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Design and Validation of an Anaerobic Bioreactor through Controlled Fermentation of Coffee to Improve the Cup Profile Villa Rica-Peru

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Abstract

Coffee is one of the most popular and valuable beverages in the world, and the quality of coffee has become a focal point for producers, roasters and consumers. Fermentation is a critical stage in the production of coffee, since it is during this process that the biochemical reactions are generated where the aroma and flavor precursors that define the quality of the coffee in the cup are developed. Given the importance of this stage, it is fundamental to establish adequate conditions for its realization. In this sense, the objective is to design, construct and validate an anaerobic bioreactor with automated controls to improve the quality of coffee in cup. Therefore, the results obtained were a design and construction of an anaerobic bioreactor for an average of 100 kg of coffee with temperature sensors and automation programs for real-time data management and process control to ensure optimal and reproducible fermentation. In addition, 86-point SCAA average profiles were achieved by cupping specialists. The design and construction of a bioreactor with automated controls for coffee fermentation would represent a significant advance in the coffee industry, providing efficient and reproducible tools that would contribute to obtaining high quality coffee and consumer satisfaction.

Keywords: *fermenter, bioreactor, coffee bioreactor, controlled coffee fermentation.*

Introduction

Coffee is one of the most popular and valuable beverages in the world, and coffee quality has become a focal point for producers, roasters, and consumers (International Trade Centre (ITC), 2022). In this context, Villa Rica, Peru, is known for producing high-quality coffee beans, but further improving its cup profile is essential to maintain its position in the international market (Cordova, 2021). As you also mention Seninde & Chambers (2020), the cup profile, which includes the flavors, aromas and sensory characteristics of coffee, is a determining factor in consumer satisfaction and product differentiation in the market.

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The problem of coffee quality has been the subject of interest for researchers and development organizations. In this context, the work of authors such as Nagaraju et al., (2016) The study in Mexico suggests that the technology of coffee fermentation requires controls of temperature, water quality, quality and health of the coffee, and the time of the fermentation process, which corroborates in its study in Mexico that controlled fermentation improves its attributes of mountain coffee with controlled fermentation (Juarez et al., 2021). It also states Janne et al. (2023), the fermentation process plays a crucial role in generating the characteristic flavors and aromas of coffee, which increases the quality of the cup profile, as well as corroborating (Jaramillo, 2020).

In the quest to improve the quality and consistency of coffee fermentation, several studies have addressed the investigation of the design of a specialized bioreactor. For example Carbajal-Guerreros et al. (2022) They conducted a study on the use of a stirred tank bioreactor for controlled fermentation of coffee. Their results showed that the control of key parameters, such as temperature and oxygen concentration, led to a more homogeneous and reproducible fermentation, resulting in improved sensory profiles obtaining 84 SCAA points of titration and consistent in the fermented coffee.

Other research, such as those conducted by Squares (2022), have focused on the implementation of smart bioreactors aimed at assisting Colombian smallholder coffee farmers in orienting the flavor profile of their coffee and in defining protocols to produce differentiated coffees by monitoring fermentation. In addition, according to Peñuela-Martínez et al. (2023) Automated control would also facilitate the optimization of other fermentation processes, such as the removal of undesirable compounds and the promotion of beneficial chemical reactions to improve sensory profiles

These previous studies underscore the importance of research in the design of bioreactors in order to achieve precise control of coffee fermentation and ultimately improve the sensory quality of the final product.

The lack of control in the coffee fermentation process can cause a number of challenges and complications for the coffee industry. As they point out Puerta & Echeverry (2015), the lack of control in fermentation results in variable and inconsistent flavor and aroma profiles in coffee, complicating the production of coffee batches with distinctive, uniform sensory characteristics. In addition, uncontrolled fermentation can lead to the appearance of undesirable flavors, such as astringent or fermented notes, which negatively impacts the consumer experience. In addition, the lack of adequate control poses obstacles to achieving reproducibility in fermentation, which, in turn, prevents the standardization of coffee quality and affects its position in the market.

Due to the above considerations, it was proposed to design and validate an anaerobic bioreactor with automated temperature and oxygen control to improve the cup profile of coffee through protocols that allow achieving a superior and consistent quality in cup coffee. The use of a bioreactor with automated control allowed precise and constant regulation of key fermentation parameters such as temperature, pH and oxygen concentration. This would help minimize variability and ensure repeatability in production, obtaining optimal and consistent sensory profiles in each batch of coffee.

Preliminary results: under non-optimal conditions, coffee quality profiles up to 86 SCAA points were obtained with the proposed controlled anaerobic bioreactor, since the aerobic bioreactor only reached 80 SCAAs. In short, the design and validation of a bioreactor with automated control becomes an essential tool for the coffee industry, allowing a significant improvement in coffee quality and consumer satisfaction.

Methods and materials

Location of the investigation

The district of Villa Rica is well known for being a coffee-producing area, located in the province of Oxapampa of the Department of Pasco. It is located at an altitude of 1467 m.a.s.l. and its coordinates: 10°44′22"S 75°16′11"W. With average annual maximum temperatures of 24.5 °C and average annual minimum of 15.9 °C. With global solar irradiance of 3500 W/m2/day.

Figure 1.

Location of the district of Villa Rica within the department of Pasco and Peru

Figure 1 shows the location of Villa Rica in the Province of Oxapampa within Peru and the right the district of Villa Rica.

Study Procedure:

The study of the design, construction and validation of the bioreactor will be carried out in three stages:

1. Anaerobic Bioreactor Design
2. Construction and assembly of the anaerobic bioreactor
3. Validation with mucilage coffee loading in the anaerobic bioreactor.

The proposed procedures are detailed below:

1. Design of the bioreactor bed and its components

The methodology followed for the design of the anaerobic bioreactor containers was followed through (Mitchell et al., 2006)

2. Anaerobic Bioreactor Construction and Assembly

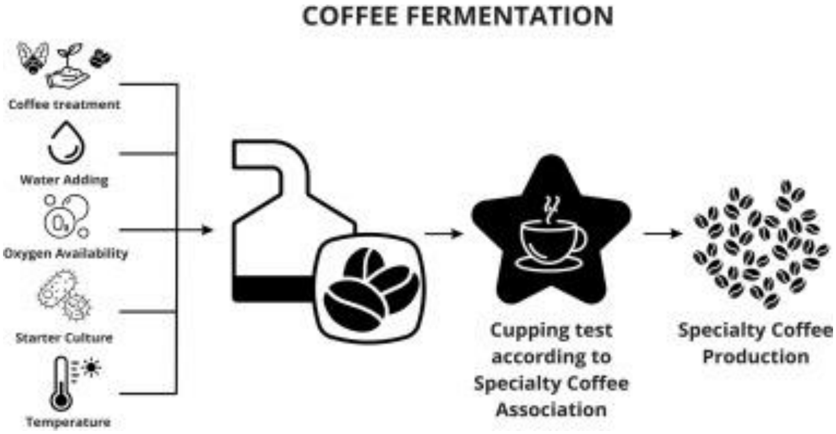
These construction and assembly activities were done with the drawings of the bioreactor and its components

3. Validation of the operation of the anaerobic bioreactor in coffee fermentation.

The validation with pulped coffee with mucilage will follow the procedures detailed in the anaerobic fermentation (closed lid) to determine the effect on the quality of the cup coffee and compare it with the aerobic fermentation with open lid of cup coffee (Coffea arabica L.) by means of the sensory profile, in the town of Villa Rica – Pasco district of the province of Oxapampa. The fermentation process to arrive at specialty coffees see figure 2.

Figure 2.

Coffee fermentation process for the production of specialty coffees.



Note. Taken from Janne et al. (2023)

Figure 2 shows the conditions of the fermentation process to reach specialty coffees ranging from cherry coffee selection, disinfection, pulping, controlled fermentation, drying, storage, roasting and milling to reach cup coffee

a) Controlled fermentation

For the sensory evaluation carried out by the experiment, fermentation with an aerobic bioreactor, also called open-lid, i.e. with the presence of air, and fermentation with anaerobic bioreactor, also called with a closed lid, without the presence of air under controlled conditions, see figure 3.

Figure 3.

Anaerobic bioreactor (lid closed)

The variables that were considered during fermentation were:

The independent variables: fermentation time, stirring speed and temperatures.

Dependent Variables: pH and Soluble Solids

After obtaining the fermented coffee, it was washed and dried in a solar greenhouse dryer see figure 4:

Figure 4.

Solar Greenhouse Dryer for Drying Coffee

Figure 4 shows the greenhouse-type solar dryer for drying coffee coming out of fermentation.

After drying, it was stored, roasted and tasted by professionals

b) Sensory Profile of Coffee Cup

For the assessment of the coffee cup profile, the SCAA protocol was followed (Di et al., 2014) in which water heated to 93-95 °C is poured over the ground coffee and left to rest for 3-4 minutes to do the cupping, each taster evaluated the coffee individually, using a standardized evaluation form that includes a scale of 1 to 10 for the attributes (Fragrance/aroma, taste, acid, sweetness, body, clean cup, mouthtaste, balance and uniformity), in addition to making a qualitative description of flavors.

Results

Design and analysis of the prototype parts.

This session describes the different parts of the design of the prototype bioreactor for coffee fermentation, analyzes the criteria that are taken into account for its manufacture, starting from an adequate size and material, a correct selection of the engine, as well as its speed. The design also includes the mechanical analysis of the various components of the bioreactor, using 3D drawing software (Solidworks) for the modeling of the components and CAD4/CAE5 software (Solidworks simulation) for the design and study of the various mechanisms that make it up.

Fermenter bed design

The bioreactor bed was defined as the space where coffee beans are placed so that they can be fermented. One of the important factors in initiating the design of the bioreactor bed is the amount to ferment from 100 kg to 120 kg of pulped coffee with mucilage, so it is room to consider the volume for this amount. Following the design principles of rotating drum bioreactors and agitators, (Mitchell et al., 2006) The load of the solid to be fermented is related to the fractional filling of the drum, i.e. it is a fraction of the entire volume of the drum occupied by the bed, typically the fractional filling must be kept below 40%, in order to allow a reasonable mixture.

We choose a value of D and L in such a way that a mass of 90 kg of coffee is met with the mucilage of 10% of the volume of coffee, to facilitate the construction we choose D = 0.6m and L = 1m, having a Vcil = 0.2827, with these measurements the Vcafé = 0.1131 m^3

Bioreactor Bed Material Modeling and Selection

Usually coffee fermenters (boxes) are built from cement pools, but bioreactors are mostly made of stainless steel, the material mainly of the bioreactor bed plays an important role, since there is a risk that the organoleptic properties will be affected if stainless steel is used.

An important point to take into account is the temperature during the fermentation process, it rises and it is necessary that it is higher equal to 45 °C so that the grain embryo dies and the enzymatic activity can develop, this temperature will be achieved with an adequate isolation of the dough in the fermentation process, This is influenced by the fermenter and the material used, which is why he decided to build it from stainless steel.

The fermenter bed is mainly made up of three parts:

- Internal bed:

It is the part in contact with the coffee beans and is made of stainless steel; the most commonly used steels in the food industry are AISI 304, AISI 304L, AISI 316 and AISI 316L; of which we will work with AISI 316L, which is generally used for parts that demand high resistance to localized corrosion, in equipment of the chemical, pharmaceutical and petroleum industries, fermentation tanks, tanks, agitators and evaporators.

Grade 316L has a low carbon content, which increases the temperature of intergranular corrosion resistance, as well as improves its weldability.

The inner bed is semicircular in shape and the thickness is 2 mm, the amount of dough to be fermented is about 100 kg and this dough only occupies 40% of the total volume of the bed; At the bottom it contains holes to facilitate the drainage of the mucilage during the first two days of fermentation.

The internal chamber had to be jacketed around so that the temperature control water circulated by means of a water-cooled chiller.

Removal System Design

The removal system is responsible for removing the cocoa beans that are in the process of fermentation, so that these beans come into contact with air so that the aerobic phase takes place and to homogenize the temperature throughout the dough to be fermented. This system is mainly made up of four vanes attached to a shaft that rotates by an electric motor, the design of these three subsystems is described below.

Design of the bioreactor removal vanes.

The palettes to be designed have the shape of the letter "C", this allows you to take an adequate amount of coffee beans and stir them; the height of the dough to be fermented is approximately 300 mm and the height of the paddle is 120 mm, the material used to build them is AISI 304 stainless steel since the pallets are in contact with the coffee beans

Bioreactor Support Shaft Design

The support shaft is responsible for transmitting the movement to all the vanes and supports the total weight of the bioreactor bed, for this reason it is considered as one of the most critical components, this means that its static and dynamic design are very important.

The shaft is made of AISI 316L stainless steel, whose properties were mentioned above, assuming a 1.5" (38.1 mm) shaft we determine the stresses present on the shaft.

For the design of the shaft, only the static analysis is considered, because having very low duty cycles its ultimate stress is not altered by the Dina effects

- We consider the bioreactor to be completely filled with mucilage coffee beans, when in fact the coffee mass occupies almost 40% of the total volume. Where the actual cocoa mass = 81.3 kg coffee mass for design = 200 kg

- The pillow blocks that allow the paddles and shaft to rotate weigh approximately 2.5 kg each; A total weight of 5 kg.

- The inner bed weighs approximately 40 kg and we assume the same weight for the outer bed .

- The bed frame weighs approximately 10 kg. Reaching a total mass of 335 kg.

Engine Power Calculation

To remove the coffee mass that is in the process of fermentation, it is necessary for the designed paddles to rotate, in this way it is guaranteed that the coffee beans that are initially in the lower part of the bioreactor bed pass to the top and can also come into contact with the air.

An electric motor is used to generate the rotation of the vanes together with the shaft, the power of which is determined by equation 1.

Power = Torque x Speed equation 1

The computing power is Power = 0.66HP

With these results, a 0.75 HP electric motor is selected, which perfectly meets the requirements and whose characteristics are shown in Table 1

Table 1.

Features of the Single-Phase Motor

Measure	Value
Power	0.75 Hp / 0.559 KW
Velocity	1800 rpm
Tension	220 V
Frequency	60 Hz

In table 1 it is observed that to obtain a speed of 20 RPM it is necessary to couple a helical gearbox to the motor shaft and obtain a geared motor together, even so, it is difficult to find a geared motor with these characteristics, so it is considered convenient to place a frequency inverter with single-phase input and three-phase output to regulate the speed of the geared motor; This also allows removal tests to be carried out at different speeds.

Aeration System Design

The aeration of the mass is carried out by means of a lid that covers the entire bed of the bioreactor, this lid when opened allows air to enter and at the same time allows the CO2 accumulated in the internal part of the bioreactor to escape.

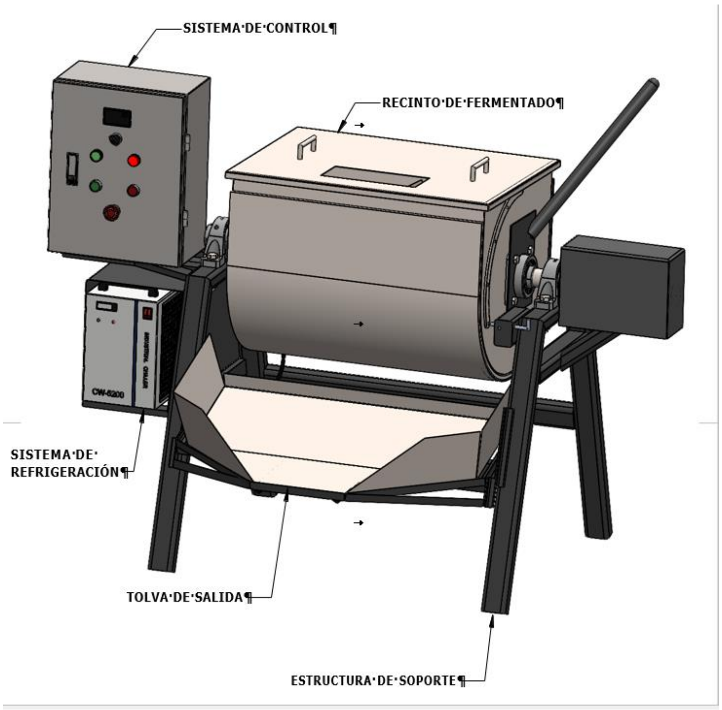
The lid of the bioreactor is made up of a 2 mm thick AISI 316L stainless steel sheet, a 0.8 mm thick ASTM A36 steel sheet and a 22 x 22 mm ASTM A36 square tube structure with a thickness of 1.2 mm (Figure 5); This structure serves as a separation between both sheets, where it is also placed as an insulating material, this allows the heat losses in the coffee beans to be reduced when the bioreactor is closed.

The approximate weight of the entire lid is 20 kg, it opens and closes by two hinges and remains open by means of a manual actuator, to facilitate the emptying of the beans when the fermentation has finished there is a lever that rotates the entire fermentation bed.

With all the above considerations, below are the corresponding plans for its construction and assembly for the corresponding tests before taking the equipment to the field for its respective validation with controlled fermentation versus uncontrolled fermentation, see figures 5, 6, 7 and 8 where the details and components of the anaerobic bioreactor are shown.

Figure 5.

Isometric plane of anaerobic bioreactor



In Figure 5 the anaerobic bioreactor has 5 main components, which are:

- Control system: Responsible for managing the start, pause and emergency stop of the machine, as well as allowing access to the menu and configuration of parameters
- Cooling system: In charge of maintaining a stable temperature in the system to avoid overheating.
- Fermentation area: Space where anaerobic fermentation takes place
- Outlet hopper: Space where the fermented product will be collected
- Support Structure: The one in charge of physically joining and supporting each part securely.

The anaerobic fermenter has overall dimensions of 1.26 meters wide, 1.95 meters long and about 1.4 meters high. In this way, you have an easy-to-use machine, which avoids discomfort to the user and awkward positions in use.

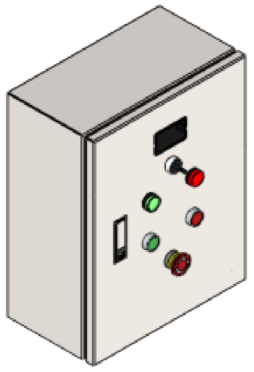
There is also a chamber of 0.839 m long and 0.65 m wide, located about 0.6 meters high. This makes the filling and collection of the input to be fermented convenient and practical.

Control System

The control system consisting of a control board and its components is shown in Figure 6

Figure 6.

Dashboard



In Figure 6 the control board contains the set of control buttons, where the menu entry and parameter placement buttons are located. It also has the power, pause and emergency stop buttons. Finally, on the dashboard you will be able to see the parameters entered as well as the internal parameters of the machine.

The dashboard can be opened for the maintenance and collection of microSD memory.

Refrigeration system

The cooling system, consisting of a water cooling chiller, is shown in Figure 7.

Figure 7.

Cooling system

In figure 7 the cooling system is about 46.8 cm long. About 23.2 cm wide. The cooling system has a power button for activation, it also has its own electrical connection and a side grille that allows you to change fluids for cooling.

Finished anaerobic bioreactor prototype

The finished anaerobic bioreactor prototype ready for field testing is shown in Figure 8.

Figure 8.

Built anaerobic bioreactor

Figure 8 shows the anaerobic bioreactor built has all of the aforementioned elements. The control panel was also enlarged, a three-phase motor was used and a set of valves was placed for the rapid release of the input to be fermented.

The bioreactor includes a pair of temperature sensors, which constantly monitor the internal temperature of the machine, ensuring the desired value throughout the cylinder.

It also has a set of paddles that allow a uniform fermentation to be carried out by moving the contents homogeneously and constantly.

These design improvements are intended to facilitate access to menu control and its parameters. Facilitate the extraction of the fermented input and ensure the correct operation of the machine.

Validation of the operation of an anaerobic bioreactor with coffee in the cup profile

50 kg of cherry coffee was taken to the anaerobic bioreactor, which was subjected to fermentation for an approximate time of 57 hours at constant temperature, after which the cherry coffee was drained and passed to a pulping operation, then it was taken to natural drying. The dry coffee was roasted and ground in which the cup profile was evaluated, which is assessed in Table 2.

Table 2.

Total score of the attributes evaluated to cup coffee according to the SCAA assessment

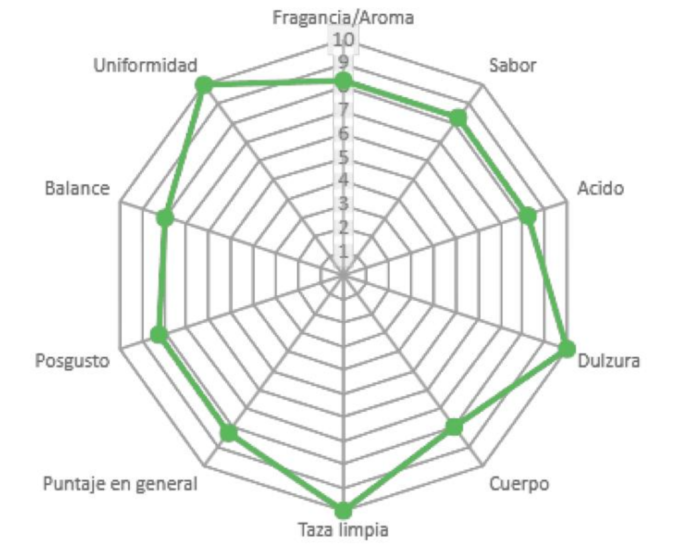
	Condition	Stocking	D.E	t	Gl	p-Value
Coffee Cup Score	Anaerobic fermentation in wells	82.83B	0,63	-7,454	4	0,002
	Anaerobic fermentation in the bioreactor	86.75A	0,66			

Note: the result is the average of the cupping of 3 certified tasters, the letters a and b indicate the difference between the fermentation conditions.

The attributes valued in cup coffee according to the SCAA rating scale are presented in figure 9, with these descriptors the coffee reaches a score of 86.75 points (Very good on the SCAA scale) in the anaerobic fermenter compared to the coffee obtained in anaerobic conditions performed in a well ($p<0.05$). The coffee also has a fruity honey flavor, juicy, fruity acidity, golden raisins, pineapple molasses, creamy body and a sweet finish.

Figure 9.

Attributes evaluated in coffee obtained in fermentation under anaerobic conditions



Sensory evaluation of coffee is a complex process that involves the evaluation of various attributes such as aroma, flavor, acidity, body, and aftertaste (Thurston et al., 2014). In addition to other factors such as altitude, genotype, processing methods, and environmental conditions (Ribeiro et al., 2019; Ribeiro et al., 2016; Alixandre et al., 2023). The chemical composition of coffee, including volatile compounds, plays an important role in determining its sensory attributes (Bressanello et al., 2018; Dulsat-Serra et al., 2016; Oliveira et al., 2021) in this regard, we must point out that coffee from Villa Rica-CUNAVIR Association processed under fermentation in an anaerobic bioreactor has organoleptic qualities that allowed its sensory evaluation and that this is a reflection of the process established in obtaining coffee (Chambers et al., 2016). But it is important to consider other factors such as origin of the raw material, selection, drying, and roasting before performing the sensory evaluation of the cup coffee. The cup coffee scores obtained sensorily by the tasters are promising, as they validate the design and operation of the anaerobic bioreactor for cherry coffee fermentation.

Conclusions:

The bioreactor has isometric, front, profile and horizontal planes with all the components for its manufacture.

The construction of the bioreactor built for an approximate 100 kg of coffee capacity in mucilage has two internal temperature sensors, a pH meter, a water cooling chiller, stirring vanes with rotation of 20 rpm to homogenize the fermentation, for temperature control, all programmed by means of a control board. In addition, it has a dataloger for data storage.

Sensory analyses of the cup profile reached 86.75 SCAA points on average, demonstrating that the anaerobic fermentation process improves coffee quality.

In conclusion, the design and validation of a bioreactor with automated control becomes an essential tool for the coffee industry, allowing a significant improvement in coffee quality and consumer satisfaction.

Gratitude:

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