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Original Article

Vertical Centrifugal Filter for the Separation of Mucilage and Water in the Coffee Demucilagination Process

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Abstract - *This research work presents the development of a vertical centrifugal filter for the separation of mucilage and water in the coffee demucilagination process in the province of Chanchamayo. The coffee demucilagination process is a crucial stage in the production of high-quality coffee, as it removes the mucilage, a sticky substance that surrounds the coffee beans. Traditionally, this process consumes large amounts of water and generates wastewater containing high levels of organic matter and sugars, contributing to the contamination of local water bodies. In the province of Chanchamayo, one of Peru's main coffee-growing regions, this issue has gained relevance due to the increasing demand for sustainable agricultural practices and the scarcity of water resources. In response to these challenges, the design of a vertical centrifugal filter is proposed, an innovative device aimed at reusing water in the demucilagination process. It features a frequency inverter to regulate the necessary RPM of the 1 HP electric motor, which spins the fine mesh centrifugal filter (0.5 mm), effectively separating the mucilage from the water for reuse. This technology aims not only to reduce water consumption but also to minimize water pollution, contributing to environmental sustainability and improving process efficiency.*

Keywords - *Centrifuge, Coffee, Demucilagenated, Filter, Water reuse.*

1. Introduction

Coffee is one of the most traded agricultural products in the world, second only to oil [1]. However, agriculture, including coffee production, is threatened by the adverse effects of climate change, water scarcity, and the need to adopt more environmentally friendly farming practices [2]. According to the World Bank [3], agriculture currently accounts for an average of 70% of the freshwater extracted globally. To address future challenges, it is essential to seriously consider water management in the agricultural sector. Therefore, raising awareness and conserving this resource in pursuit of the common good is crucial.

Peru ranks ninth in the production and export of conventional coffee worldwide [4]. In 2020, It remained among the top 10 coffee-exporting countries, with 4.3 million bags. [5]. However, the demucilagination process is a critical stage in coffee post-harvest, as it requires a considerable volume of water, ranging from 7.3 to 19.3 liters per kilogram of coffee in the first wash and 8.7 liters in the second [6]. This intensive water use not only represents a significant cost in terms of resources but also generates effluents with high organic matter content, contributing to the pollution of water bodies. [7] As a result, the province of Chanchamayo faces considerable challenges in water management during coffee post-harvest.

Despite the magnitude of these challenges, research to date has been insufficient in developing effective and sustainable technological solutions to optimize water use and reduce pollution in the coffee industry. This gap in the literature highlights a critical need that requires immediate attention, as, to this day, in Peru and other coffee-producing countries, the filtration of honey waters is still done manually through sedimentation, as seen in Figure 1. The present study addresses this need by proposing a Vertical Centrifugal Filter specifically designed to improve the efficiency of mucilage and water separation, thereby reducing water consumption and minimizing environmental impact. This innovation has the potential to revolutionize practices in the coffee demucilagination stage, promoting a more sustainable approach aligned with the environmental demands of the 21st century.

Currently, in Peru, there is inadequate technology for the separation of honey waters during the mucilage removal process. This could be due to outdated technology or the lack of consideration in the manufacture of a machine dedicated to filtration. This inefficiency leads to excessive delays of up to

48 hours in separating honey waters, as it is done manually [8]. This highlights the need for manufacturing filters that work efficiently and productively to optimize water use and reduce environmental impact. Below are 2 of the main backgrounds that we have relied on for the development of this research:

Fig. 1 Manual separation of honey waters through sedimentation in the province of Chanchamayo

Despite global advances in filtration technology, existing solutions in Peru remain inadequate. According to Huamani [9] in his thesis titled "Design of a Centrifugal Machine for the Utilization of Whey Proteins through the Production of Cottage Cheese at a Relative Humidity of Approximately 60% with a Capacity of 1kg/hour for the Rural Sector," presents a centrifugal machine designed for the recovery of whey proteins. This machine uses a single-phase motor with a frequency converter, a belt and pulley transmission system, and a filter cloth in the rotor for the retention of solids and liquid filtration. While functional, it is designed for low-capacity production (1 kg/hour) and includes manual processes, such as filter cleaning, which significantly reduce its efficiency and scalability. Additionally, its relatively high cost and limited automation make it less suitable for large-scale operations, such as those required in the coffee industry.

Another relevant reference is Xu Jing patent [10], "Horizontal Screw Centrifuge Capable of Efficient Solid-Liquid Separation" This machine features a horizontal helical screw to transport solids to a discharge port and liquids through internal orifices to a storage tank. It uses a single-phase motor and a gear system connected to the main shaft, allowing the drum to rotate continuously for centrifugal discharge.

However, this design presents notable limitations: it lacks a speed regulator for the centrifugation process, and the liquid discharge orifices allow small sediments to pass through, compromising separation efficiency. Additionally, its large dimensions make it impractical for the scale of operations envisioned for mucilage separation in coffee processing in Peru.

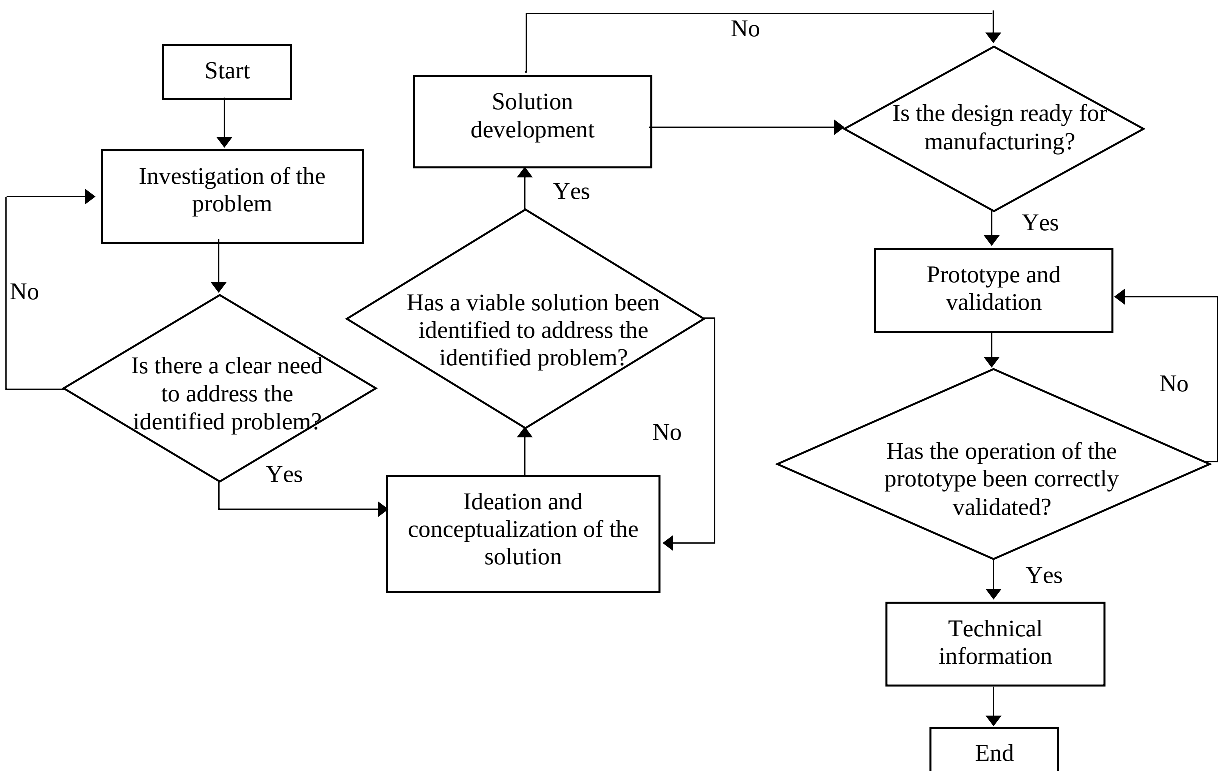

Fig. 2 Process diagram of the phases of the methodology for project development

This study addresses the gaps identified in existing technologies by developing a vertical centrifugal filter that not only improves the efficiency of the separation process but also offers scalability and better environmental performance. Unlike the designs mentioned above, this filter is designed for higher capacity, automated processes, and better sediment separation, making it a novel and critical advancement for the coffee industry in Peru. This work stands out by offering a dedicated solution to a persistent problem, significantly reducing water usage and environmental impact while increasing productivity.

The research method used is the scientific method. This choice implies a structured approach to develop the problem adequately, and the type of research is classified as technological because it is based on the development and application of new knowledge to create products or improve existing conditions.

The methodology used for this research is divided into five phases to address the identified problem. This methodology is a modification to the VDI 2221 and the I+P+D3 methodology [11]. These phases consist of problem investigation, ideation and conceptualization of the solution, solution development, prototyping and validation, and technical information. These phases are graphically detailed in Figure 2.

2. Materials and Methods

To address the problem, a process diagram (Figure 2) was developed to sequentially follow each phase until reaching the proposed solution.

Phase 1 involves thorough research to identify the problem faced by farmers in the Chanchamayo province, thus defining and focusing on the issue for better development and providing a more suitable solution. Similarly, a literature review is conducted to find background information and technologies that aid in the research.

Phase 2 involves proposing and analyzing the identified problem, using a black box (Figure 3) to understand the inputs and outputs of the machine, thereby generating accurate solution ideas aimed at finding the best solution.

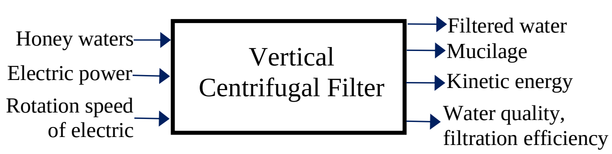

Fig. 3 Black box machine

Phase 3 puts the proposed solution into practice by applying engineering calculations to select appropriate materials for the machine's mechanisms and units (Table 1), focusing on the working conditions under which the machine will operate.

Table 1. Selection of materials according to mechanisms and units

Item	Material
Filtering mechanism	-Stainless steel plate A36 of 2mm -Fine mesh filter with 0.5 mm holes
Transmission mechanism	-1 Hp single-phase electric motor -AISI 1045 Steel shaft
Mucilage discharge unit	-Stainless steel plate A36 of 2mm
Fluid discharge unit	-1 inch PVC pipes
Structure	-Square tube of 20x20 mm ASTM 554

Phase 4 involves manufacturing the vertical centrifugal filter (Figure 4) for evaluation and performance testing under real working conditions to confirm the machine's performance and efficiency through results validation. Figure 4 also shows the main components of the mechanisms and units of the vertical centrifugal filter.

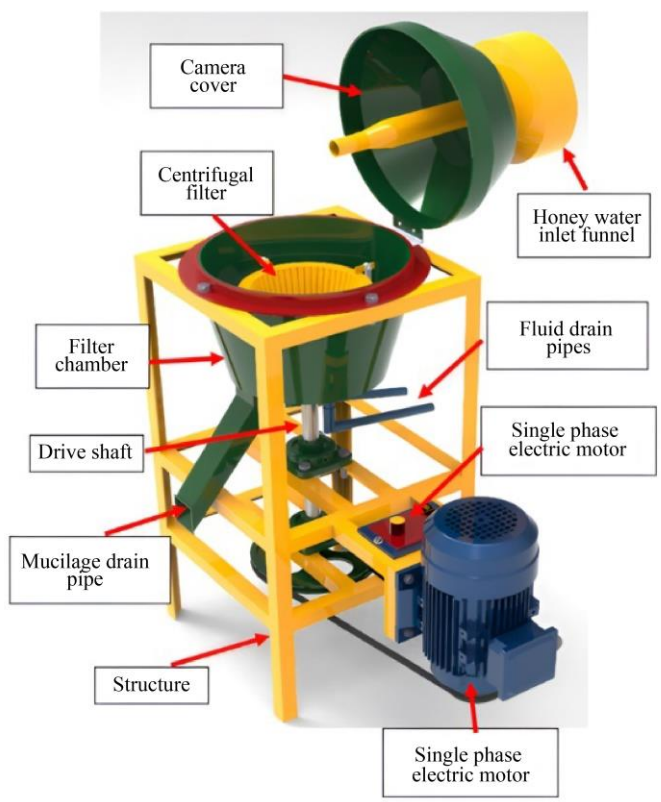

Fig. 4 Main components of the mechanisms and units of the vertical centrifugal filter

Finally, phase 5 generates detailed documentation of the research, outlining each of the previous phases and providing relevant information about the process and execution of the machine, from problem conception to results validation.

3. Results and Discussion

3.1. Filtering Mechanism

The filtering mechanism primarily features a filtering chamber. This chamber has holes at its base for extracting mucilage and water without mixing them. Additionally, the filtering chamber houses most components of this mechanism. Inside the filtering chamber is a conical centrifugal filter with a fine mesh of approximately 0.5 mm, which separates solids from liquids. This filter rotates thanks to the movement transmitted by a shaft connected on one side to the filter base and on the other to the driven pulley, which operates synchronously with the electric motor. This mechanism also includes a conical filter cover to prevent contact between mucilage and water after separation. Finally, to extract the mucilage outward, removal paddles are housed between the centrifugal filter and the filtering chamber. The results of the calculation of the main internal components are shown in Table 2.

Table 2. Calculation of the internal components of the filtering mechanism

Parameters	Equation	Results
Conical filter surface area	$A = \pi * r * l$	$A = 809.557\ cm^2$
Conical filter volume	$V = \frac{1}{3} * A * t$	$V = 80.956\ cm^3$
Filter housing surface area	$A = \pi * r * l$	$A = 1452.291\ cm^2$
Filter housing volume	$V = \frac{1}{3} * A * t$	$V = 145.229\ cm^3$
Area of the circular filter base	$A = \pi * r^2$	$A = 176.71\ cm^2$
Volume of the circular filter base	$V = A * t$	$V = 53.013\ cm^3$
Hexagonal coupling area	$A = 6 * \frac{s^2\sqrt{3}}{4}$	$A = 11.68\ cm^2$
Hexagonal coupling volume	$V = A * t$	$V = 22.336\ cm^3$

3.2. Transmission Mechanism

The transmission mechanism consists of an electric motor that drives a system of belts and pulleys connected to a shaft, with the aim of transmitting motion to the next mechanism. The calculations for determining the motor power and the diameter of the shaft are shown in Tables 4 and 5, respectively, where it is observed that the power of the motor is 1 Hp. The diameter of the transmission shaft is 30mm, and Figure 5 shows the simulation of the shaft deformation analysis, which indicates a maximum deformation of 0.192 mm, which demonstrates that the material used is appropriate. Additionally, this mechanism includes a frequency converter that allows the motor's RPM to be regulated according to the task. The RPM is adjusted based on the concentration of mucilage in the honey waters to optimize the separation process, as shown in Table 3.

3.3. Mucilage Discharge Unit

The mucilage discharge unit is made with a square cross-section of A36 stainless steel sheet to ensure more efficient evacuation of the mucilage. This unit is located at the bottom of the filtering chamber and helps evacuate the mucilage to the outside.

Table 3. Concentration of mucilage in honey waters

Parameters	Results
Low concentration	350-500 RPM
Medium concentration	500-850 RPM
High concentration	850-1200 RPM

Table 4. Electric motor power calculations

Parameters	Equation	Results
Conical filter inertia	$I_{fil.} = \frac{1}{2} * m_{fil.} * r^2$	$I_{filtro} = 0.00109\ kg * m^2$
Inertia of the circular base	$I_{b.} = \frac{1}{2} * m_{b.} * r^2$	$I_{b.} = 0.0086\ kg * m^2$
Inertia of honey waters	$I_{a.m.} = \frac{3}{10} * m_{a.m.} * r^2$	$I_{a.m} = 0.00139\ kg * m^2$
Total filter inertia	$I_{t.fil.} = I_f + I_b + I_{a.m.}$	$I_{t.f.} = 0.011126\ kg * m^2$
Effective inertia	$I_{ef} = I_{t.f} * \left(\frac{n_2}{n_1}\right)$	$I_{ef} = 0.0742\ kg * m^2$
Total inertia	$I_{t.} = I_{ef} + I_{motor}$	$I_{t.} = 0.0699 kg * m^2$
Motor starting time		$t_{arr} = 4s$
Angular velocity	$\alpha = \frac{n_1}{t_{arr}}$	$\alpha = 39.27 \frac{rad}{s^2}$
Starting torque	$T_{arr} = I_{total} * \alpha$	$T_{arr} = 2.7456\ N.m$
Motor power	$P_{m.} = T_{arr} * \omega$	$P_{motor} = 431.27\ W$ $P_{motor} = 0.57 HP \approx 1\ HP$

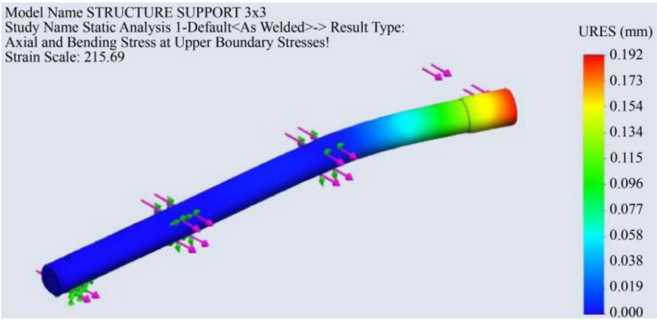

Fig. 5 Shaft deformation analysis in SolidWorks

Table 5. Transmission shaft diameter calculations

Parameters	Equation	Results
Centrifugal force	$F_c = m * r * \omega^2$	$F_c = 1243.149\ N$
Bending force		$F_b = 125.21\ N$
Torque moment	$Mt = \frac{60 * P_m}{2 * \pi * n_2}$	$Mt = 7.162\ Nm$
Support force (R2)	$R2 = \frac{F_b * L3 - F_c * L1}{L2}$	$R2 = -1407.11N$
Support force (R1)	$R1 = F_c + F_b - R2$	$R1 = 2775.471\ N$
Bending moment	Obtained from software	$M2 = 248.63\ N.m$ (critical point)
Material		SAE 1045 steel-cold welding
Creep Resistance	According to Table	$S_y = 531\ MPa$
Ultimate Strength	According to Table	$S_{ut} = 627\ MPa$
Hardness	According to Table	$H = 179\ HB$
Stress co-concentration factors	According to Table	$K_t = 2.2$ $K_s = 3$
Fatigue stress concentration factor	$K_f = 1 + q(K_t - 1)$ $K_{fs} = 1 + q_c(K_{ts} - 1)$	$K_f = 1.768$ $K_{fs} = 2.56$
Shaft diameter	$d = (\frac{16n}{\pi S_y}(4(K_f M)^2 + 3(K_{fs}T)^2)^{\frac{1}{2}})^{\frac{1}{3}}$ $\frac{D}{d} = 1.2$	$d \cong 24.5\ mm$ $D \cong 30\ mm$

3.4. Fluid Discharge Unit

The fluid discharge unit consists of two 1" diameter pipes connected to the filtering chamber to facilitate the drainage of water separated from the mucilage. This unit includes two drainage pipes, connection elbows, and outlet pipes.

3.5. Structure

The structure is made of a 20x20 mm ASTM A554 square tube, capable of supporting the weight of all the mechanisms and units mentioned earlier, as well as functioning under real working conditions. Additionally, this material is resistant to water oxidation. To verify the structure's resistance, an axial stress analysis was performed using SolidWorks, as shown in Figure 6.

In this analysis, it can be observed that the maximum stress found in the structure is 117.015 MPa, which indicates that the structure operates efficiently and that the loads do not exceed the elastic limit of the material.

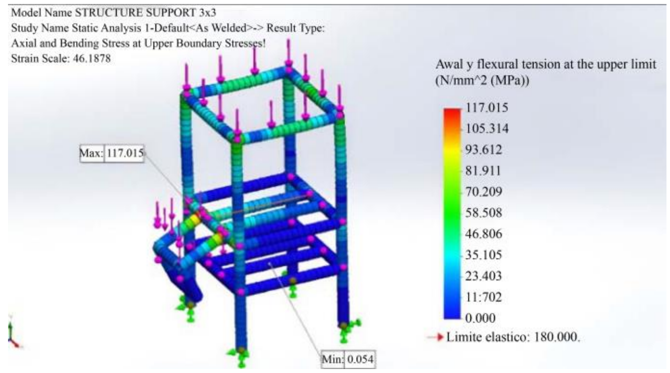

Fig. 6 Axial stress analysis of the structure in SolidWorks

3.6. Discussion of Results

The vertical centrifugal filter has proven to be highly efficient in the water reuse process used in the removal of mucilage in coffee processing. During real tests conducted in Chanchamayo, it was observed that the machine achieved a 90% separation of mucilage, thereby reducing the amount of freshwater needed for subsequent processes. This efficiency not only optimizes water usage but also decreases operating costs for coffee growers.

In comparison to traditional methods of separating honey waters, the vertical centrifugal filter offers clear advantages. Conventional methods generally require large amounts of fresh water for each processing cycle [8]. On the other hand, the vertical centrifugal filter reduces water consumption by 80%, representing a significant step towards more sustainable practices. This drastic reduction is achieved thanks to the innovative design of the centrifugal system, which applies high-performance forces to efficiently separate the mucilage from the water without the need for additional dilutions.

The machine achieves better results than the state-of-the-art techniques reported in the literature due to several key factors. Firstly, its compact and vertical design optimizes space and allows for more controlled centrifugal acceleration, improving separation efficiency compared to horizontal or inclined systems that are more prone to inefficiencies due to the uneven distribution of the mixture. Secondly, the filter employs specific materials and geometries in its internal components that maximize laminar flow and minimize the formation of turbulence, which is critical for maintaining the integrity of the recovered water and avoiding recontamination of clean water with residual mucilage particles.

The environmental impact of this machine has been positive, as the quality of water in effluents after the process has greatly improved, achieving a significant reduction in contaminant concentration in the water in the province of

Chanchamayo, where water pollution is a significant environmental concern [7].

4. Machine Description

The first mechanism, the core of the machine, is the filtering mechanism. It has a filtering chamber with an entry hole for the output shaft, two water drainage holes, and a mucilage evacuation hole. The chamber protects internal components and houses the conical centrifugal filter, which separates solids and liquids. Honey waters enter through a funnel and paddle direct mucilage to its evacuation hole, with a conical cover preventing contact between mucilage and water after separation.

The second mechanism is the transmission, providing mobility and dynamism for the machine's operation. It consists of an electric motor driving a belt and pulley system, transmitting rotation to an output shaft connected to a centrifugal cone filter. Flange bearings ensure precise alignment, and a speed variator adjusts the motor's RPM based on mucilage concentration in the honey waters, optimizing separation.

The next unit is the mucilage discharge, made with a square cross-section to ensure efficient evacuation of the mucilage. It is divided into a mucilage drainage pipe, an inlet fastening flange, and a central body of the drainage pipe.

The following unit is the fluid discharge, which is connected to the filtering chamber to facilitate the evacuation of water separated from the mucilage. It consists of circular drainage pipes, connection elbows, and water outlet pipes.

Finally, all these components are assembled in a robust structure composed of uprights and reinforcing crossbars, providing stability and support during the machine's operation. The structure also includes supports for the motor and speed variator.

5. Conclusion

The design of the vertical centrifugal filter has demonstrated high efficiency in the separation of solids and liquids, achieving a 90% separation of mucilage. This result highlights the effectiveness of the machine both in the separation of mucilage and in the reuse of water in the coffee demucilagination process.

The implementation of the vertical centrifugal filter has significantly contributed to reducing water consumption in coffee production, decreasing water usage by 80%. Additionally, a substantial reduction in effluent contamination has been observed, mitigating the environmental impact in the province of Chanchamayo.

The research has confirmed that the vertical centrifugal filter is technically feasible and can be optimally integrated into existing coffee processing systems. Field tests have shown that the equipment is robust and requires minimal maintenance, ensuring high operational reliability in the long term.

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