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Characterization and construction of a compact hammer mill for laboratory use to homogenize natural fibers of *Elaeis guineensis* and *Acrocomia* sp.

Caracterización y construcción de un molino de martillos compacto para uso de laboratorio para homogeneizar fibras naturales de *Elaeis guineensis* y *Acrocomia* sp.

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Abstract

This article provides an overview of the characterization and construction of a low-cost compact hammer mill for laboratory use to homogenize natural fibers of *Elaeis guineensis* and *Acrocomia* sp., in order to reduce the particle size of these fibers and other materials to study their physicochemical properties. The hammer mill was characterized by determining the theoretical output angular velocity in the rotor, the energy required per unit of mass during grinding (kJ/kg), the rotational speed of the rotor with its respective uncertainty extended to 95 %, the calculation of the stress and the safety factor in the rotor and hammers, the resulting particle size of the empty bunch of fruit oil palm (*Elaeis guineensis*) and the nutshell of the macaw fruit palm (*Acrocomia* sp.). The hammer mill was built with materials that can be obtained in an industrial hardware store, and a recycled vehicle part. The construction methodology was based on precision machining and metalworking. Residual lignocellulosic materials, such as the empty fruit oil palm cluster, the nutshell of the macaw fruit palm, rocks, coconut shell, wood, sludge, and aluminum slag were ground using this device. The construction of the hammer mill is compact and versatile, and it allows grinding a wide variety of materials for research processes that require the reduction of organic and inorganic materials. Due to its modest size, it can be placed in a laboratory, and since its powered by 110 V, no special requirements are necessary.

Keywords:
Biomass, circular economy, crusher, grinding mill, particle reduction, residual lignocellulosic.

Resumen

Este artículo proporciona una visión de la caracterización y construcción de un molino de martillos compacto de bajo costo para uso de laboratorio para homogeneizar fibras naturales de *Elaeis guineensis* y *Acrocomia* sp., para reducir el tamaño de partícula de estas y otros materiales y estudiar sus propiedades fisicoquímicas. El molino de martillos se caracterizó por determinar la velocidad angular teórica de salida del rotor, la energía por unidad de masa en molienda (kJ/ kg), la velocidad de rotación con su respectiva incertidumbre extendida al 95 %, el cálculo del esfuerzo y el factor de seguridad en el rotor y los martillos, el tamaño de partícula resultante del pinzote de palma aceitera (*Elaeis guineensis*) y el coquito de la fruta de palma de coyol (*Acrocomia* sp.).El molino de martillos fue construido con materiales que se pueden obtener en una ferretería industrial y una pieza de vehículo reciclada. La metodología de construcción se basó en el mecanizado de precisión y la metalistería. Los materiales lignocelulósicos residuales, como el pinzote de palma aceitera, el coquito de la palma de fruta del coyol, rocas, cáscara de coco, madera, lodo y escoria de aluminio se molieron utilizando este dispositivo. La construcción del molino de martillos es compacta y versátil, y permite moler una amplia variedad de materiales para procesos de investigación que requieren la reducción de materiales orgánicos e inorgánicos. Debido a su modesto tamaño, se puede colocar en un laboratorio, y dado que funciona con 110 V, no son necesarios requisitos especiales.

Palabras Clave:
Biomasa, economía circular, lignocelulósica residual, molino, quebrador, reducción de partículas

1. INTRODUCTION

For industrial applications, there are different types of mills, depending on their application. Some kind of mills used for particle size reduction are ball mill, roller mill and impact mill. The ball mill contains hard spheres mixed with the material to be crushed, that rotate inside a large cylindrical vessel. It is used in mining for both metallic ores and non-metallic minerals. The roller mill compresses the material against a horizontal rotary table using rollers that rotate on the surface of the table. It is used in mining for non-ferrous metals and non-metallic mine construction materials. The two previous mills can be used in a wet or dry environment. The impact mill projects the material against a hard flat surface, while the impact fractures the parts into smaller particles. This mill can be employed in coarse or fine crushing in batches or continuous [1]. The compact blade mills for laboratory use have sharp and robust blades which rotate inside the housing. They are used for preparation of laboratory samples, mainly foods with water, oil and fat content [2].

Another type corresponds to the hammer mill, which consists of metal bars that hit the material, fragment it, and force it against another surface. An advantage of hammer mills is that these are capable of processing many types of materials [3]. Hammer mills included a high-speed rotor inside a cylindrical casing. The position of the shaft is usually horizontal, and the material to be ground is fed from the top of the casing, split into pieces, and then falls through an opening located at the bottom. The particles of the material to be ground are broken by a series of rotating hammers coupled to a rotor disc [2].

A hammer mill is a machine used for crushing and grinding. The mill works by impact or percussion. In this case, the hammer mill is of the impact type [3]. The principle of impact grinding consists in throwing particles against a hard surface at a high speed. This impact fractures the material into smaller particles [1]. This machine can generally only grind and crush dry materials like grains, rocks, biomass dry and others [1]. The components of a hammer mill are the feed and discharge hopper, the frame, the power transmission system, the electrical system and the crushing system [3].

The issue that triggered this research and led to the construction of this mill was the need to defiber and grind the empty fruit oil palm cluster fiber. Initially, a blade mill was used, but the fiber was not milled. The empty fruit oil palm cluster fiber became entangled in the blades and heated the mill engine. For the research process of the empty fruit oil palm cluster fiber, it was necessary to reduce the particle size to place it in the drying scales, where the fiber is deposited on plates of 66 cm^2, and then it is proceeded to characterize the physicochemical properties of this material.

This fiber has an elastic natura, so to solve the problem with the grinding process, it was decided to build a compact mill, since the cost of purchasing an impact mill for laboratory use is considerable. Additionally, these mills do not provide certainty that the grinding is effective for a fiber of this nature. Researching articles about milling, designs of mills for grain grinding or mill construction were found in final graduation papers, but no scientific articles were found, where details of the characterization and construction of a mill were considered. The objective of this article was the characterization and construction of a compact hammer mill for laboratory use to homogenize natural fibers of *Elaeis guineensis* and *Acrocomia* sp.

2. MATERIALS AND METHODS

2.1 Location of the study

This research was carried out in the Biomass Laboratory of the School of Chemistry of the University of Costa Rica, San José, Costa Rica and Desarrollos Tecnológicos Teck S. A., San José, Costa Rica.

2.2 Sample collection and storage

Samples residual lignocellulosic materials were ground from the empty fruit oil palm cluster (*Elaeis guineensis*), the nutshell of the macaw fruit palm (*Acrocomia* sp.). Both materials were obtained from the Biomass Laboratory of the School of Chemistry. These were collected in Costa Rica, in the plantation areas of Palma Tica S. A. and Green Integrated Energies S. A.

2.3 Building requirements of the hammer mill

The purpose of building this hammer mill was to grind residual lignocellulosic materials such as oil palm empty-fruit bunch (*Elaeis guineensis*) and the nutshell of macaw palm (*Acrocomia* sp.). One of the premises for the construction of the hammer mill was that it must be small enough in size to be located within laboratory space. In addition, it should be easy to move from one place to another, and its operation should be simple. It was decided to use a 110 V electrical power supply system, which is typically available in Costa Rica.

When the research to characterize the nutshell of macaw palm was initiated, tests were carried out to process this biomass using a knife mill. Nevertheless, the results were not satisfactory since it was not possible to grind nutshell of macaw at all. Therefore, the product had to be crushed in a stone crusher used to process gravels. The hammer mill described in this article allowed to completely grind the nutshell of the macaw shell and, therefore, it was not necessary to continue using the stone crusher.

The nutshell of macaw palm has a high hardness. The parameter was measured in the Metallurgy Laboratory of the School of Mechanical Engineering of the University of Costa Rica using a diamond indenter. The hardness was measured using the Rockwell A test [4], and the value obtained was (30,5 ± 1,7) HRA. This same hardness scale is used for characterizing thin sheets of steel [5].

Therefore, it was determined that an option to crush the nutshell of macaw palm (*Acrocomia* sp.) was to use a hammer mill, since, due to its construction characteristics, is more suitable for grinding materials that exhibit a greater hardness than common natural fibers, such as wood, bagasse, rice husk, among others. All hammer mills must be manufactured from a forged and tempered material that has a high enough hardness to perform grinding and crushing operations effectively. For the residual lignocellulosic materials of oil palm empty-fruit bunch, it was necessary to reduce the size of the fiber and homogenize it before studying its physicochemical properties, a hammer mill can also be used.

2.4 Materials and equipment used for the construction of the hammer mill

This hammer mill was built in Costa Rica using equipment such as a lathe, welding machine, sheet metal bender, and other required tools. The materials needed for the construction of the hammer mill were obtained from general warehouses. The components are: electric motor 373 W (1/2 hp), pulley of 200 mm in diameter, pulley of 50 mm in diameter, bearing of diameter 25,4 mm, flat belt type A, thickness of steel sheets of 1,59 mm, steel angles 38,5 mm x 3,5 mm, steel bar 14,5 mm in diameter, control box and Sandvick tube of 220 mm and second-hand leaf spring obtained from a suspension system of a vehicle, which was obtained from truck waste materials. A complete list of materials used is shown on TABLE I.

TABLE I
LIST OF MATERIALS FOR HAMMER MILL CONSTRUCTION

Quantity	Description
1	Electric motor, 373 W (1/2 hp)
1	Pulley, 200 mm diameter
1	Pulley, 50 mm diameter
2	Bearing, 25,4 mm diameter
1	Flat belt, type A
3	Steel sheets, 1,59 mm thickness
2	Steel angles, 38,5 mm x 3,5 mm
1	Steel bar, 14,5 mm diameter
1	Control box
4	Leaf spring, obtained from the suspension system of a vehicle
1	220 mm Sandvick tube

The construction of the hammer mill required precision machining, welding, metal cutting and electrical installation. The rotor was mounted horizontally because this position gives the advantage of occupying less space. This horizontal position allows the operator to swing the mill forward and backward easily. With this movement, the material to be ground is distributed more evenly in the hammers, improving grinding.

2.5 Hammer mill construction methodology

The first step of the construction was the mill casing, the chamber where the material to be homogenized is ground and crushed. For the construction of the casing, a 105 mm portion of Sandvick tube of 220 mm in diameter was used. Using the 1,59 mm steel sheet, two caps with the same diameter were made. One of the caps is fixed on the back, and the other is mobile and corresponds to the access of the mill housing.

In Fig. 1, the following elements can be observed: 1) Mill casing, 2) belt, 3) shaft, 4) block bearing and 5) pulley 200 mm diameter.

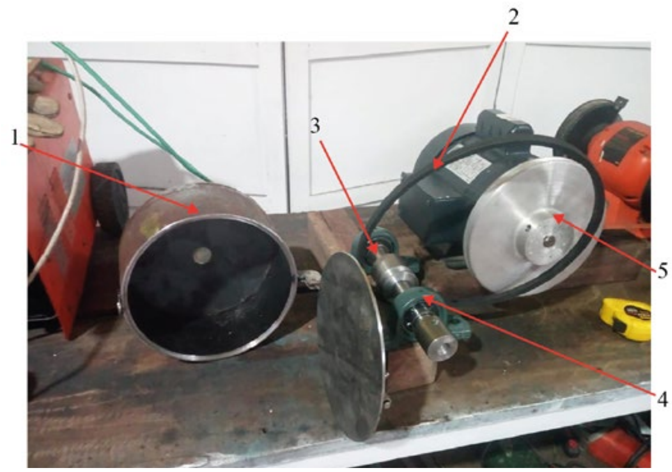

Fig. 1. Mill shell of the hammer mill.

The feed hopper has a height of 210 mm, and it lies above the mill housing. The feed mouth of the hopper and its corresponding cover measure 100 mm x 100 mm. The entire hopper was built from the 1,59 mm sheet. In Fig. 2, the following elements are shown: 1) mill shell and 2) hopper.

Fig.2. Mill shell and hopper built.

The base of the machine is rectangular, with a length of 350 mm and a width of 160 mm. It was built using steel angles of 38,5 mm x 3,5 mm, welded at the corners. Two vertical supports were welded on top, and a 15 mm welded tube with a length of 160 mm and 15 mm in diameter was placed over it. Inside the tube, there is an axis of the same length and a diameter of 14,5 mm, as it is shown in Fig. 3, where the following parts can be found: 1) shaft 14,5 mm diameter, 2) pipe (welded to the machine), 3) angle profile (350 mm x 38,5 mm x 3,5 mm) and 4) angle profile (160 mm x 38,5 mm x 3,5 mm).

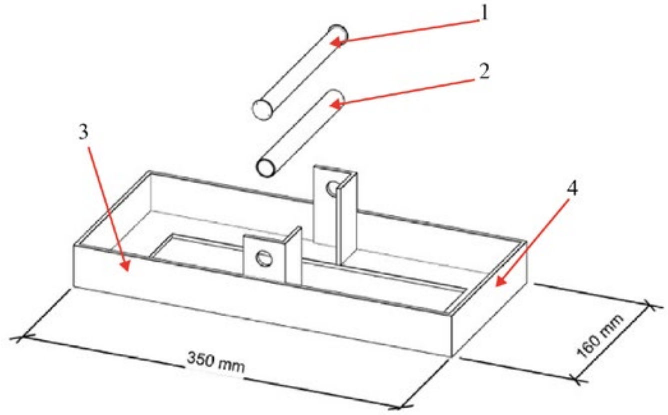

Fig.3. Element of the base of the hammer mill.

The base where the motor rests was built from a plate with dimensions of 190 mm x 130 mm and it was placed at a height of 250 mm from of the base, as shown in Fig. 4. In this design drawing, there are elements shown such as 1) the mill casing, 2) the blocks bearings base (250 mm x 38,5 mm x 3,5 mm), 3) the motor base (190 mm x 130 mm x 3,5 mm), 4) the angular profile (175 mm x 38,5 mm x 3,5 mm), 5), the angular profile (250 mm x 38,5 mm x 3,5 mm), and 6) the hinge. All materials were obtained from a hardware store.

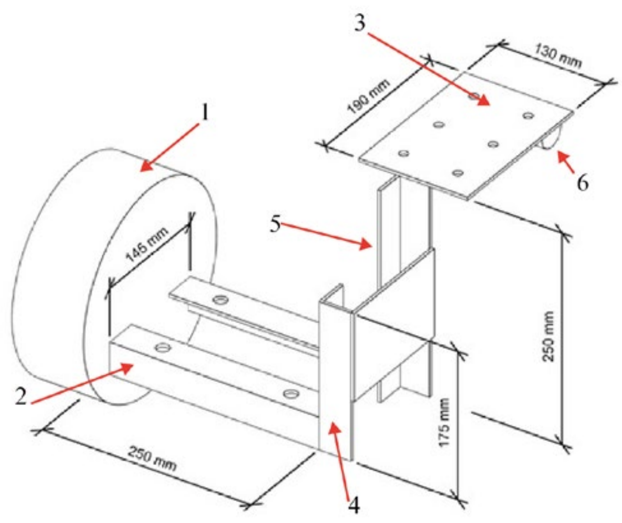

Fig.4. Assembly sketch of the mill shell and mill Base.

The mill was fitted with a 373 W (1/2 hp) engine, with an output speed of 1720 rpm. A set of two pulleys with a ratio of 4:1 was used. The largest diameter pulley has a diameter of 200 mm, and it was directly attached to the motor. The smaller pulley has a diameter of 50 mm, and it was coupled to the transmitting shaft attached to the blades. According to [6], the angular velocity of output in the rotor is giving by equation (1).

$$\omega_{out} = \frac{r_{in}}{r_{out}} \cdot \omega_{in} = \frac{200\ mm}{50\ mm} \cdot \ 1720 \text{ rpm} = 6880 \text{ rpm} \quad (1)$$

With this pulley arrangement, it was possible to increase the speed of the hammers relative to the speed of the motor shaft. Fig. 5 shows the assembly of the motor, the set of pulleys (50 mm and 200 mm diameter), the feed hopper and the mill casing, and the following components are indicated: 1) motor, 2) pulley set, 3) block bearing, 4) hopper and 5) mill casing.

Fig.5. Real Assembly of the mill shell and mill base.

Once the construction of the mill was completed, the rotational speed of the rotor was measured using a digital optical tachometer with a resolution of 0,1 rpm. Four runs were made, the corresponding measurements were averaged, and the value was reported with its respective uncertainty with a probability of coverage of 95 %.

For the design of the crushing hammers, vehicle leaf springs were used. The springs can be manufactured of any kind of steel that has at least 0,55 % carbon and heat-treated to a hardness between 42 HRC and 49 HRC [7].

According to equivalences of hardness scales [4], the values of 40 HRC and 45 HRC correspond to 70,5 HRA and 73 HRA, respectively. Therefore, the hardness of hammers is much higher than the nutshell of macaw palm and oil-palm empty fruit bunch.

In the case of biomass corresponding to the nutshell of macaw palm (*Acrocomia* sp.), hammers, instead of metal blades, should be used for grinding. This is because, before starting the construction of the hammer mill, a full-scale crusher was used to reduce the size of the nutshell of macaw palm. Due to its high hardness, it was not reasonable to use a mill with metal blades, but instead one with hammers was used.

All hammers were made from leaf springs. In the process of designing and building the mill, it was required to modify the shape of the hammers twice. For the first design, only two long hammers of 6 mm x 13 mm x 80 mm and four short hammers of 6 mm x 13 mm x 35 mm in length with an inclination of 25º with respect to the axial direction of the rotor were included.

While testing this design, it was observed that the oil palm empty-fruit bunch fiber became entangled with the hammers, accumulating at the bottom of the hopper and, finally, it failed to grind. This was due to the fact that oil-palm empty fruit bunch has a high elasticity. To solve this problem, a second design was proposed, with two horizontal sections of 35 mm welded into the shorter hammers. In addition, six additional blades were welded inside the mill housing along the circumference, to function as a trap for the fiber, and also to redirect the oil palm brush fibers to the center of the hammers, thus avoiding its accumulation in the lower part of the hopper. In this way, it was possible to obtain an effective grinding. Fig. 6 shows section A-A and the front view of the hammer mill feed hopper. The front view and A-A (internal) section show the design of the hammers and blades inside the mill housing. The A-A section shows the blades, slanted to a 40º angle, which were built from truck springs. Elements shown in section A-A are 1) 40° slanted blades 2) hammers 3) welding stainless-steel.

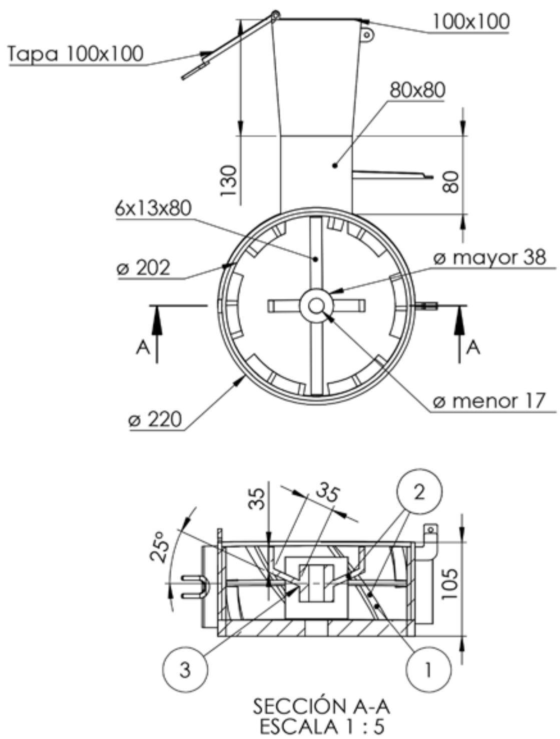

Fig.6. Front view and section A-A (internal) of the mill housing and feed hopper.

Four hammers (element 1) and a total of twelve complementary 100 mm blades were welded along the internal circumference of the drum, with an inclination of 40° with respect to the axial direction (element 2). The cover lid for the mill casing (element 3) confines the fiber while it is being ground. Fig.7 shows the following elements: 1) hammers, 2) complementary blades already installed and 3) cover lid.

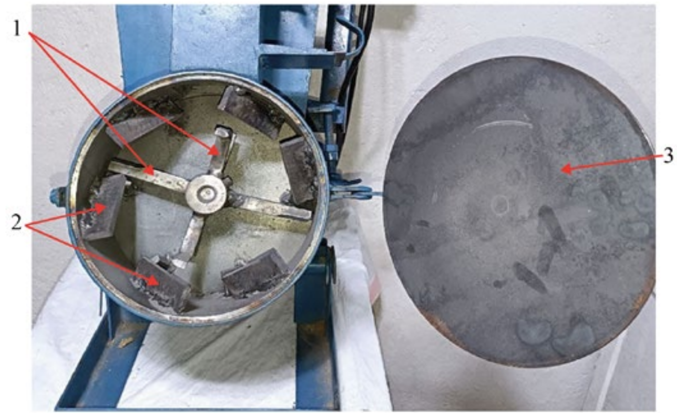

Fig.7. Elements of principal and complementary blades inside mill casing

2.6 Methodology for measuring the rotational speed of the rotor

The methodology used to verify the rotational speed of the mill rotor utilized an optical tachometer. A reflective label was placed on one of the hammers of the mill. Subsequently, the mill was lit with the door open. The optical tachometer was pointed at the reflective label and the measurements were obtained.

Four hammer mill shaft rotor speed values were obtained and averaged. To find the value of the uncertainty of this average [8], the expanded uncertainty was calculated by equation (2):

$$U = k \cdot \frac{s}{\sqrt{n}} \tag{2}$$

Where,

U: is the expanded uncertainty.

k: is the coverage factor obtained from the t-Student distribution with 3 degrees of freedom and a confidence level of 95 %.

s: is the sample standard deviation of the 4 runs.

n: is the number of runs.

2.7 Methodology for Finite Element Analysis

Finite element analysis was used to determine the stress generated by the material on the hammers. Since the hammers and the material to be crushed are moving inside the casing, determining the forces involved is not a simple problem, so the following simplifications were considered [9]:

- The material is homogeneous, and the mass is constant.
- The force is applied at the tip of the hammers.
- Gravity force was not included in the calculations.

- The analysis was performed in a steady state.
- The friction factor between the casing walls and the material is equal to 1,0 (worst case possible).
- The maximum force that the hammers may experience is the stationary weight of the material inside the casing.

The methodology utilized for the analysis was the following:

- The rotor and hammers were drawn in a CAD software (Autodesk Inventor).
- Carbon steel was chosen as the material.
- The maximum force that the hammers may apply was calculated, considering the motor power (373 W), the theoretical rotational speed (6880 rpm), and the total hammer length (100 mm). The obtained value was 5,18 N. The equations (3), (4) and (5) show how these data were obtained:

$$\omega_{out} = 6880\ \frac{rev}{min} \cdot \frac{2\pi}{1\ rev} \cdot \frac{1\ min}{60\ s} = 720\ \frac{rad}{s} \tag{3}$$

$$\tau = \frac{\mathrm{P}}{\omega} = \frac{373\,\frac{J}{s}}{720\frac{rad}{s}} = 0{,}518\ \mathrm{Nm} \tag{4}$$

$$\tau = \mathrm{F} \cdot \mathrm{r} \rightarrow F = \frac{\tau}{r} = \frac{0{,}518\ \mathrm{Nm}}{0{,}1\ \mathrm{m}} = 5{,}18\ \mathrm{N} \tag{5}$$

- A vector of 5,18 N in magnitude was positioned at the tip of each of the hammers, tangentially opposed to the direction of the rotational movement, to simulate the forces that the material would apply.
- The central axis was considered as a fixed restriction.
- The simulation was run in the software.
- Results were obtained and analyzed.

2.8 Methodology for the analysis of particle size of the empty fruit oil palm cluster (*Elaeis guineensis*) and the nutshell of the macaw fruit palm (*Acrocomia* sp.)

The fibers of the empty fruit oil palm cluster (*Elaeis guineensis*) and nutshell of the macaw fruit palm (*Acrocomia* sp.) were weighted, and then, they were sieved, according to the methodology indicated by the standards INTE / ISO 17827-1: 2022 / INTE / ISO 17827-2: 2022 [10], [11], using the AS 200 sieve manufactured by Retsch. The particle size was determined from the mesh size of the sieves used, and the granulometric analysis was developed with the percentage of matter retained and that which passes through the holes of the mesh.

2.9 Methodology for estimating energy per unit mass invested in grinding

The estimate of the energy required for grinding was obtained by dividing the energy delivered by the motor during a time interval by the mass of the grinding [12]. The energy delivered by the motor was obtained from the rated power and a measurement of the grinding time interval. Mathematically the equation that defines the energy per unit mass is as follows:

$$\varepsilon = \frac{P \cdot t}{m} = \frac{(373\,J/s).(120\,s)}{0{,}1\text{ kg}} = 450\text{ (kJ/kg)} \tag{6}$$

here:

ε: The energy invested per unit mass in grinding (kJ/kg).

P: Motor power (W).

t: grinding time (s).

m: mass of the biomass (kg).

3. RESULTS

3.1 Description of the hammer mill elements

The hammer mill was successfully built, and it managed to grind the oil-palm empty fruit bunch fiber effectively. It also managed to crush the nutshell of macaw palm, reducing the size of the biomass. Thus, it was possible to prepare the materials for an eventual study of their physicochemical properties. Additionally, other materials such as stone, coconut shell, balsa wood, sludge and aluminum slag were milled. Although, this was not the initial purpose of the hammer mill, it is important to consider it because this machine meets other needs of researchers who need to grind different materials.

Care must be taken to avoid saturating the feed hopper with an excessive amount of the biomass to be ground or crushed, so that the hammer mill rotor is not locked. It is important to note that the purpose of this hammer mill is to grind small samples for laboratory applications.

The hammer mill was designed and built with eight main elements: the mill base (element 1), mill casing and feed hopper (element 2), eight hammers (element 3), 200 mm diameter pulley (element 4), 50 mm diameter pulley (element 5), 1/2 hp engine (element 6), blocks bearings (element 7) and control system (element 8). The design and assembly were done by authors and Fig. 8 illustrates the device in question; the following components are indicated: 1) mill base, 2) mill casing and feed hopper, 3) hammers, 4) 200 mm pulley, 5) 50 mm pulley, 6) motor, 7) blocks bearings and 8) control system.

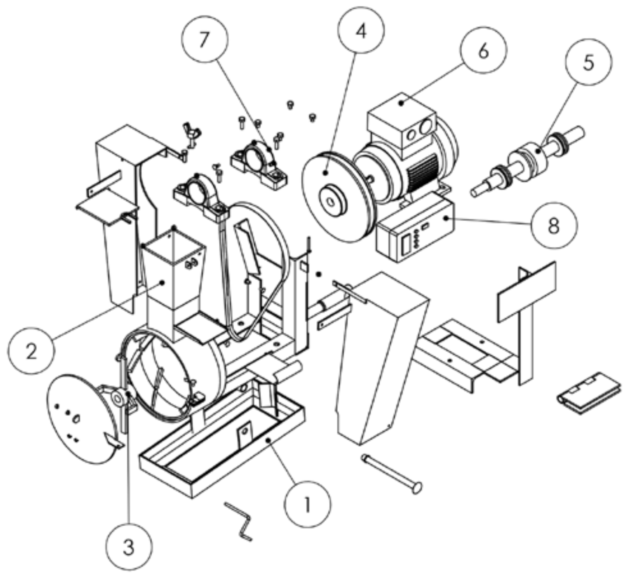

Fig.8. Exploded view of the main pieces of the mill.

Fig. 9 shows the hammer mill fully assembled and ready to be used in biomass reduction. The total cost of construction, including materials and labour was approximately 1000 US dollars. The cost of a mill for a similar application available in the market is around 25.000 US dollars. Therefore, the mill has a lower cost than the commercial equipment available.

It is important to note that this mill that was built has blades distributed in the inner circumference of the casing, with spaces between them so that the longest hammers (80 mm) can rotate without impacting with them. This allows to achieve a better defibration of the fiber of the empty fruit oil palm cluster (*Elaeis guineensis*).

Commercially, it is possible to find mills that have internal stands that, together with the blades, impact the material. But those mills and their elements are not designed to grind elastic fibers as the empty fruit oil palm cluster (*Elaeis guineensis*).

Fig.9. Hammer mill.

3.2 Rotational speed of the rotor

The analysis of the rotational speed of the hammer mill rotor was compared with the design value. Four runs were done, each one lasting approximately 30 s to 50 s. The results of these measurements confirm that the measurements of the rotational speeds were between 6400 rpm and 7300 rpm, as it is shown on the Fig. 10. This test was conducted with an optical tachometer. On one of the hammers, a reflector paper was placed. The motor was turned on to turn the hammers. The optical tachometer was taken and pointed to the reflector paper to take the measurements.

A dispersion of 900 rpm can be observed between the four runs, these variations may be due to stochastic effects associated with variations in the power supply and the starting state of the engine. After a long time, it is expected that the angular velocity of the motor may converge.

Fig.10. Hammer mill rotational speed of the rotor graph based on four measurements over time.

The averages of each of the four runs (twenty speed data were taken in each run), and then, a combined average of those values was obtained as shown in TABLE II.

TABLE II
AVERAGE SPEED IN EACH RUN, TEST CONDUCTED WITH AN OPTICAL TACHOMETER

Race number	Rotational speed /rpm
1	6465
2	6917
3	6599
4	6796
Average	6694

The report of the rotational speed of the rotor with its respective uncertainty expanded to 95 % corresponds to (6694 ± 321) rpm. As it can be seen, the confidence interval includes the design value of the rotor rotational speed which is 6880 revolutions per minute. This data confirms that the design speed has been reached. Variations in measurements may be due to belt clearance, friction losses in rotating elements, and variations in mill operating conditions. It was possible to demonstrate from the measurements made that the hammer mill complies with the design speed of 6880 rpm.

3.3 Finite Element Analysis

Results reveal that the rotor and hammers assembly should not suffer any damage with the considered materials and planned use. Calculated stress values were well below the maximum for carbon steel, and safety factor was calculated at 7.0 minimum by the software. The possible point of failure, according to the analysis, is the welding between the hammers and the rotor, as shown in Fig. 11.

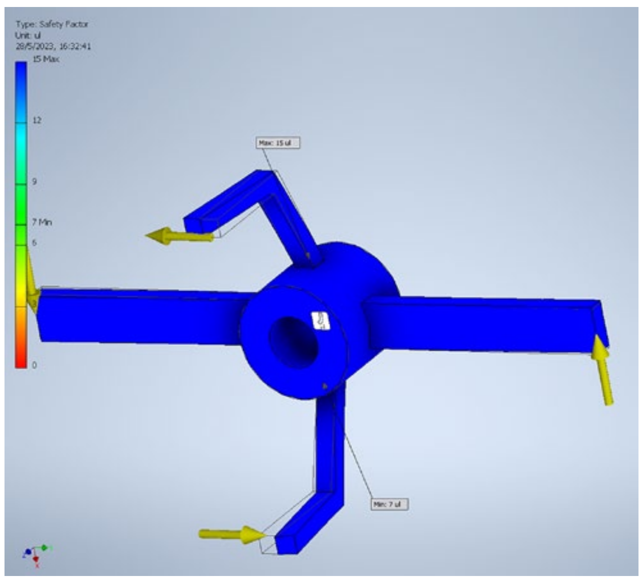

Fig.11. Safety factor of hammers.

3.4 Results of particle size of the empty fruit oil palm cluster (*Elaeis guineensis*) and the nutshell of the macaw fruit palm (*Acrocomia* sp.)

The residual biomass of the empty fruit oil palm cluster had an average size of 2,49 mm. The nutshell of the macaw fruit was ground to an average particle size of 2,70 mm.

3.5 Energy per unit mass required for grinding

The energy per unit mass required for grinding was estimated considering that a time of 120 s is required to grind 100 g of biomass. The result obtained was 450 kJ/kg.

3.6 Ground and crushed materials

This section shows the results of particle reduction of organic and inorganic materials obtained with the hammer mill. The device built exceeded the expectations, managing to grind not only the nutshell of macaw palm and the residual lignocellulosic materials of oil palm empty-fruit bunch, but also materials such as stone, coconut shell, wood, sludge and aluminum slag.

Fig. 12 shows the comparison of the residual lignocellulosic materials of oil palm empty-fruit bunch defibered and the same material after grinding. It can be observed that ground the empty fruit oil palm fiber is more homogeneous and presents a reduction in the physical particle size of the fiber.

Fig.12. Comparison of the empty fruit oil palm cluster (*Elaeis guineensis*)
a) not ground and b) ground.

Even when the nutshell of macaw palm has a high hardness, it can be observed that the hammer mill fulfilled the function of crushing it, as shown in Fig. 13. The aluminum slag, a ductile metal, was easily ground under the action of hammers, as observed in Fig. 14.

Fig.13. Comparison of the nutshell of the macaw fruit palm (*Acrocomia* sp.)
a) not ground and b) ground.

Fig. 14. Comparison of aluminum slag a) not ground and b) ground.

4. DISCUSSION

In this research, the hammer mill was able to reduce the particle size of the residual biomass. The average diameter of the nutshell of the macaw fruit is 20 mm to 25 mm, and it was ground to an average particle size of 2,49 mm. The average diameter of the empty bunch of a fruit oil palm cluster is 70 mm and a length of 10 mm, and it was possible to grind it to an average particle size of 2,70 mm. The hammer mill energy per unit mass required for grinding was 450 kJ/kg. The rotational speed of the rotor was determined as (6694 ± 321) rpm, and it allows grinding of materials that have high hardness. The safety factor was calculated at 7.0 minimum, so it is not expected the hammers to fracture when grinding similar materials. The hammer mill was built to reduce the particle size of different biomasses. This hammer mill is different from traditional laboratory mills, as these mills grind a spectrum of limited materials, because these have blades or balls instead of hammers [13]. The designed machine can process materials that other laboratory mills cannot grind, like stone, coconut shell, balsa wood, sludge and aluminum slag.

This hammer mill was designed with complementary blades installed internally around the mill casing to allow cutting the empty bunch of fruit oil palm, which a traditional hammer mill cannot process because elastic fibers tend to roll around their axis, making it impossible to grind [1]. A set of two pulleys with a ratio of 4:1 was used to reach a higher rotational speed than hammer mills with a larger dimension [13]. The hammer mill was driven by a 1/2 hp motor for grinding samples of different materials, compared to traditional hammer mills that require a 5 hp or more powerful motor to grind only grains [3]. The power supply system operates at 110 V, allowing the hammer mill to be easily used in a laboratory, not requiring a 220 V power supply, which is used at an industrial level [13].

The hammer mill is designed to reduce materials that will not be consumed by humans. If it were required to grind materials for human consumption, it would be necessary to build the hammer mill from stainless steel, like an industrial level equipment [13]. In addition, the design of the hammer mill would have to be modified by adding seals, so that there are no internal or external leaks [1].

5. CONCLUSIONS

The grinding process has the capacity for an optimal operation of 100 g/min, an adequate sample size for laboratory experiments. The angular velocity of the mill is (6694 ± 321) rpm, with an energy consumption of 450 kJ/kg, which allows to reduce the particle size of the fibers *Elaeis guineensis* and *Acrocomia* sp. at an average particle size between 2.5 mm to 3 mm, approximately. The hammer system has a safety factor of 7, which makes this compact mill extremely robust for grinding materials such as gravel, slag, coconut shell, among others.

For the construction of the hammer mill of this article, the application of the knowledge and principles of mechanics was required. Commercially available supplies were used, as well as recycled materials such as spare leaf springs from a vehicle suspension system used for building the hammers of the mill. These parts were very important, since they perform the grinding of the materials, therefore they require high hardness and toughness. Since they are recycled elements, its use collaborates with the reduction of waste in the environment, promoting the concept of circular economy, which is very necessary at this time.

The mill was built in order to provide compact, versatile, efficient and low-cost equipment for biomass researchers who need to reduce the particle size of the materials they are researching, either to study their physical, chemical or physicochemical properties. The construction exceeded the expectations of the authors, since it managed to reduce and homogenize the particle size of a wide variety of materials of organic and inorganic nature such as: *Elaeis guineensis* fiber, wood, nutshell of *Acrocomia* sp., gravel, aluminum slag that was even contaminated with steel particles. All these materials reduced their respective particles for research processes, where the grinding or breaking of the materials was necessary for the subsequent study of their properties. The constructed mill is a real-life application for the use of the researchers, as it provided them to have particle size reduction quickly and efficiently in a wide variety of materials of different nature and hardness, as well as being so compact and versatile; it also presents a modest size, which allows it to be placed on a laboratory bench without requiring large spaces. The power supply of the hammer mill is 110 V, so it does not need special electrical requirements which is necessary for medium to large industrial mills.

The cost of this hammer mill is low compared with commercially available equipment of similar characteristics, since it is approximately 1000 US dollars, which makes this design a versatile and economical option for investors with austere budgets.

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ROLES

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