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Technological status of prickly pear (*Opuntia ficus-indica* Mill.) fermentation to increase the protein value of its fodder

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ABSTRACT

Objective: To analyze the state-of-the-art technology and the application of the fermentation process, in order to increase the protein value of prickly pear (*Opuntia ficus-indica*), as a source of fodder, in three technological levels.

Design/Methodology/Approach: The technological parameters and mechanization level of three fermenters —employed to increase the protein value of prickly pear fodder— were characterized. The conceptual technical analysis was determined through quantitative and qualitative indicators, based on mathematical expressions and equations.

Results: Quantitative indicators showed a fermentation technology with limited efficiency, which provides an opportunity for technical improvements.

Findings/Conclusions: The application of fermentation technology results in significant savings in water, soil, and fertilizer resources. Furthermore, it provides an alternative for fodder production and food security for livestock in the semi-arid region of Mexico.

Keywords: Fermenters, technological parameters, *Opuntia* spp.

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INTRODUCTION

The scarcity of rainfall during the year limits fodder production in northern Mexico (Murillo *et al.* 2012). Therefore, supplementing diets with fodders and commercial concentrate feeds is fundamental to meet the animals' protein and energy requirements. Adding concentrates to animal feed increases food costs by 40%; consequently, producers must develop technological alternatives to produce fodder (Herrera *et al.*, 2014), such as the use of prickly pear (*Opuntia ficus-indica*) biomass (Gutiérrez *et al.*, 2009).

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The scarcity of fodder and protein sources led to the development of a technology that fortifies the protein content of prickly pear. This technology is based on the semisolid fermentation of prickly pear through the application of *Saccharomyces cerevisiae* yeast (1%). Additionally, an external nitrogen source (made up of 1% of urea and 0.1% of ammonium sulfate) was used. The aerobic condition, the temperature (25±3 °C), and acid pH (4.35) were maintained for 8-10 h. The fermentation was subjected to 45-minute mixing, with 30-minute breaks (Flores *et al.*, 2011; Flores *et al.*, 2014).

The implementation of fermentation technology to enhance the nutritional value of solid or semi-solid prickly pear —extracting biomass from the existing carbohydrates (Peláez *et al.*, 2011)— was carried out using fermenters with different mechanization levels. However, the technological parameters of this equipment have not been analyzed. According to Rebollar-Rebollar *et al.* (2011), a low technological and mechanization level in agroindustry results in poor quality products.

Technological parameters such as grinding, cutting power, and particle size are crucial for the fermentation process of green waste, because the biochemical changes involved can impact the process (Pinos *et al.*, 2008). According to Fuentes-Rodríguez (1997), 1-3 cm particles facilitate air elimination during mixing, while Durán-García *et al.* (2012) determined that the cutting and working tools consume most of the energy during the development of technological processes. Therefore, the state-of-the-art technology and technique implemented in the fermentation process —aimed to increase the protein value of prickly pear fodder— were evaluated at three technological levels.

MATERIALS AND METHODS

A technical assessment was carried out to determine the consumption of resources (fertilizer, water, and land) used to produce animal feed proteins, through the cultivation of alfalfa (*Medicago sativa*). Subsequently, this process was compared with the implementation of the prickly pear fermentation process. In addition, a technical analysis was carried out to evaluate the technological parameters of the fermentation process, in three mechanization levels, currently used in the Potosino-Zacatecano plateau (Table 1).

The fermentation technology was characterized through field visits to the locations where the technologies were developed. In addition, an experience exchange with developers and users of the technology was conducted. Measurements, physical comparisons, and

Table 1. Technological levels applied to prickly pear fermentation.

Technology level 1 (experimental)	Technology level 2 (applied)	Technology level 3 (experimental)
This technology was developed by the Central North Regional Universitary Center of the Chapingo Autonomous University (CRUCEN), it is an experimental desing and it is aimed at small producers and to carry out field demonstrations and training.	This technology was developed and adapted to the producer needs, to generate cactus forage with high protein content for intensive feeding of sheep, this technology is considered as a success case.	This technology was developed by the Arid Zones Regional Universitary Unit (URUZA) of the Autonomous University of Chapingo and others collaborators, is an experimental desing for small and medium-sized producers. This technology is in the patent process

calculations of some static and dynamic mechanical elements and tools —used to design and construct the fermentation process equipment— were carried out. This process analyzed the parameters and obtained the quantitative indicators required to determine the mechanization index of the fermentation process technological chain. A flexometer and an Extech 461750 contact tachometer were used to measure the structural elements and to quantify the cutting speed during the prickly pear grinding process, respectively.

Technical evaluation of parameters

The mechanization index was calculated using equation 1, which is based on the principle of incorporating machinery, equipment, and tools into the production systems and processes of agroindustry operations, in order to achieve greater technical, economic, and environmental efficiency, increasing production without degrading natural resources (Aristizábal and Cortés, 2012).

$$nt = HPha^{-1} \tag{1}$$

where: *nt* is the number of tractors and HP is the power (Watts).

The efficiency of motors, tools, and mechanisms integrated in a power system is defined as the capacity of the motor to transform electric power into mechanical energy. The electric power and mechanical energy output of a shaft is determined in watts or kilowatts (W, kW) (Quispe, 2002). In this study, equation 2 was used to determine the output.

$$\%EF = \frac{Mechanical\ output\ power}{Electrical\ input\ power} \times 100 \tag{2}$$

where: *EF* is the efficiency.

The tangential speed was determined based on the characteristics of the cutting systems, using equation 3.

$$ts = \omega * r \tag{3}$$

where: *ts* is the tangential speed $m*s^{-1}$; ω is the angular speed ($Rad*s^{-1}$); *r* is the radius of the cutting shaft (mm).

The grinding torque was determined based on equation 4.

$$T = \frac{P(63000)}{S} \tag{4}$$

where: *T* is the torque (Nm); *P* is the required power (HP); and *S* is the rotation speed (rpm).

The electric power of the motor is defined based on the equation 5.

$$Ep = \frac{M_p}{n} \tag{5}$$

where: Ep is the electric power consumed (Watt); M_p is the mechanical power on the shaft (Watt); and n is the efficiency of the motor.

Martínez-Rodríguez, Valdés-Hernández, Diaz-Suárez, and Maturrell Padín (2004) have described the grinding process. They pointed out that its suction and cutting power smooths the flow of material and prevents blockages in the grinding machine. Cutting power was determined with equation 6.

$$Cp = Cf * \omega_r * r \tag{6}$$

where: Cp is the cutting power (HP, CV, Watts); Cf is the cutting force (N); ω_r is the angular speed of the rotor (rad/s); and r is the radius of the rotor (mm).

The system or cutting tool was calculated with equation 7.

$$b = 2\frac{\pi S}{n\omega} \tag{7}$$

where: b is the length of the tooth or blade; S is the feed speed; n is the number of blades; and ω is the angular speed.

Finally, the transmission ratio index was calculated with equation 8.

$$i = \frac{Nm}{n_c} \tag{8}$$

where: i is the gear ratio index; Nm is the drive shaft rotational speed (rpm); and n_c is the lay shaft speed (rpm).

RESULTS AND DISCUSSION

Technical resource evaluation

The application of fermentation technology has enabled the enhancement of crude protein content, consequently consuming less water, soil, and fertilizer resources than traditional fodders, such as alfalfa (Flores-Hernández, 2019). Since a 67 t ha^{-1} alfalfa average yield and a 160 t ha^{-1} prickly pear average yield are obtained with a 180 cm and 60 cm irrigation depth, respectively, the production of 1.0 kg of prickly pear dry matter will require 52% less water than the same amount of alfalfa dry matter (Table 2).

Table 2. Resources required for 1.0 kg of dry matter (MS).

Species	Water consumption $\left(L\,kg_{MS}^{-1}\right)$	Ground surface $\left(m^2\,kg_{MS}^{-1}\right)$	Protein $\left(g\,kg_{MS}^{-1}\right)$	Fertilizer $\left(g\,kg_{MS}^{-1}\right)$
Prickly pear	480.15	0.80	330	***
Lucerne	916.98	0.49	260	9.91

Technical characterization of the implementation of fermentation technology

The cutting method (grinding) has been incorporated directly into the experimental fermentation equipment. In the case of the applied technology, this operation works better with the direct connection to the power take-off of a tractor, obtaining a higher cutting power (64 W) and a larger cutting tool (15 mm). In all cases, a 2-3.5 cm particle size was obtained, applying a 1,000-1,500-rpm cutting speed (Table 3).

Following grinding, the plant material was transferred to the fermenter for further processing. The volume of the experimental formers ranged from 0.2 to 0.3 m^3. Meanwhile, in the implemented technology, volume should be increased up to 1.2 m^3, which requires greater mixer speed, torque, and motor power (Table 4).

Development of the new fermentation technology

The technology analysis indicated that the parameters can be optimized through the advancement of technology and the improved design and redesign of the elements

Table 3. Analysis of parameters applied to prickly pear grinding.

Technical parameters	Technology level 1 (experimental)	Technology level 2 (applied)	Technology level 3 (experimental)
Windmill	Its structure is made with 12 gauge galvanized sheet structure, 1/8 inch iron flat bar and 1 inch iron angle, and it is mounted to fermenter chassis	It uses a Hammer mill No 16 coupled to the tractor's "PTO" through a mechanical transition.	It is made of stainless steel and the mill is integrated into the fermenter. It is fed manually and unloaded by gravity.
Cutting tool	76.2 mm diameter shaft with serrated steel blades	Oscillating hammer system, the nopal is cut by impact	The system has a vertical axis and a horizontal cutting jagged disc.
Cutting power (W)	2	64	2
Cutting tool length (mm)	7.97	15	13
Particle size (cm)	3	3.5	2
cutting speed (rpm)	1500	1000	1500
Moment of torque (Nm)	9.49	843.6	10.9
Transmission type (windmill)	Mechanical transmission with pulley system and "V" belts	Mechanical transmission tractor power take-off shaft (PTO)	Mechanical transmission with pulley system
Ratio index transmission	1.87	1.1	1.6

Table 4. Technical analysis of the fermenters.

Technical parameters	Technology level 1 (experimental)	Technology level 2 (applied)	Technology level 3 (experimental)
Fermenter	Experimental equipment with an integral design, with a plastic hopper, the grinding falls by gravity since the mill placed at the top, its transmission is mechanical with a system of pulleys and bands.	The equipment was adapted to the production needs, the cactus is loaded to the fermeter through a conveyor belt and unloaded by gravity and worm screw. It uses a mechanical transmission with speed variation trough motor-reducer, chain and sprocket.	It has an integral design (structure, tank and mill), and is made of stainless steel. The mill is on the top of the fermenter. The loading and unloading of material are by gravity. It has a mechanical transmission with pulleys.
Fermenter volume (m^3)	0.2	1.2	0.3
Design (mixer)	Stirrer with galvanized blades integrated into a drive shaft	Double helical agitator action.	Simple stainless steel spiral stirrer.
Transmission of fermenter	Mechanics (pulley and V-belt)	Mechanics (chain and sprockets) and 2 output motor-reducer	Mechanics (pulley and V-belt)
Mixer speed (m/s)	0.119	1.9	0.119
Mixer torque (Nm)	316.3	711.8	316.3
Motor power (KW)	1.492	3.73	1.492
Fermentation Time (h)	8	6	10
Mixing intervals	45 min. of mixing and 30 min. rest	30 min of mixing and 30 min of rest	45 min. of mixing and 30 min. rest
Start System	Electronic system (timer)	Electronic system (timer)	Electronic system (timer)
Equipment cost fermenter	$25,000.00	$120,000.00	$250,000.00

of the fermentation process, improving the efficiency of the mechanization chain. This aim can be achieved through the integration of 4.0 generation technological tools and systems, as well as automation and digital systems. Based on the technology analysis, the technological development can include conveying systems, the optimization of parameters in the grinding equipment, and more efficient cutting tools that guarantee a tailored particle size structure and cut. Furthermore, redesigning the fermenting equipment is key to facilitate a large-scale production of fodder to feed larger cattle herds. In order to achieve a larger high-protein fodder production, improving the technical conditions of each parameter —through the implementation of technological innovations in the process, equipment, and/or integral systems— is fundamental.

CONCLUSIONS

The fermentation technology of fresh prickly pear residues is an effective alternative to increase the protein content and, by extent, the nutritional value of this species. This technology can contribute to the conservation of resources, such as water, fertilizers, and land. Although it has already been adopted by producers, fermenters can still be improved and optimized, through automation and digitalization, and integrated into Agriculture 4.0.

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