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Physical-mechanical properties of three highly consumed species of nopal in Mexico

Propiedades físico-mecánicas de tres especies de nopal de alto consumo en México

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Abstract

Nopal is one of the most consumed foods in Mexico (consumed both by humans and animals, mainly ruminants), with an increased demand in the last ten years. The nopal (*Opuntia spp*.) develops favorably in conditions of low precipitation, in thin, rocky soils which are typical of arid zones, where other crops only grow at a certain time of the year. The physical-mechanical properties of the product to be processed are fundamental in the design and construction of agricultural machinery, since previous knowledge and evaluation of the material that is going to be processed enables a correct selection of the work elements or mechanisms that will intervene in the machine. In the case of nopal processing, the presence of areolas and thorns directly affects some mechanical properties of the product, as presented in this paper.

Keywords: Nopal rheology; mechanical strength; cutting.

Resumen

En México, el nopal es uno de los alimentos de mayor consumo (tanto por humanos como por animales, principalmente rumiantes), siendo en los últimos años cuando más se ha incrementado su demanda. El nopal (*Opuntia spp*.) se desarrolla favorablemente en condiciones de poca precipitación, en suelos delgados y rocosos, propios de las zonas áridas, en las que otros cultivos solo prosperan en cierta época del año. Las propiedades físico-mecánicas del producto a procesar son fundamentales en el diseño y construcción de maquinaria agrícola, pues conocer y evaluar previamente el material a trabajar permite que, posteriormente, se puedan elegir correctamente los elementos de trabajo o mecanismos que intervendrán en la máquina. En este trabajo se detallan aspectos como la influencia de la presencia de aureolas y espinas en algunas de las propiedades mecánicas del nopal.

Palabras clave: Reología del nopal; resistencia mecánica; corte.

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Introduction

The plant commonly called nopal is a cactus that lacks leaves; instead, it is formed by racket-shaped, fleshy leaves, which in botanic terms are called cladodes or quills; an important characteristic of this plant is the presence of thorns in the fleshy leaf. The nopal (*Opuntia spp*) develops favorably in low-precipitation conditions, in soils typical of arid zones, where other crops can only thrive at certain times of the year. It extends over a great part of Mexico in natural and abundant form. It occupies 16 575 408 ha and is cultivated in 55 000 ha for forage purposes (*Instituto Nacional de Estadística y Geografía* [INEGI], 2014). Also, in central Mexico, the nopal is cultivated for the production of prickly-pear fruit (also known as tunas) occupying an area of 80 000 ha, and 12 000 ha for the production of nopal for human consumption (*Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación* [Sagarpa], 2016). The nopal is a plant with oblong and flattened cladodes with a tendency to be thicker near the internode as age increases. Most species, according to different authors (Meraz *et al*., 2012; Muñoz, 2016; Tavera, Escamilla, Alvarado, Salinas & Galicia, 2014), have a maximum thickness of 60 mm, 600 mm long, and 350 mm wide for cladodes of three years. Cladodes younger than two years are typically 20 mm thick, 400 mm long, and 190 mm wide, this being the maximum age recommended for dehydration. As pointed out, an increased consumption of nopal has been observed in Mexico during the last ten years, becoming one of the most consumed foods by both humans and animals, especially ruminants. According to producers of milk and meat of bovine origin, the cladodes suitable as food material are the ones located up to the third position, from the upper end of the plant down. Further down, the cladode becomes very hard, and its fibers become quite lignified due to aging; such characteristic considerably reduce the capacity of the cattle to digest such material. Based on this consideration, the biological material of interest comprises from the first to the third cladode. In general, biological products are difficult to handle because the harvesting, transporting, or storing involves an interval of time in which, if not consumed or kept in a suitable place, they decompose.

In the design of machines for nopal chopping, the knowledge of the physical-mechanical properties is an important aspect, as these are determinant to improve and increase energy efficiency and establish guidelines that serve as parameters for cutting, avoiding damage to the raw material. As it is known, there is no commercially available equipment capable to cut the nopal in an efficient way, since it possesses thorn and shape characteristics that do not facilitate its processing. Some machines require the thorns of the nopal to be removed and the nopal itself to be restricted to a specific size. If cutting of a different size is required, a change of some mechanical components is also required. In addition, one nopal at a time must be supplied. The objective of the present work is to determine the physical properties of the nopal that influence the design of machinery that facilitates its processing, specifically, size and shape, coefficient of friction (static and dynamic), specific cutting power and apparent density.

Materials and Methods

One of the most important tasks in the design and construction of agricultural machinery is the determination of the physical-mechanical properties of the product to be processed, in order to know and evaluate, first, the construction material and, then, to choose the work elements or mechanisms that will intervene in the machine. The main reasons for the study of these properties are: a) influence in the design and construction of machines and facilities; b) quality-control improvement of agricultural products; and c) in industrial processes, physical and mechanical properties are important in a wide range of equipment.

The material used in the experiment was collected in the arid zone of the state San Luis Potosí, where the climate according to the climatic classification of Köppen, modified by García (1973), corresponds to a BS or KW (w) (i), which is equivalent to a cold dry steppe climate, with an annual average temperature of 18

°C, being 7.5 °C the minimum and 35 °C the maximum, with an average annual rainfall of 374 mm. The vegetation is microphytic desert scrub (Rzedowski, 1996), with dominant abundance of shrubs, mesquite, huizache, and nopal. The physical-mechanical properties of the nopal that were determined are: size and shape, coefficient of static and dynamic friction, apparent density and specific cutting energy.

Statistical analysis

In order to determine the physical-mechanical properties of the cactus, the mean values and the standard deviation for ten cladodes (F_e = 10) of each of the species studied were considered. The data analysis was performed by means of descriptive statistics, using the UNIVARIATE procedure of the Statistical Analysis System (SAS) program (1999).

Determination of the friction coefficient

The friction force acts in a plane containing the points of contact, opposing the relative motion between surfaces. It plays an important and, in many cases, decisive role in all fields of mechanics. The friction is always present during the motion of bodies and is produced by a force exerted over a surface (Valdés, González & Martínez, 2008). The coefficient of static friction (F_e) occurs when a surface is about to slide relative to another one, by the action of a force (F). If the magnitude of the F exceeds the value of the F_e, the static state is broken; in this condition, the frictional force (F_f) between the contact surfaces decreases relative to the F_e to a slightly smaller value referred to as the dynamic friction force (F_d), then the coefficient of f_d will be considered. In order to determine the coefficient of friction, the following materials were used: a piece of unpainted steel sheet of approximately 1 m^2 and a protractor. One end of the sheet is matched with the center of the protractor, placing a stop to prevent it from sliding when it is lifted at the opposite end. With this test the angle of repose (or slope) (φ) is obtained, which is used to calculate the coefficient of friction. The magnitude of φ depends on the adhesion force between the nopal particles and the F_f that arise in the displacement of this with a contact surface of interest. Then, two types of tests were carried out. The first one was performed with the whole cactus, i.e. with epidermis; the second test was performed with nopal without the epidermis (the thorns were removed).

Determination of apparent density

In order to determine the apparent density, the cactus prick is first weighed and then immersed in a vessel with water (Laffita, Martínez, Toledo, Sabin & Valdés, 2014). Once the displaced volume of water is known, the density is determined by the expression: $\rho = m/V$;

where:

ρ = density of the cactus, t/m^3;

m = mass of the sample, t;

V = sample volume, m^3.

Determination of specific cutting energy

In accordance with Singler, Valdés, Laffita, Ayala & Maldonado (2015), the specific cutting energy is calculated as follows: $e_c = E_c/F_g$ (equation 1); where:

e_c = Specific cutting energy, J/mm^2;

E_c = Cutting energy consumed by the sample, J;

F_g = Geometric surface of the sample, mm^2.

In order to determine the cutting energy (E_c) a pendulum-like device was devised, where the oscillating mass is that of the blade, with a cutting edge of 25° and a thickness of 4.76 mm, as shown in figure 1 (Pendulum for determination of cutting energy). The test was performed as follows: along the trajectory of the center of gravity of the blade (point b of figure 2) and under the pivot point, a sample with known cross-section was placed. The blade is released from a vertical position on its rotating path (point a); the circular motion is recorded by using a pen on a sheet of paper, placed near the center of rotation, and then the same operation is performed by releasing the blade from the same position but without obstructing its rotation. So, the trajectory described in this case was greater than the previous one as no energy is consumed to cut material. In this way, two displacement angles (θ_1 and θ_2) are obtained, formed by the vertical that passes through the pivot point and the string holding blade at the highest point on its path (points c and d, respectively) where the kinetic energy is equal to zero. The potential energy is determined by using the equation V = W (L) (L-cos θ), (equation 2); where:

V = potential energy of the blade, J;

W = blade weight, N;

L = pivot length to center of gravity of blade, m;

θ = angle described by the blade rope with respect to the vertical, °.

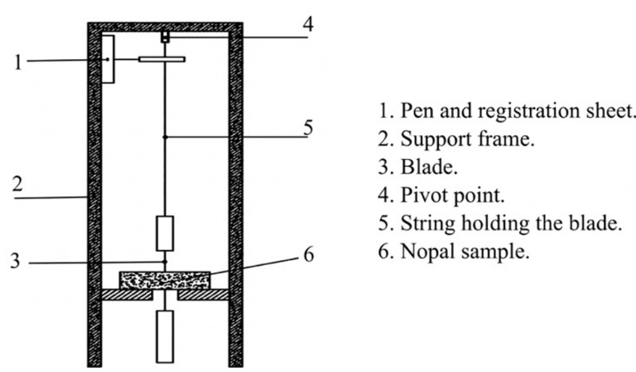

Figure 1. Pendulum for determination of cutting energy.
Source: Author's own elaboration.

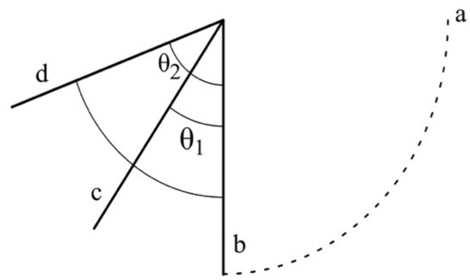

Figure 2. Pendulum diagram used to determine the cutting energy.
Source: Author's own elaboration.

Assuming that the difference in the potential energy of the two positions corresponds to the energy consumed in cutting a sample of material, the following relation is obtained: $E_c = V_2 = V_1$ (equation 3); where:

V_2 = Potential energy at point d;

V_1 = Potential energy at point c;

By substituting equations (1, 2, and 3): $E_c = (W) (L) (\cos \theta_1 - \cos \theta_2)/Fg$ (equation 4) where:

θ_1 = angle described by the blade with the sample on its path, °;

θ_2 = angle described by the blade without obstructions, °.

Results and Discussion

Each of these species of nopal has characteristics that make them very different from each other, in terms of the properties described in this paper. Regarding the general characteristics, it can be observed that, in the case of the *Nopalea cochenillifera* species, the thorns are small and scarce, on average 14 areolas per side of the cladode, each areola has two very fine thorns. In the case of the *Opuntia ficus indica*, it is observed that it has 35 areolas in average on each side of the cladode, from which two or three thorns sprout reaching a maximum size of 10 mm. Finally, the *Opuntia robusta* species has an average of 25 areolas per side of the cladode, from which two or three thorns sprout, each of 10 mm but very thick. Table 1 shows the results obtained from the nopal suitable for human consumption that was studied (*Nopalea cochenilli* F_f *ra, Opuntia ficus indica* and *Opuntia robusta*).

Density

The density varies greatly from species to species. The *Opuntia ficus indica* is the species with the highest density, followed by *Opuntia robusta* and *Nopalea cochellinifera*. It can be observed that there is a direct relationship between the number of areolas per cladode and density; also, the direct relationship between the angle of repose and the coefficient of friction is visible, but such a relationship is not observed in terms of the specific energy of cut, since *Opuntia robusta* is the one demanding the most energy.

Coefficient of friction

Two types of tests were carried out. The first one was done with the whole cactus, i.e. the part in contact with the metallic surface was the fleshy leaves with spines, obtaining a value of φ_1 equal to 22.10° $\pm$ 2.67°. In the case of *Opuntia ficus indica*, the second test consisted of placing nopal without thorns in contact with the metal surface, obtaining a value of φ_2 equal to 28.13° $\pm$ 3.22°. The coefficient of friction is related to the angle by the following expression: $\mu = \tan\varphi$ (Durán, González & Márquez, 2012). Substituting φ_1 and φ_2 gives the corresponding coefficients of friction: $f_1 = 0.40 \pm 0.003$ and $f_2 = 0.53 \pm 0.004$. The coefficient of f_d is directly related by the expression: $f_d = (0.7 \ldots .0.9)$ (f); considering $f_d = 0.8$ (f) and substituting data for the two types of tests done, f $f_{d1} = 0.32 \pm 0.005$ and $f_{d2} = 0.42 \pm 0.008$.

Specific cutting energy

In the determination of this property, several repetitions were performed in order to reduce possible errors and to make the results more representative; the mean value obtained was e_c = 7941.75 J/m^2 $\pm$ 56.7 J/m^2 for *Opuntia ficus indica*, 7156.13 J/m^2 $\pm$ 50.9 J/ m^2 for *Nopalea Cochenillifera* and 8653.65 J/ m^2 $\pm$ 63.7 J/m^2 for *Opuntia robusta*. The test of specific resistance to the cut was performed both in the ends of the fleshy leaf as well as in the central part. Considering the different values of the specific cutting energy between species, it is assumed that there is a direct relationship between the hardness of the thorn (specifically in *Opuntia robusta*) and the fiber content, as consulted literature mentions that the resistance to the penetration is associated to insoluble fiber content (Singler *et al*., 2015); therefore, the presence of lignin is undesirable. It is considered that a penetration force greater than 6.4 kgf (62.72 N) is unacceptable. Penetration has been evaluated in vegetables such as asparagus, with a permissible value less than 62 N (Sanchez, Cano & Hermida, 1994). Singler *et al*. (2015) mention that the specific cutting energy depends on the type of material to be processed, its growth stage, moisture content, and the cutting site in the plant. In addition to the above, the conditions of production are also important (Rössel, Durán & Ortíz, 2015). The authors mentioned that the differences found in the various studies are probably related to the content and availability of water in parent plants, lignin content and cuticle thickness. Calvo, Hernández, Peña, Corrales & Aguirre (2010) also mention that aridity conditions can also influence the physical-mechanical properties, since they observed that the greater the aridity, the greater the content of calcium oxalate crystals aligned between the epidermis and collenchyma.

The results presented herein can be used as a basis for the design of machine components associated with the mechanical processing of the nopal leaves. The design of this type of machines is relevant considering the elevated rate of consumption of this plant and, among the machine components whose design may depend on the properties presented, material feed accesses, cutting elements, conveyor for processed material, etc., can be considered. As presented, the design of such machine components must be accommodated specifically for the species of nopal that is to be processed.

Table 1. Physical mechanical properties of nopal for human consumption.

Parameter	*Nopalea Cochenillifera*	*Opuntia ficus indica*	*Opuntia robusta*
Thickness, mm	41.24 ± 6.12	59.32 ± 7.22	60.7 ± 6.55
Length, mm	201.42 ± 13.27	589.14 ± 23.34	403.21 ± 17.33
Width, mm	150.6 ± 7.45	348.78 ± 9.23	301.54 ± 8.75
Density, ρ, t/m^3	0.88 ± 0.003	0.97 ± 0.007	0.95 ± 0.004
Resting angle with cuticle, φ_1, (º)	17.31 ± 2.34	22.10 ± 2.67	19.11 ± 3.06
Resting angle without cuticle, φ_2, (º)	25.43 ± 2.87	28.13 ± 3.22	27.12 ± 3.16
Static coefficient of friction with epidermis, f_1	0.31 ± 0.006	0.40 ± 0.003	0.34 ± 0.009
Static coefficient of friction without epidermis, f_2	0.47 ± 0.005	0.53 ± 0.004	0.51 ± 0.002
Dynamic coefficient of friction with epidermis, f_{d1}	0.24 ± 0.009	0.32 ± 0.005	0.27 ± 0.006
Dynamic coefficient of friction without epidermis, f_{d2}	0.38 ± 0.001	0.42 ± 0.008	0.40 ± 0.009
Specific cutting energy, e_c	7156.13 ± 50.9	7941.75 ± 56.7	8653.65 ± 63.7

Source: Author's own elaboration.

Conclusions

In this paper, important mechanical and physical properties of three highly consumed species of nopal were presented. It was found that the presence of areolas and thorns directly affects the angle of repose, the coefficient of friction, and the density. As it is observed, as the number of areolas increases, the angle of repose, the coefficient of friction, and the density also increase.

The specific cutting energy does not have the same behavior as the density, the angle of repose, and the coefficient of friction; therefore, it can be assumed that the cutting energy is more related to the hardness of the spine, the geometry of the cladode, and the uniformity of the thickness.

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