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Control of suction in forage mills without forced feeding during moringa processing

Control de la succión en molinos forrajeros sin alimentación forzada durante el procesamiento de moringa

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ABSTRACT: In Cuba, as an alternative to imported concentrates, the production and inclusion of protein-rich plants grown on farms is being promoted in animal diets. moringa (*Moringa oleifera*) is a prominent example, requiring adjustments to the parameters of forage mills to efficiently process this type of forage. On livestock farms, the predominant type of forage mill is one that does not use forced feeding, with the forage being drawn in by the cutting blades themselves. The mill's suction capacity, the size of the ground particles, and the load-capacity ratio depend on a set of machine design and operating parameters, as well as certain physical and mechanical properties of the processed material. This work derives, through conceptual mechanical-mathematical modeling of the interaction of a cutting element in a drum-type forage mill without forced feeding, the expressions that allow the calculation of the mill's design and operating parameters. These parameters ensure an efficient suction effect, with the required material flow and particle size, during the processing of a plant mass composed of thin stems, branches, and leaves. Additionally, a set of moringa properties, required as input data for the models, is experimentally determined. These properties are evaluated using specially developed software, thus determining, for this forage plant, the mill's operating parameters that guarantee efficient operation and the required particle size of the processed forage.
Keywords: Moringa oleifera, Particle Size, Cutting Blade Action, Conceptual Modeling.

RESUMEN: En Cuba, como alternativa al uso de concentrados importados, se promueve la producción y adición en las dietas, de plantas proteicas producidas en las propias granjas, entre las cuales sobresale la moringa (*Moringa oleifera*), siendo necesario adaptar los parámetros de los molinos desmenuzadores, de manera de procesar eficientemente este tipo de forraje. En las granjas ganaderas predomina el tipo de molino forrajero sin alimentación forzada, siendo la masa succionada mediante la propia acción de las cuchillas de corte. La capacidad de succión del molino, el calibre de las partículas desmenuzadas y la relación carga-capacidad, dependen de un conjunto de parámetros de diseño y operación de la máquina, así como de determinadas propiedades físico-mecánicas del material procesado. En el trabajo se obtienen, mediante la modelación mecánico-matemática conceptual de la interacción de un órgano de corte de un molino forrajero del tipo de tambor, sin alimentación forzada, las expresiones que permiten calcular los parámetros de diseño y operación del molino que garanticen un efecto de succión eficiente, con un flujo de material y calibre de las partículas requeridos, durante el procesamiento de una masa vegetal compuesta por tallos de pequeño grosor, ramificaciones y hojas. Asimismo, se determina experimentalmente un conjunto de propiedades de la moringa, requeridos como datos de entrada a los modelos, los cuales son evaluados con el auxilio de softwares elaborados a los efectos, determinando, para esta planta forrajera, los parámetros de operación del molino que garantizan un trabajo eficiente del mismo y el calibre requerido del forraje procesado.
Palabras clave: Moringa oleifera, calibre de partículas desmenuzadas, acción de cuchillas de corte, modelación conceptual.

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INTRODUCTION

Due to the high protein, vitamin, and mineral content found in moringa (*Moringa oleifera*) leaves, several researchers Garavito (2008); Olson & Fahey (2011); Alvarado *et al.* (2018); Kekana *et al.* (2019); Bashar *et al.* (2020); Su & Chen (2020); Rizwan *et al.* (2024) have argued for the benefits of this species as an alternative to increase the nutritional quality of forages used in livestock feed.

Furthermore, Padilla *et al.* (2012), explain that it grows well in arid and semi-arid conditions, tolerating drought, especially in tropical regions where the dry season is prolonged and reduces the availability and quality of forage for livestock. moringa is also considered a multipurpose plant that promotes nutrient recycling, water conservation, and soil fertility (Alvarado *et al.*, 2018).

In Cuba, the technologies used in dairy cattle development programs until the late 1980s were intensive, high-input systems that relied heavily on imported feed. Consequently, farms did not produce the volumes and quality of nutrients required for animal feed supplementation.

Starting in 1989, economic difficulties arose in the country that made it impossible to maintain the levels of imported inputs that had sustained the national livestock feed supply. As a result, a feed self-sufficiency program was developed, based on the production of feed by the farmers themselves to meet the needs of their livestock.

Among the alternatives for the production of food for livestock, the production of forages was considered, initially based on Sugar Cane, King Grass and other grasses, providing the farms with forage shredding mills, initially of the disc type (Figure 1a), later proliferating the production of drum type mills (Figure 1b), designed and regulated for the shredding of thick or semi-thick stems.

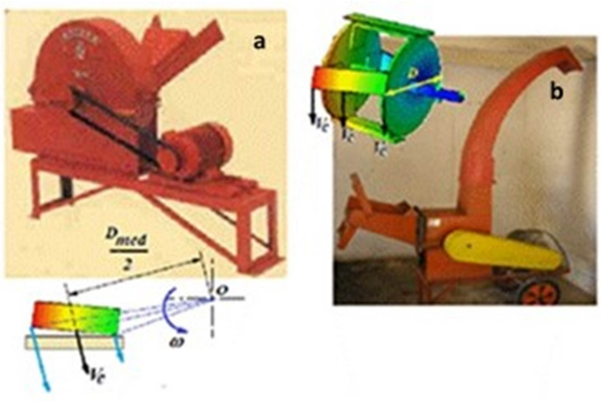

Figure 1. Typical forage mills used in Cuba: a) disc type mill; b) drum mill

In recent years, with a view to enriching animal feed with nutrients as an alternative to imported concentrates, the production and inclusion of protein-rich plants in diets has been promoted. Moringa (*Moringa oleifera*) stands out among these plants, making it necessary to adapt the construction and operating parameters of mills to efficiently process this type of forage. Moringa is composed primarily of thinner leaves and stems, and processing it in these types of mills does not guarantee the required particle size and uniformity. Stationary forage choppers are commercially available with mechanical feeding via roller feeders (Fig. 2). These offer different options for the size of the cut particles, ensuring satisfactory uniformity of this indicator, egardless of the type of forage processed.

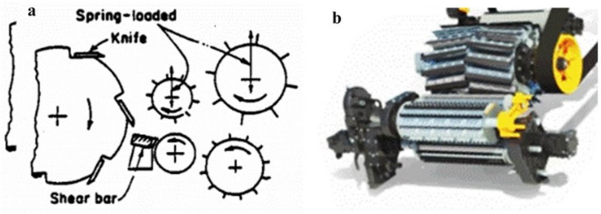

Figure 2. Roller system for forced feeding in forage harvesters. Source: Barrientos-Rivera et al., 2023

In both types of mills available on livestock farms in Cuba (Figure 1), the forage to be processed is not fed by forced rollers. Instead, the operator places the forage directly onto the feeding ramps. The action of the blades on the plant mass must create a suction effect, which will determine the size of the shredded particles and the productivity of the process, among other important parameters that ensure efficient mill operation.

Both the mill's suction capacity, the load-capacity ratio, and the power consumed in the cutting and propulsion process of the processed material depend on a set of machine design and operating parameters, as well as certain physical and mechanical properties of the processed material. Theoretical and experimental aspects aimed at determining the parameters of forage mills and other types of forage cutters have been addressed, both in the classic literature Sáblikov (1963); Rieznik (1964); Basoi *et al.* (1976), as well as in subsequent research Alfiorov *et al.* (1981); Fernández & Martínez (1988); Koegel *et al.* (1990); Shinners *et al.* (1991); Carmolinga (1995), from which more recent findings have been achieved Martínez & Valdés (2004); Valdés et al. (2010; 2012); Valdés & Martínez (2011), to develop and validate calculation models for these parameters for manually fed forage choppers. Although primarily applicable to processing thick stalks, these models are not suitable for processing a mixed plant mass like moringa, composed of leaves, branches, and thin stalks. Unlike thick stalks, these thin stalks, when interacting with the blades, significantly increase in density until they reach a level of compaction sufficient to generate the resistance required for the actual cutting process.

Therefore, the problem to be solved in this research lies, on the one hand, in the need to adapt the calculation models for the design and operating parameters of rollerless forage choppers available in Cuba so that they can be used efficiently during moringa processing.

This adaptation aims to achieve suction conditions for the processed plant mass that guarantee a finely chopped particle size and productivity in accordance with the requirements. On the other hand, the need arises to experimentally determine certain physical-mechanical properties, specific to this type of plant material, that affect the suction process and are required as input data for these calculation models.

Based on this problem, the objectives of this research are:

- To develop mechanical-mathematical models that allow the calculation, for drum-type forage mills without feed rollers and during the processing of mixed plant material, of the mill's suction capacity, the size of the processed particles, and the load-capacity relationship.
- To determine the main physical-mechanical properties of moringa that are required as input data for the developed models.
- To calculate, through the evaluation of the developed models, the main design and operating parameters to be recommended for controlling the suction conditions in drum-type forage mills without feed rollers during moringa processing.

MATERIALS AND METHODS

Method applied for the development of the calculation models

To develop the calculation models for the design and operating parameters of the forage mills under study, the conceptual modeling method was used, specifically mechanical-mathematical modeling, based on the application of the laws of mechanics to the interaction processes between the mill's working parts and the processed plant material.

This modeling method, unlike empirical modeling, is deterministic, meaning that for the same input variables, the same output variables are always obtained, without uncertainty (Martínez, 2007).

The aspects modeled to determine the design and operating parameters were:

- The suction process of the plant material during its interaction with the cutting blades;
- The load-to-throughput ratio of the mill.

To model the suction process of the plant material by the mill's cutting element, the interaction forces generated between the cutting blades, the plant material, and the die are analyzed. This is done by summing forces in the plane perpendicular to the cutting plane and adjusting the parameters so that the resultant of the horizontal component of the force exerted by the blades on the plant material overcomes the frictional force between the plant material and the die. The expressions that allow us to determine the speed imparted by the suction effect to the processed material, upon which the particle size and process productivity depend, are obtained by applying the work-energy principle to the interaction process of the blades with the plant material.

The load-to-throughput ratio of the mill is one of the fundamental aspects during the calculation of any working element that performs a given technological process. Generally, the analysis of the load-capacity relationship yields functions that allow us to relate the different parameters involved in a given technological process, with a view to establishing the appropriate operating regime for the working components of the machines that carry out said process.

In the case at hand, the load is determined based on the daily forage consumption required by the livestock to be fed on the farm and the working time allocated to its processing, while the capacity is determined based on the kinematic and structural parameters of the mill, depending also on certain physical and mechanical properties of the processed material and the particle size to be obtained as a result of its processing.

Finally, to ensure an accurate calculation of the mill parameters, the load q (kg/s) and the throughput qo (kg/s) are matched to prevent blockages and guarantee efficient operation of the equipment. The modeling process began with an analysis of previously developed models based on the processing of thick stems Martínez & Valdés (2004); Valdés et al. (2010), adapting them for the processing of mixed plant material, such as moringa.

Materials and methods used to determine the properties of moringa

Various properties of the forage plant material, related to its interaction with the working parts of the mills, constitute input parameters in the calculation models under study. These properties include: the loading area, the coefficient or angle of friction of the processed material with the metal, generally steel; the density of the processed mass, both in its initial and compacted form; and the specific cutting energy. In this work, the following were experimentally determined:

- The loading area
- The density of the processed mass during cutting by the blades
- The static friction angle of the plant mass with the cutting die material.

The dynamic friction angle and specific cutting energy were determined through calculations based on experimental data from other authors.

Loading area

The loading area ($\boldsymbol{Fc}$, m^2) is defined as the cross-sectional area of the plant mass that the blades encounter during each cutting action (Martínez, 2019). Depending on the type of plant mass being processed and the type of mill, the loading area is determined in three different ways:

- In the case of cutting thick stems in mills without feed rollers, the loading area can be determined according to the following expression according to Martínez *et al.* (2004) and Valdés *et al.* (2012a):

$$F_{ctg} = c \cdot \frac{\pi \cdot d^2}{4} \qquad (1)$$

where:
d- is the average outer diameter of the processed stems, m
c- is the number of stems fed simultaneously.

- During the processing of compacted plant material with feeder rollers, it is determined by the following expression:

$$F_{cra} = a \cdot \ell \cdot \varepsilon \qquad (2)$$

where:
a- is the clearance (a) between the rollers, m
ℓ- is the effective length or width of the feed throat, m
ε- is a filling coefficient

- During the processing of plant material, composed of a mixture of branches and leaves, compacted by the action of the blades themselves, in mills without a forced feeding system, the loading area (F_{sra}, Figure 3) will depend on the area assumed by the plant material at the moment the cutting begins.

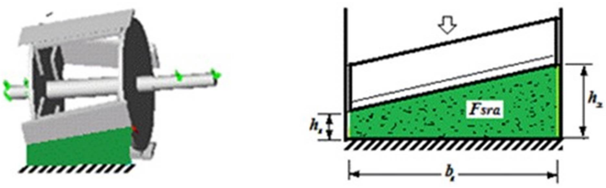

Figure 3. Loading area (f_{sra}) during the cutting of plant mass without a forced feeding system

In these cases, the determination of the loading area must be approached experimentally, since the fed material is pre-compacted by the blades until the level of compaction generates the resistance required for cutting to occur. This method of determination is applied in this work for the case of moringa.

For the experimental determination of the loading area during the blade-vegetable mass interaction, an installation was prepared (Figure 4) consisting of a drum mill from which the outer casing, the feed ramp and the blowing system of the crushed particles were removed, in order to have free access to the cutting zone.

A lever (2, Figure 4), made of rectangular steel tubing, was fitted with a clamp (1) for coupling to the pulley concentric with the drum shaft. This allowed for different values of the moment $M=P \cdot b$ to be obtained by attaching a calibrated weight (3) that could be slid along the lever. A sample of plant material was placed between the feed throat's pressure plate and the blade closest to it. The samples were prepared beforehand (Figure 5) to fill the feed space and have a uniform length and weight, while their uncompacted cross-sectional dimensions were adapted to the distance between the pressure plate and the blade.

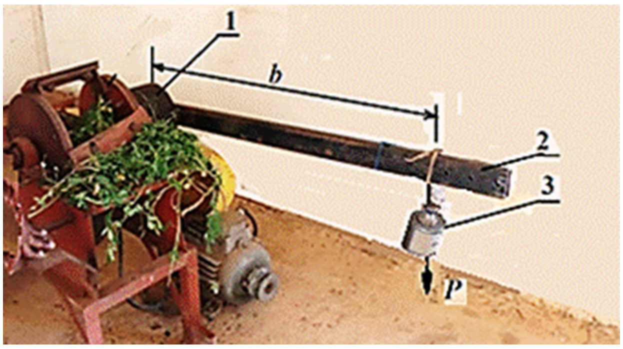

Figure 4. Installation used for measuring the loading area in a drum mill fed with plant mass taken from moringa plants.

Figure 5. Samples of moringa plant mass

Starting from this situation, the weight is moved away, increasing the arm b until the moment when the cutting of the portion of plant material was imminent. At that moment, the arm (2) was fixed and the measurements h_1, h_2, and b_s shown in figure 3 were taken with a graduated ruler with a smallest division of 1 mm. With this data, the loading area (F_{sra}) corresponding to a manual feeding system without feed rollers was calculated by the expression:

$$F_{sra} = b_s \cdot \frac{h_1 + h_2}{2} \qquad (3)$$

The sample size (nm) was calculated (with the data resulting from a pre-experiment carried out with 10 samples) for a significance level of 0.05 and a mean error of 10%, according to the expression based on the Student's t-distribution:

$$n_m = \frac{\sigma^2 \cdot t^2}{\Delta^2} \qquad (4)$$

Where:
σ: mean square deviation,
t: Student's t-test criterion
Δ: expected mean error.

The calculation, performed with the data obtained from the previous pre-experiment, yielded a sample size $\boldsymbol{n}_m$ = 12.19, with a total of 15 samples processed.

Density of the processed mass

The volumetric density of the moringa bundles to be processed was determined under two conditions:

- Density in the uncompacted state (γ_d), which is the natural state of the plant mass prior to its introduction into the mill throat, composed of a mixture of stems, branches, and leaves.

- Density in the compacted state (γ_c), occupying the loading area between the blade and the die, prior to imminent cutting.

To determine γ_d, the samples prepared in bundles (Figure 5) were weighed using a digital balance with a precision of up to 0.1 g.

Under both conditions, density was determined by dividing the sample mass by its volume. In the case of uncompacted samples, the volume was determined by measuring the perimeter of the uncompressed bundle with a cloth tape measure (with a minimum division of 1 mm) and calculating the cross-sectional area of each sample. Multiplying this area by the average length of each bundle yielded its volume.

In the case of determining the compacted density, the cross-sectional area of the bulk corresponded to the load area F_{sra} determined by expression 3.

The sample size calculation for this determination was performed using the same procedure employed for determining the load area, applying expression 4 for a significance level of 0.05 and a mean error of 10%, resulting in $n_m = 9$. However, the same 15 samples were processed.

Friction angle

The friction angle of the plant mass with the bearing material was determined by measuring the static friction angle using an inclined plane with a variable angle. A steel surface of the same material and finish as the bearing material was placed on the inclined plane. The angle of imminent slippage was measured with a graduated protractor with a minimum division of 1°. The sample size, determined by expression 4, resulted in $n_m = 14$, for a significance level of 0.05 and a mean error of 5%, taking a sample size of $n_m = 20$.

Starting from the determination of the static friction angle, the dynamic friction angle is determined by applying the trend in the difference between these two parameters for the case of interaction of plant mass with steel, determined Rieznik (1964), as well as by Valdés *et al.* (2010), being able to arrive at the following relationship rϕ between the static (ϕe) and dynamic (ϕd) friction angle:

$$r_\varphi = \frac{\varphi_e}{\varphi_d} = 1{,}6 \div 2{,}2 \qquad (5)$$

In this investigation, a mean value is applied to this interval, resulting in the following relationship:

$$r_{\varphi m} = \frac{1{,}6 \div 2{,}2}{2} = 1{,}9 \qquad (6)$$

Specific cutting energy

The Specific Cutting Energy (*Ae*) is not determined for moringa, so its value is estimated using experimental results reported by Rieznik (1964) for forage plant stems between 3 and 15 mm thick, obtained at cutting speeds up to 25 m/s with standardized blades. These results reported values for this property ranging from 0.6 x 10^4 to 2.4 x 10^4 N·m/m², with the lower values corresponding to the higher cutting speeds.

Method Applied for Evaluating the Developed Models

To facilitate the evaluation of the models developed for calculating the mill's load-capacity relationships and the suction conditions of the plant material during its interaction with the cutting blades, the expressions derived from the modeling were programmed using Mathcad 2000 Professional software. In this way, by inputting the parameters or properties that constitute the models' inputs variables into the developed programs, the parameters to be determined are obtained as outputs in an expedited manner.

Method applied for the statistical analysis of experimental results

The results of the experimental runs carried out to determine the loading area, the density of the compacted mass, and the angle of friction were statistically analyzed. For all the samples measured in each case, the mean value, the root mean square deviation, and the mean error were determined at a significance level of 0.05.

RESULTS AND DISCUSSION

Modeling the Suction Process of Plant Mass

Controlling the suction of plant mass in manually fed forage mills is of paramount importance in obtaining a controlled and uniform size of the shredded particles (Martínez *et al.*, 2004a; Martínez, 2019).

A model Martínez & Valdés (2004) that satisfactorily clarifies which parameters influence material suction, allowing for its control to obtain adequate sizes of shredded particles and specifically designed for processing thick stems, is adapted in this work for application during the processing of a mixture of plant mass composed of stems, branches, and leaves, such as moringa.

The fundamental objective of this model is to determine the parameters that influence the suction of the self-feeding material by the shredding element of forage mills and to establish the corresponding expressions that allow for the calculation of these parameters.

The analysis is based on the hypothesis that, in the cutting process, there must be a component of the interaction force between the blades and the plant material, in the direction of the material feed to the cutting element, capable of "dragging" the fed material at an average speed that ensures the flow corresponding to the capacity of the cutting element. A second hypothesis is that the work done by this component of the cutting force in the feed direction is used to provide a certain amount of kinetic energy to the fed material, which will acquire a given speed in the feed direction, ultimately causing the suction effect.

Figure 6 shows the interaction of the cutting element with the plant material in the plane perpendicular to the cutting plane. Note that, to be consistent with the first hypothesis, an eccentricity (e) of the rotor's axis of rotation with respect to the feed line (x-axis) has been assumed in the case of the drum element.

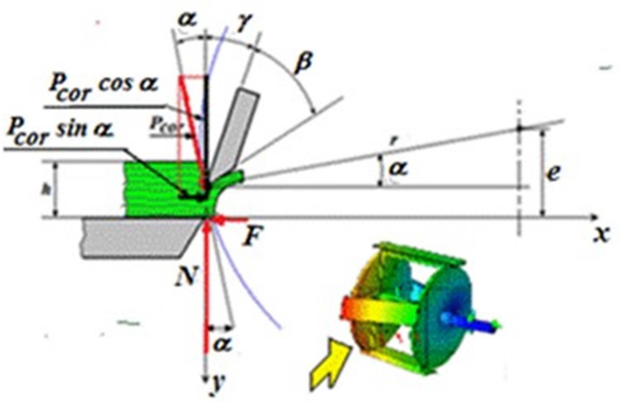

Figure 6. Schematic of the blade-plant mass-stress interaction

Under these conditions, the shear force (P_{cor}) is decomposed into a vertical component ($P_{cor}.cos\ \alpha$) that is used in the actual cutting action and a horizontal component ($P_{cor}.sin\ \alpha$) that is used in the pulling of the plant material. The normal (N) and horizontal (friction force F) components of the reaction force of the die also act on the free body of the fed material. The effect of the weight of the material fraction in the cutting zone is neglected in the model.

The first condition for material suction must be met:

$$P_{cor} \cdot \sin\alpha > F_{max},\ \mathrm{N} \qquad (7)$$

where F_{max}: maximum friction force, N.

$$F_{max} = N \cdot \tan\varphi,\ \mathrm{N} \qquad (8)$$

where φ is the angle of friction between the plant mass and the bearing material.

The angle of friction should preferably be considered dynamic (Ϫd), given the dynamic nature of the interaction between the bearing and the plant mass when it is struck and dragged by the blades.

Since:

$$N = P_{cor} \cdot \cos\alpha,\ \mathrm{N} \qquad (9)$$

Then, substituting 8 and 9 into 7, we obtain:

$$P_{cor} \cdot \sin\alpha > P_{cor} \cdot \cos\alpha \cdot \tan\varphi$$

$$\tan\alpha > \tan\varphi$$

$$\text{that is: } \alpha > \varphi \qquad (10)$$

This means that, as a first condition for the possibility of suction of the plant material by the cutting element, the angle α between the direction of the cutting force and the perpendicular to the plane of the cutting edge must be greater than the angle of friction between the plant material and the cutting edge material.

This condition is necessary but not sufficient, since for the movement of the plant material to occur in the direction of the feed, it must acquire a velocity in that direction, and this velocity must correspond to the design flow rate (throughput capacity, qo) of the mill, as well as guarantee the desired particle size (ΔL).

Applying the principle of work and energy, it can be stated according to Martínez *et al.* (2004a) that the work of the horizontal component of the resultant of the forces is used to provide kinetic energy to the fed mass, with a part of the energy also being dissipated by the effect of friction, that is:

$$(P_{cor} \cdot \sin\alpha - F_{max}) \cdot \Delta L = \tfrac{1}{2} m (V_{al})^2 \qquad (11)$$

where m: average mass of the material fed, kg.

This value of the feed mass can be determined as:

$$m = F_{sra} \cdot \frac{L_t}{2} \cdot \gamma_c,\ \mathrm{kg} \qquad (12)$$

where *Lt* is the length of the clump of stalks fed, m.

The loading area F_{sra} corresponds to a manual feeding system without feed rollers and is determined experimentally, evaluated according to expression 3, while the density of the compacted mass γ_c is also determined experimentally within the framework of this work.

Returning to expression 11, the size of the shredded particles (ΔL) and the average velocity of the fed mass (V_{al}), corresponding to a flow rate qo (kg/s) equal to the mill's throughput, are related according to the expression;

$$V_{al} = \frac{\Delta L \cdot Z \cdot n}{60},\ \mathrm{m/s} \qquad (13)$$

The average speed that the fed mass must have is also determined based on the material flow rate, as follows:

$$V_{al} = \frac{q_o}{F_{sra} \cdot \gamma_c},\ \mathrm{m/s} \qquad (14)$$

On the other hand, regarding the vertical axis, it can be stated that:

$$(P_{cor} \cdot \cos\alpha) \cdot \Delta s = F_{sra} \cdot A_e,\ \mathrm{N} \qquad (15)$$

Therefore, the shear force can be determined as:

$$P_{cor} = \frac{F_{sra} \cdot A_e}{\Delta s \cdot \cos\alpha},\ \mathrm{N} \qquad (16)$$

where:

Ae: the specific cutting energy of the processed product, N·m/m2

Δs: the displacement of the cutting force during contact of the blade edge with the fed mass, m

Solving for α the system of equations 9 to 16, we obtain:

$$\alpha = tg^{-1}\left[tg\ \varphi_d + \frac{L \cdot {q_o}^2 \cdot \Delta s}{4 \cdot A_e \cdot {F_c}^2 \cdot \gamma_c \cdot \Delta L}\right],\ \text{rad} \qquad (17)$$

Equation 17 allows us to determine the angle α that guarantees an average suction velocity corresponding to the flow rate q_o (kg/s), while also ensuring the desired average particle size ΔL for the shredded particles. The value of α depends on the physical and mechanical properties of the feed mass, such as Ae and γc, and the length of the clump of stalks being fed, as well as the loading area $F_{sra.}$

The displacement of the cutting force (Δs) during the cutting process can be approximately determined by the average of the extreme travels of the blade (h_1 and h_2, Fig. 3), that is:

$$\Delta s = \frac{h_1 + h_2}{2} \qquad (18)$$

egarding the flow rate (q_o) of the material processed by the machine, its determination will be addressed below.

Modeling for calculating the load-capacity relationship

In the case of feed mills for animal feed, the load calculation is based on the mass of material processed (G, kg/day) consumed daily in a livestock facility:

$$G = Q \cdot g,\ \text{kg/día} \qquad (19)$$

Where: Q: the number of animals to be fed; g: the daily consumption of each animal, in kg/day.

If T (h/day) is defined as the daily operating time of the shredding machine, during which the feed required for one day must be processed, then the load q (kg/s) of the working element will be given by:

$$q = \frac{Q \cdot g}{3600 \cdot T},\ \text{kg/s} \qquad (20)$$

on the other hand, the throughput q_o (kg/s) of the shredding element will depend on a set of construction and operating parameters of the mill, as well as the properties of the plant material and the required particle size of the processed product, such as:

- The number of blades on the drum or disc (Z);
- The rotational speed of the cutting element (n, rev⁄min);
- The loading area faced by a blade in each cut (F_{sra}, m^2);
- The density of the plant material at the time of cutting (γ_c, kg/m3);
- The length of the shredded particles (ΔL, m). It is appropriate to clarify that, in the case under study, the loading area (Fsra) is taken to be that corresponding to a drum mill without feeder rollers and processing a mixed plant mass, composed of thin stems, branches and leaves, as represented in Figure 3. Likewise, the density of the mass at the time of cutting (γ_c) corresponds to these conditions.

The volume of stems V_n (m^3/rev) cut in one revolution of the cutting organ will be given by:

$$V_n = F_{sra} \cdot \Delta L \cdot Z,\ \text{m}^3/\text{rev} \qquad (21)$$

Then the volume processed per unit of time Vt (m^3/s) will be:

$$V_t = F_{sra} \cdot \Delta L \cdot Z \cdot n \cdot \frac{1}{60},\ \text{m}^3/\text{s} \qquad (22)$$

and the mass of stems that can be processed per unit of time by the working organ (throughput capacity) will be given by:

$$q_o = F_{sra} \cdot \Delta L \cdot Z \cdot n \cdot \frac{1}{60} \cdot \gamma_c,\ \text{kg/s} \qquad (23)$$

As is well known, during the calculation of parameters for forage shredding machines, as with other working components of harvesting or processing machines, the match between the loading capacity (q) and the throughput (q_o) must be ensured to prevent blockages and guarantee efficient equipment operation.

Results of the experimental determination of moringa properties

Table 1 shows the statistical data obtained during the experimental determination of the loading area (Fsra) of moringa plant material during its processing in a drum mill without forced feeding.

It can be seen that the mean value of the loading area reached 105.02 cm² with a mean square deviation of 20.96 cm², resulting in a mean error of 9.5 cm², with a significance level of 0.05.

Table 1. Results of the determination of the load area f_{sra}

	h_1 (cm)	h_2 (cm)	b_1 (cm)	*Loading área* F_{sra}, (cm^2)
Mean value	1.65	6.92	24.5	105.02
Mean Square Deviation	0.75	0.99	0.00	20.96
Mean error				9.5
Calculated sample size				12
Sample size used				15
Student's t-test				1.75
Significance level				0.05

The results of the volumetric density determination of moringa, both in its natural state at the beginning of the feeding process and after compaction by the blades prior to cutting, are shown in table 2.

Table 2. Results of the volumetric density determination of moringa plant material

Statistician	Density of the initial mass, γ_{sc} (kg/m^3)	Compacted density γ_c (kg/m^3)
Mean value	40.41	188.04
Mean Square Deviation	5.39	32.78
Mean Error	4.04	9.8
Calculated sample size	3.85	9.30
Sample size used	15	15
Student's t-test	1.47	1.75
Significance level	0.05	0,05

The table shows that the volumetric density of moringa, when compacted by the blades up to the moment of cutting, increases from just over 40 kg/m³ to 188 kg/m³, exceeding the density of the bulk material in its normal state by 4.6 times.

The results of the experimental determination of the static moringa-steel friction angle (φ_e), as well as the calculation of the dynamic friction angle (φ_d), are shown in table 3.

Table 3. Results of the determination of the moringa-steel friction angle

	moringa-steel friction angle	
Statistician	**Static, ϕ_e (°)**	**Dynamic, ϕ_d (°)**
Mean value	52.50	27.63
Mean Square Deviation	5.64	
Mean Error	2.62	
Calculated sample size	13.67	
Sample size used	20	
Student's t-test	1.72	
Significance level	0.05	

The table shows that the static friction angle reaches 52.5° with a mean error of 2.62°, for a significance level of 0.05, which means there is a 95% probability that the population mean lies between 49.88° and 55.12°. Furthermore, the dynamic friction angle is found to be approximately half of the static friction angle.

Results of the evaluation of the developed models

Figure 7 shows screenshots of the first page of the software developed for calculating the parameters that guarantee, on the one hand, the appropriate load-capacity relationships, and on the other hand, the suction conditions required for efficient work of a drum mill, during the processing of a mixed plant mass, composed of thin stems, branches and leaves

The software programs contain the expressions developed for calculating load-capacity relationships and suction conditions for the plant material, in order to quickly obtain the desired output variables based on the input variables entered. In this case, the programs were applied using the properties of moringa, with the aim of obtaining the mill's operating parameters that guarantee efficient operation during the processing of this plant material.

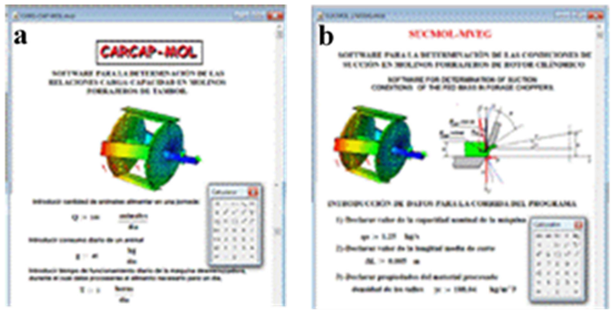

Figure 7. Screenshot taken from the software developed: a) For calculating load-capacity relationships; b) For calculating suction conditions.

The following data were declared as inputs to the CARCAP-MOL program:

- Number of animals to be fed per day: Q = 100 animals/day.
- Daily consumption per animal: g = 40 kg/day.
- Daily operating time of the mill: T = 1 h/day.
- Average length of the particles to be ground: ΔL = 0.005 m.
- Rotation speed of the chopping drum: n = 1900 rpm.
- Number of blades on the chopping drum: Z = 4
- Density of the compacted plant material: γc = 188.04 kg/m³.
- Loading area: F_{sra} = 0.0105 m².

For these input data, the following outputs are obtained:

- Machine load: q = 4.10³ kg/h.
- Throughput capacity: q_o = 1.25 kg/s = 4.5 x 10³ kg/h. Verifying that the load does not exceed the machine's throughput capacity.
- For the evaluation of the SUCMOL-MVEG program, the following input data are used:
- Throughput capacity: q_o = 1.25 kg/s.
- Average length of the particles to be shredded: ΔL = 0.005 m.
- Density of the compacted plant material: γc = 188.04 kg/m³.
- Specific cutting energy: Ae = 0.6 x 10⁴ N/m².
- Loading area: F_{sra} = 0.0105 m²
- Moringa-steel friction angle: φd = 27.63°.
- Length of the plant material bundle being fed: L = 0.75 m.
- Drum diameter (at the blade edge): D = 0.34 m.
- Inner drum width: b_1 = 0.245 m.
- Blade angle (Fig. 3): θ = 100 = 0.175 rad.

Shortest distance from the blade to the cutting edge at the start of cutting: $h_1 = 1.65 \times 10^{-2}$ m.

Longest distance from the blade to the cutting edge at the start of cutting: $h_2 = 6.92 \times 10^{-2}$ m.

With this input data, the program calculates the angle α between the direction of the cutting force and the perpendicular to the plane of the cutting edge, according to equation 17. This ensures an average suction velocity corresponding to the flow rate qo (kg/s), while also guaranteeing the desired average particle size ΔL for the shredded particles.

It also provides the verification result for compliance with the first condition for the possibility of suction of the plant material by the cutting element, checking if the obtained angle α is greater than the friction angle. In this case, the following results were obtained:

$$\alpha = 28.53° > \varphi d = 27.63°$$

Finally, the program provides the eccentricity value e (Fig. 6) of the drum axis with respect to the plane of the die, which is the adjustment parameter indicated to achieve the desired angle α. In this case, the value obtained is e = 0.103 m.

CONCLUSIONS

- Through conceptual mechanical-mathematical modeling of the interaction of a cutting element in a drum-type forage mill without forced feeding, expressions are obtained that allow the calculation of the mill's design and operating parameters to guarantee an efficient suction effect, with the required material flow and particle size, during the processing of a plant mass composed of thin stems, branches, and leaves.
- For a plant mass composed of moringa (*M. oleifera*) stems, branches, and leaves, parameters and properties required as input data for the developed models are experimentally determined, such as: the loading area, which reaches an average value of 105 cm²; The density of the compacted mass during the cutting action reaches an average value of up to 188 kg/m³, exceeding the density of the mass in its normal state by 4.6 times. The static friction angle of the plant mass with the steel reaches an average value of 52.5°, decreasing to 27.63° under dynamic conditions.
- The mathematical models developed were programmed using computer software to facilitate their evaluation. The evaluation of the models, using data related to the processing of moringa in a drum-type forage mill available on Cuban livestock farms, showed that setting the eccentricity of the drum shaft to 0.103 m relative to the level of the grinding wheel ensures the required material flow and particle size.

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