratory of the Faculty of Agricultural and Forestry Sciences at the Autonomous University of Chihuahua. Organic matter was determined using the Walkley-Black method, and pH was measured using the saturated paste technique. Available nutrients were quantified through specific procedures: nitrates (NO_3) as extractable nitrates, phosphorus (P) using the Olsen method, potassium (K) through ammonium acetate (AA) extraction, and the micronutrients iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn) using the diethylenetriaminepentaacetic acid (DTPA) extraction method. Soil texture was characterized using the Richards method, and total calcium carbonate ($CaCO_3$) content was quantified through an acid analysis measuring the total carbonate concentration present in the sample.

Economic viability and financial analysis

The methodology proposed by Baca Urbina (2013) was applied to estimate economic viability, considering fixed, variable, and labor costs. In addition, the financial indicators Net Present Value (NPV), Internal Rate of Return (IRR), and the Cost-Benefit Ratio (CBR) were calculated in order to facilitate replication of the study under similar conditions and to extrapolate its results to other arid regions with comparable characteristics.

RESULTS AND DISCUSSION

Implementation of Forage Cactus Planting

The results obtained showed that propagation through cladodes proved to be an efficient technique, as it enabled the establishment of vigorous plants within a relatively short period. Irrigation frequency, adjusted to environmental conditions, contributed to optimizing water use without compromising growth. In addition, the application of practices such as formative pruning and the use of disinfected tools during crop management activities reduced the risk of diseases and promoted the expected product quality. Overall, crop establishment demonstrated that adequate land preparation, sanitary selection of plant material, and efficient water management positively influenced the initial development of forage cactus, laying the foundation for a sustainable and technically sound production system. These findings are consistent with those reported by González-Gaona *et al.* (2024), who indicated that deep mechanical soil preparation favors the initial establishment of forage cactus. Similarly, Navarro-Álvaro (2018) highlighted that land leveling improves irrigation efficiency, which aligns with the homogeneous water distribution observed in this plantation. Likewise, Robles-Contreras *et al.* (2008) emphasized the importance of soil analysis and agronomic management adapted to site-specific conditions, aspects reflected in the favorable crop response.

Design and installation of the irrigation system

Overall, the results showed that the implementation of drip irrigation enhanced water-use efficiency, improved soil moisture conditions, and strengthened crop establishment, consolidating it as a relevant alternative for production systems in areas with limited water availability. This approach proved more suitable than the traditional surface irrigation schemes commonly used in the region. Controlled flow application allowed adequate moisture conditions to be maintained with lower water volumes, representing a significant optimization of the resource. This response is consistent with Torres-Cobo (2024), who indicated that drip irrigation aligns well with forage cactus physiology by delivering water directly to the root zone. Similarly, the findings agree with López-Medina *et al.* (2024), who reported efficiencies above 90% and considerable reductions in water consumption under proper management. Under semi-arid conditions, the installed system demonstrated to be a technically viable strategy to enhance crop sustainability. Reduced losses through evaporation and runoff contributed not only to water savings but also to greater stability in forage cactus growth. Furthermore, the continuous and trouble-free operation reflected adequate hydraulic planning and system compatibility with site-specific terrain characteristics.

Positive variables

Organic matter

Two organic matter analyses were conducted, one prior to planting and the other after crop establishment. An increase was observed (Figure 1), indicating an improvement in soil fertility and suggesting more favorable conditions for crop development. The observed increase may be associated with the applied management practices and the integration of sustainable strategies, which evidenced greater biological activation of the soil and an enhancement of its potential fertility. This is essential for the development of forage cactus cultivation (Izquierdo-Bautista & Arévalo-Hernández, 2021). Organic matter improves the physical and chemical properties of the soil, including nutrient transport, moisture retention, aeration, and porosity. It also contributes to reducing bulk density (Brechelt, 2004).

Soil pH

Soil pH increased from 6.85 to 8.12 (Figure 2), approaching the range reported as optimal for forage cactus cultivation (8.34) according to Orona-Castillo *et al.* (2003). The observed increase may be attributed to a higher concentration of alkaline elements such as potassium and magnesium, which reached values of 396 mg kg^{-1} and 2.65 mmol L^{-1}, respectively (Rodríguez-González, 2014).

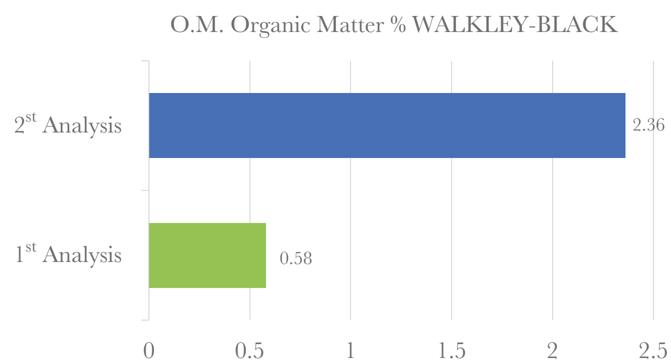

Figure 1. Organic matter increase. Source: Author's own elaboration.

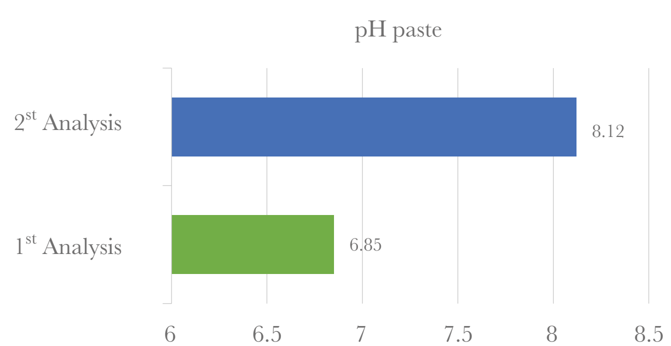

Figure 2. pH increase. Source: Author's own elaboration.

Together with the increase in organic matter, this shift changed the soil reaction from slightly acidic to alkaline, a condition that has been reported as favorable for the establishment and production of forage cactus (Rivera *et al.*, 2018).

Available Nutrients

Increases were recorded in the concentrations of nitrates, phosphorus, potassium, iron, zinc, and manganese, while copper remained constant (Table 1). These results were consistent with the increase observed in soil organic matter (Martínez-Nevárez *et al.*, 2024). Rodríguez and Flórez (2004) emphasize that these elements are essential for plants to complete their life cycle, and the absence of any one of them cannot be replaced by another.

Soil texture

Regarding soil texture, a change from sandy clay to sandy clay loam was observed. This texture type falls within the classes reported as suitable for forage cactus, which thrives in soils with a high calcium carbonate content and loamy textures, such as sandy loam or sandy clay loam (Ruiz-López, 2011). Likewise, Ruiz-Corral *et al.* (2013) indicated that optimal forage cactus growth occurs in sandy and sandy-clay soils, provided they are calcareous and have a high salt content, conditions that promote better crop development.

Variables to monitor

Total Calcium Carbonate ($CaCO_3$)

Total $CaCO_3$ content showed a decrease (Figure 3), dropping from 33.02% to 12.03%, which represented a reduction of 20.99%. This change should be considered in soil management, since low calcium carbonate levels may influence nutrient availability (Cruz-Macías *et al.*, 2020). Although forage cactus is a tolerant and adaptable species, marked reductions in this component could affect its development if appropriate fertilization strategies are not implemented (López-Collado *et al.*, 2013).

Economic Viability

The initial investment required was $50,000 MXN, allocated to land preparation and conditioning, installation of the drip irrigation system, and the acquisition of basic tools

Table 1. Increases in available nutrients.

Available Nutrient (mg kg^{-1})		1st analysis	2st analysis
NO_3	Nitrates	2.03	35
P OLSEN	Phosphorus	1.25	38.02
K AC. AMONIO AA	Potassium	854	1250
Fe DTPA A.A	Iron	0.36	1.2
Zn DTPA A.A	Zinc	0.24	0.36
Cu DTPA A.A	Copper	0.21	0.21
Mn DTPA A.A	Manganese	1.02	2.36

All concentrations are reported in mg kg^{-1} (ppm).

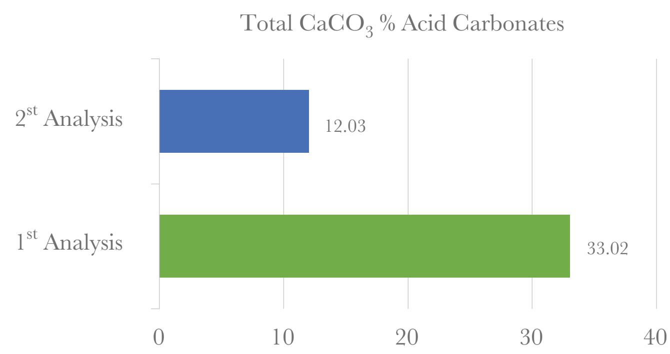

Figure 3. Decrease in Total CaCO′ Content. Source: Author's own elaboration.

and equipment for operation. Annual fixed and variable costs were estimated at $20,000 MXN, including crop management activities, maintenance of the irrigation system, and plant replacement.

Based on the projected yield and a selling price of $3.25 per kg, the estimated annual income would allow recovery of the initial investment within an approximate period of three years.

Financial Analysis

The financial analysis was conducted over a five-year evaluation horizon using a 12% discount rate. The obtained indicators included a NPV of $42,075.89 MXN, an IRR of 39.48%, and a BCR of 2.03. These results are presented in Table 2.

The financial projection showed favorable performance over the five-year evaluation period. Constant annual revenues of $37,498.50 MXN were estimated, resulting in an annual net cash flow of $17,498.50 MXN. During the first two years, the cumulative cash flow remained negative due to the recovery of the initial investment of $50,000.00 MXN. The break-even point was reached in the third year, when the cumulative cash flow became positive. From that moment onward, the project generated net profits that increased overall profitability.

The discounted net cash flow indicated that, even when applying a 12% discount rate, the benefits exceeded both operating costs and the initial investment, thus confirming the economic viability of the productive model. These results are consistent with those reported by SAGARPA (2015), which estimated an investment of approximately

Table 2. Five-year financial projection.

Year	Revenue (MXN)	Costs (MXN)	Net Cash Flow (MXN)	Discounted Net Cash Flow (MXN)	Cumulative Cash Flow
1	37498.5	20000	17498.5	15623.66	−32501.5
2	37498.5	20000	17498.5	13949.7	−15003
3	37498.5	20000	17498.5	12455.09	2495.5
4	37498.5	20000	17498.5	11120.61	19994
5	37498.5	20000	17498.5	9929.12	37492.5

$50,000.00 MXN per hectare in the states of Aguascalientes, Guanajuato, and Zacatecas, with cost recovery beginning in the third year and annual revenues of $40,800.00 MXN. Similarly, Morales *et al.* (2016), in a business plan for forage cactus production in the state of Morelos, estimated an investment of $49,000.00 MXN and confirmed medium-term recovery.

CONCLUSIONS

The forage cactus production system proved to be technically viable and economically profitable, supported by a strategic initial investment aimed at maximizing critical resources such as water in a context of recurrent droughts and soils deficient in organic matter and nutrients. The use of drip irrigation optimized water resources, promoting sustainability by reducing costs and increasing feed production. This confirms the feasibility of the project and establishes a precedent for future initiatives that prioritize water-use efficiency and profitability.

Furthermore, this model enables the conversion of low-fertility soils into productive land, taking advantage of the benefits of forage cactus, which has traditionally been considered a low-value crop. The results obtained are replicable in the south-central region of Chihuahua, Mexico, and may serve as a reference for producers interested in sustainable and profitable strategies.

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