UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

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Techno-economic Analysis of the Production of Formic Acid from Agro Industrial Recovered Biomass

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RESUMEN

El ácido fórmico es un líquido incoloro que en Ecuador se utiliza principalmente para procesos de ensilaje, los cuales consisten en preservar los nutrientes del pasto para la alimentación de ganado. En el 2019, se importaron aproximadamente 763 toneladas de ácido fórmico, las cuales representaron $615,000. En el presente trabajo se realizó un análisis de prefactibilidad para la implementación de una planta de producción de ácido fórmico a partir de biomasa residual en el Ecuador, con el objetivo de disminuir los costos de importación y fomentar el desarrollo de la industria química en el país. En primer lugar, se llevó a cabo un análisis de mercado para definir el precio de venta presentación del producto. Posteriormente, se seleccionó el proceso de oxidación catalítica "OxFA" como el más favorable para utilizar biomasa residual como materia prima. Después, se realizó el dimensionamiento de los equipos apoyado en el balance de masa y energía del proceso. Con esta información, se llevó a cabo un análisis económico mediante el cual se determinó el tiempo de retorno de la inversión (ROI), apoyado también por el VAN y el TIR, concluyendo que el proyecto es económicamente rentable ya que se recuperará la inversión en un período inferior a 5 años.

Palabras clave: pergamino, cáscara de café, proceso OxFA, economía circular, prefactibilidad, oxidación catalizada.

ABSTRACT

Formic acid is a colorless liquid whose principal usage in Ecuador is for silage processes, which preserves the grass' nutrients for livestock feeding. In 2019, 763 tons of formic acid were imported, which represented $615,000 to the private chemical industry. In this work, a prefeasibility study for the implementation of a formic acid production plant from agro-industrial recovered biomass in Ecuador with the purpose of reducing import costs and developing the chemical industry in the country was performed. First, a market study was conducted to define the product's sale price and unit of measure. Afterwards, a catalytic oxidation process, also known as OxFA Process, was selected as residual biomass is used as raw material. Then, the sizing of the equipment was made based on the mass and energy balances of the process. With this information, an economic analysis determined that the time of return of investment, supported by the IRR and NPV, was lower than 5 years, making this project economically feasible.

Key Words: Coffee husk, OxFA Process, circular economy, prefeasibility, catalytic oxidation.

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1. INTRODUCTION

1.1 Background

With diversified natural resources, a young population, and highly trainable professionals, Ecuador has a great potential for internal growth. Among the petrochemical and mining industries, the use of agricultural waste represents a good alternative for the production of energy and bio-based products, as it has been shown in several studies [1]. However, lack of investment, incorrect public policies, insufficient scientific and technological development, as well as other circumstances, have limited the development of such technologies.

Biomass can be used as a future raw material for energy generation and for the production of different chemicals through gasification, depolymerization, pyrolysis and dehydrogenation [2]. Furthermore, biomass can also be used as fuel for incineration plants. However, in Ecuador, biodiesel and bioethanol production processes have been developed without contributing significantly to the energy production [3]. Nevertheless, for large applications, it can become problematic because of its low energy density, high water content, heterogeneous nature, and high levels of nitrogen and sulfur constituted compounds [4]. In this sense, using agricultural wastes, as raw material, would promote a circular economy in which wastes can be used to produce different commodities and a variety of chemicals, such as hydrogen, syn-gas, formic acid, and acetic acid, among many others.

In particular, formic acid is an important chemical due to its variety of uses in the textile, leather, pharmaceutical, and agriculture industries [5]. Globally, more than 70% of formic acid production is used in silage and animal feed (27%), leather and tanning (22%), pharmaceuticals and food chemicals (14%), and textile industry (7%) [6]. Moreover, it has been widely studied as an energy carrier since it can be easily decomposed to hydrogen and carbon dioxide through catalyzed processes under optimal conditions [4]. Formic acid is known to contain about 53 grams of hydrogen per liter of formic acid [7].

In Ecuador, its principal usage is for silage, a process in which grass' nutrients are preserved for livestock feeding. However, as mentioned above, formic acid has great potential for developing different industries and for satisfying future energy demands. In a scenario where this chemical is produced locally, many other industries could develop processes that use it as a raw material. Currently, almost all the chemical compounds that are distributed in Ecuador are imported from other countries; in 2019, for instance, 763 tons of formic acid were imported [8] with a total cost of $615,000, mainly from China, Germany and Sweden, which represents 0.15% of the world's production of this chemical compound [7]. As this product is not produced locally, an opportunity to satisfy this demand can develop the local chemical industry while motivating investors to reach out to the country.

The current methods to synthesize formic acid are hydrolysis of methyl formate and formamide, which are methods that depend on fossil fuels. In the process of hydrolysis of methyl formate, carbon monoxide from gasification reacts with methanol to produce methyl formate, using sodium methoxide at high pressures and low temperatures. Other processes used worldwide are the carbonylation of methanol and the partial oxidation of butanes or naphtha, but these too are also based on fossil raw materials [7]. Thus, the use of a green route for obtaining formic acid is attractive. In this sense, the novel partial catalytic oxidation, also known as the OxFA process, of biomass appears to be a good alternative. Formic acid can be obtained in high yields using only oxygen or air as oxidants [7]. Interestingly, this process seems to be highly applicable at farm scale to produce commodities with self-produced biomass.

1.2 Justification

This project proposes to impulse the chemical industry to supply Ecuador the local demand of formic acid for silage, with potential of growth to export formic acid to the region; this would create many jobs in the country, reducing the unemployment rate, and reducing its current importation cost. A project which is both financially feasible and beneficial for the whole of the country's economy can be developed.

1.3 Objectives

To complete this project, one general and three specific objectives must be accomplished, as explained below:

General objective: perform a pre-feasibility study for a formic acid production plant in Ecuador able to produce 1000 tons per year of formic acid.

Specific objectives: considering technical aspects like equipment design and sizing; as well as economic analysis, determining the time of return of investment with the aim of fulfilling the local demand of formic acid. Using this as a guide, the project will be used as a foundation for future implementation.

1.4 Expected Results

The implementation of this project will reduce importation costs and create a source for new jobs, which will help develop the local chemical industry, motivating and encouraging more organizations to invest in this type of projects. Moreover, the implementation of this project will provide a real valorization of the high amounts of residual biomass produced in Ecuador.

By using agricultural residues, the cost of raw materials decreases, as they do not have to be imported from foreign countries. Nevertheless, some raw materials must be imported as there no local industries that produces them. From this process, formic acid and acetic acid are obtained as valuable products for the market, which in the future can be exported to other countries in the region. Afterwards, the viability of this project will be determined in order to evaluate the possibility for these results to be obtained.

2. DESIGN PARAMETERS

2.1 Process Selection

Formic Acid can be produced by different methods. The two methods that are going to be compared as candidates for this project are the OxFA process and the hydrolysis of methyl formate and formamide. In Figure 1, we can visualize all the unit operations present in the OxFA process using a block flow diagram. Meanwhile, in Figure 2, all the steps necessary to obtain formic acid through hydrolysis is demonstrated [9].

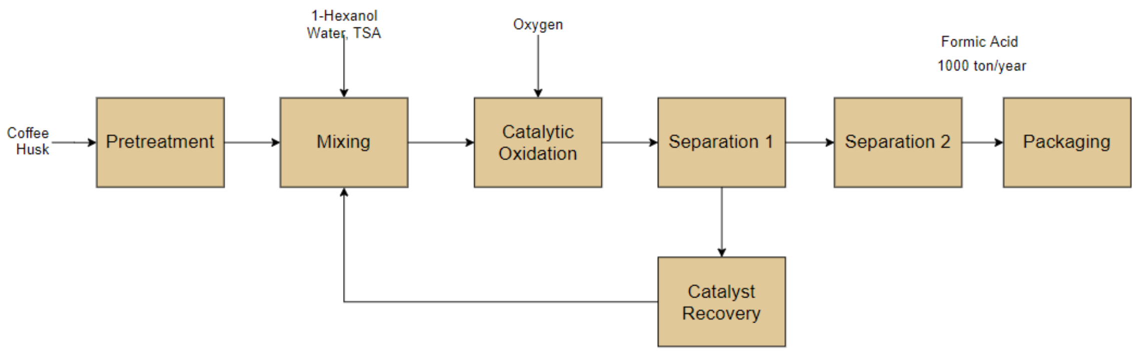

Figure 1. Block Flow Diagram of OxFA Process.

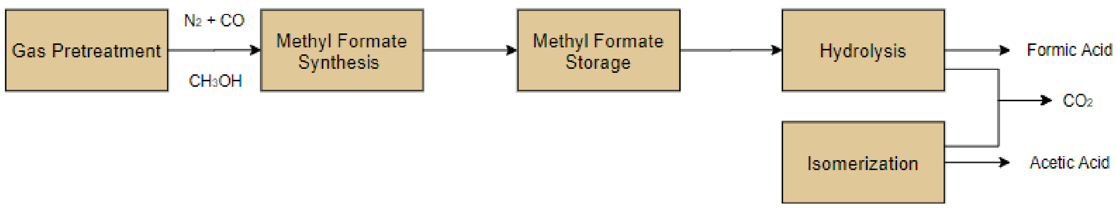

Figure 2. Block Flow Diagram of Hydrolysis of Methyl Formate.

Interestingly, the OxFA process operates under mild temperature conditions, uses widely availabe oxygen or air as oxidants, and residual biomass as raw material. Thus, compared to the standard hydrolysis which uses fossil raw materials, operates at higher temperature and whose conversion is significantly lower, as seen in Table 1, the OxFA process offers many benefits; in fact, the OxFA process appears as an environmental solution for a future bio-based economy. Moreover, a number of non-soluble biomass sources can be considered, as already demonstrated in several studies [10]. Formic acid and acetic acid obtained by the OxFA process are the only products present in the organic phase, and the only by-product is CO_2 which is in the gas phase [10]. However, a separation step will be needed later to separate water, the catalyst, and the formic acid. It also differs from the reductive biomass valorization, which leads to the formation of solid byproducts. Each of these methods was given a score based on a quantitative scale from 1 to 5, with 1 being the minimum as non-optimal conditions and 5 the maximum as the optimal conditions. A score was assigned for each parameter, and the results are shown in Table 1. As can be seen, the OxFA process appear to be a better alternative than the common processes.

Table 1. Comparison between OxFA Process and Hydrolysis of methyl formate and formamide.

Parameter/Process	OxFA	Score	Hydrolysis of methyl formate and formamide	Score
Raw Material	Residual biomass and water	5	Methyl formate (fossil raw materials) and water	2
Operating conditions	90 ºC y 20 bar	4	110 ºC y 4 bar	4
Conversion	100%	4	70%	5
Products separation	Formic acid and acetic acid	5	Formic acid and carbon dioxide	3
TOTAL	18		14	

2.2 Product Description

It is necessary to define the final presentation of the product as well as its purity. The production unit of measure (UOM) will be of 25 kg, which are commonly used in the Ecuadorian market, for both formic acid and acetic acid. The currently available suppliers are Quimpac Ecuador S.A, Brenntag Ecuador, and Relubquim Cia. Ltda. The purity of the formic acid will be 93% on a weight basis, and for acetic acid will be of 80% on a weight basis. None of the formic acid that is sold on the Ecuadorian market is produced by residual biomass.; with these characteristics, the product will be differentiated from the others, as agricultural residues will be used as raw material.

Many agricultural residues can be used as raw materials for this process, but some have better selectivity for formic acid and acetic acid rather than for carbon dioxide. The operating conditions of the batch reactor are demonstrated in Table 2. As shown in

Table **3**, experiments conducted indicate that coffee husk and sugarcane bagasse have higher yields and selectivity to formic acid and acetic acid than other substrates. As coffee Husk has a greater combined selectivity to both products of 66.3% compared to sugarcane bagasse's combined selectivity of 64.5%, the location of the plant will be determined so that the transport cost would be as low as possible.

Table 2. Operating conditions for batch reactor.

Condition	Value
Pressure	20 bar
Temperature	363 K
Residence time	24 hours
Agitation	1000 rpm

Table 3. Selectivity to formic acid and acetic acid for different substrates [11].

Substrate	S_{FA} [%]	S_{AA} [%]
Cocoa husks	36.2	17.4
Coffee husk	**43.4**	**22.9**
Sugarcane bagasse	**48.3**	**16.2**
Palm rachis	34.2	19.9

2.3 Location of the Plant

To determine the location of the plant, the provinces with the most coffee agricultural residues must be identified. Coffee is produced mainly in El Oro Province, with total residues of 9,616 ton/year, and Loja Province, with 25,854 ton/year of total coffee residues, from which 30% is coffee husk. Ground transportation is the cheapest and more feasible transportation mode; however, air transportation can also be considered. Even though light aircraft and small airports are available in the region for agricultural purposes, this is not a real option due to the low load capacity of these means of transportation. As the goal is to produce 1000 ton/year of formic acid, we can focus on using the residues from El Oro Province.

In Figure 3, the location of El Oro Province within the context of the whole ecuadorian territory can be observed. Shaded zones show the fact that coffee agriculture is concentrated in two counties: Piñas and Balsas. It is important to identify basic services in the potential location, such as are potable water, electricity services, and transport infrastructure.

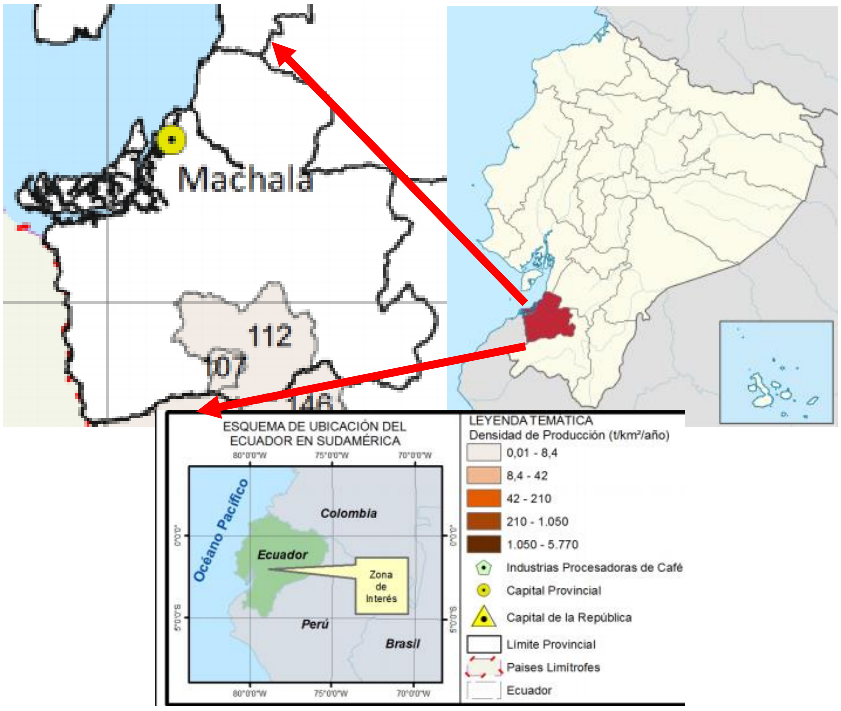

Figure 3. El Oro Province’s location in the country [1].

The electricity and water services are present in the zone as it has a notorious growth in the agricultural industry. Figure 4 shows the main roads and country roads available in the zone. It is important that the location of the plant is near to E50 and 585 roads, as they are asphalted and have a minimum of two lanes, facilitating the transport of raw materials and finished goods.

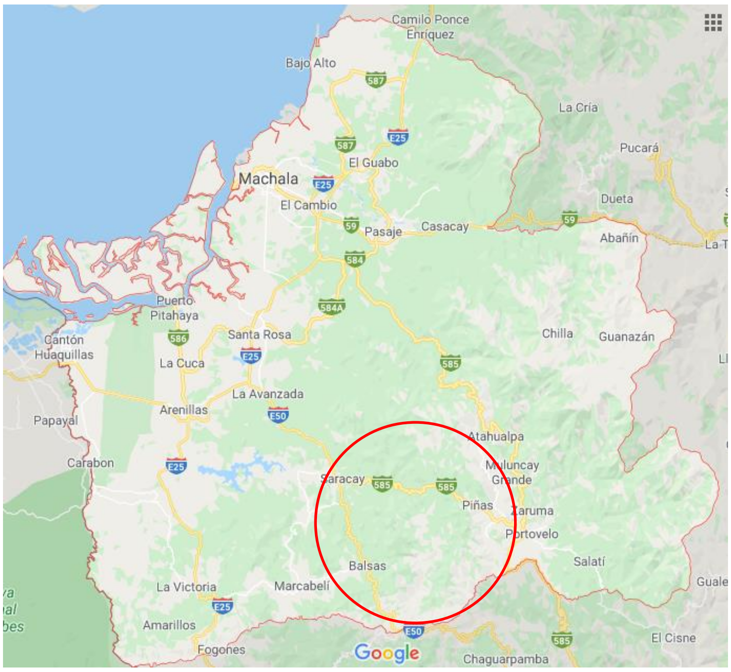

Figure 4. Map of El Oro Province with its main roads [12].

Another important aspect is to identify and assess natural disasters risks, that can be potentially dangerous. The scale presented in Table 5 is used to determine the risk factor on Table 4. In Table 4, using a quantitative risk assessment tool [13], the severity and likelihood of every risk was determined and multiplied, obtaining a Risk Factor. The major risks identified due to the location of the zone in the Circum-Pacific Belt and the abundant rivers across the province are floods, forest fires and earthquakes. Meanwhile, volcano eruptions and tornados have been deemed as negligible risks.

Table 4. Natural disasters risk assessment.

Risk	**Severity**		**Likelihood**		**Risk Factor**	
	Balsas	**Piñas**	**Balsas**	**Piñas**	**Balsas**	**Piñas**
Flood	4	4	4	2	16	8

Forest Fire	5	4	3	3	15	12
Volcano eruption	3	3	1	1	3	3
Earthquake	3	3	4	4	12	12
Tornado	3	3	1	1	3	3

Table 5. Risk score.

Range	Color
1-6	
7-12	
>13	

Considering all these factors, the county where the plant is going to be installed is Piñas, as it has more transportation media facilities (road 585) and both risk factors for flood frequency and forest fire are lower than those of Balsas county.

2.4 Applicable Regulations and Constraints

Considerations such as the availability of the catalyst, restrictions for use of the other chemicals and waste disposal in this process must be analyzed. According to a local regulation named as "LEY ORGÁNICA DE PREVENCIÓN INTEGRAL DEL FENÓMENO SOCIO ECONÓMICO DE LAS DROGAS Y DE REGULACIÓN Y CONTROL DEL USO DE SUSTANCIAS CATALOGADAS SUJETAS A FISCALIZACIÓN" [14], it is required that every substance that is mentioned must be reported to the government monthly.

The quantities imported, stored, produced, and distributed must be carefully measured handling of these is strictly controlled. As per the regulation, the following substances to be used in this project are considered controlled:

- Acetic Acid

- Formic Acid
- Trichloroethylene

Environmental regulations such as wastewater disposal, carbon dioxide emissions, soil and water contamination, must be considered in all stages of the project implementation in order to ensure compliance. The Ministry of Environment of Ecuador establish several regulations about these topics. The main legal body to be considered is “Ley de Gestión Ambiental” [15].

3. RESULTS AND DISCUSSION

3.1 Unit Operations and Raw Materials

After selecting the OxFA process as the best option, the unit operations must be defined. As it can be seen in Figure 5, first, the raw material, coffee husk, must be milled to reduce its particle size. Then, it is mixed with water, 1-hexanol, HPA-5 (catalyst), and p-toluenesulfonic acid (TSA) in the batch reactor for its catalytic oxidation, which operates at 20 bar and 363 K for 24 hours [4]. From the reactor, two phases are separated: the organic phase, which contains acetic acid, formic acid, 1-hexanol, and TSA; and the aqueous phase, which contains water and HPA-5.

The process must undergo two distillations; the first one consists of TSA and 1-hexanol, which are separated from the products of interest, and are returned to the batch reactor with the catalyst and water. Then, trichloroethylene is mixed with the formic and acetic acids to be directed to final extractive distillation. The residue of this distillation is acetic acid, while trichloroethylene and formic acid condensate from the gas phase. Finally, they are separated in a decanter.

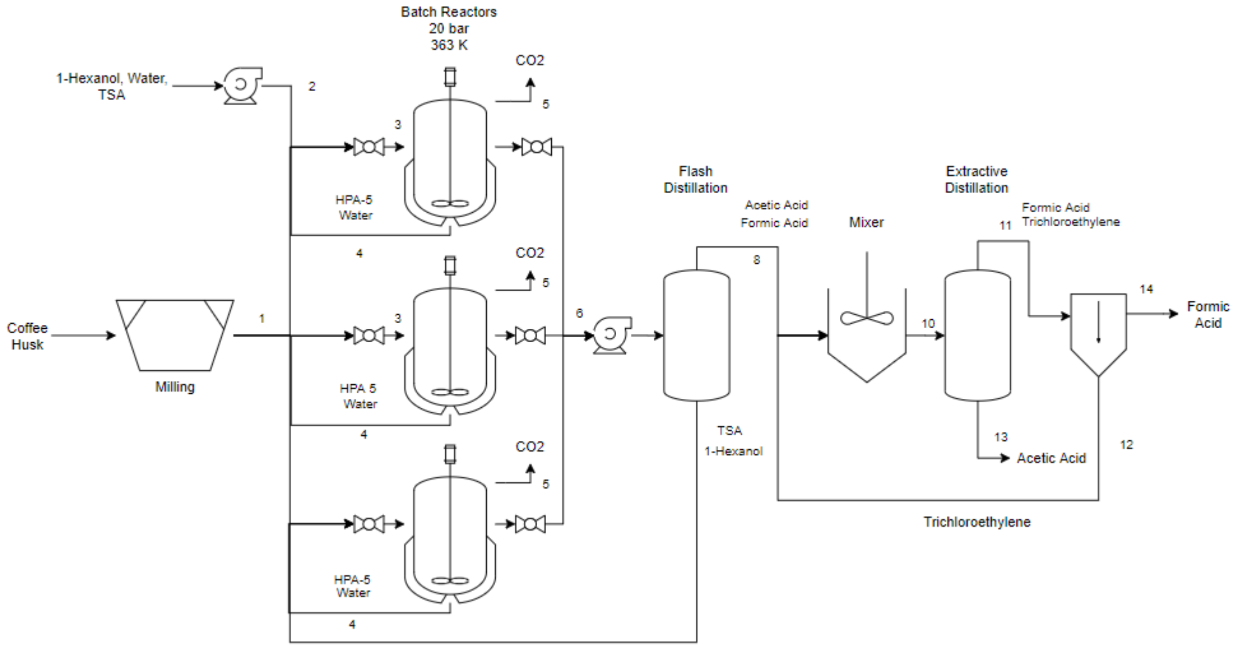

Figure 5. Flow Diagram of OxFA Process.

Based on Figure 5, a list of the necessary equipment for the process is presented below in Table 6. As the residence time in the batch reactor is 24 hours, three reactors of the same capacity must be implemented in order to meet the required production rate. One reactor will start a reaction every 12 hours, and after 24 hours of reaction, the batch reactor will supply the flash distillation equipment for 12 hours, following the timeline demonstrated in Table 28. In this way, the rest of the process will be performing at steady state conditions.

Table 6. List of equipment.

Quantity	Equipment
1	Milling Machine
1	Mixers
3	Batch Reactor
1	Flash Distillation Equipment
1	Extractive Distillation Equipment
1	Decanter
2	Pumps
6	Ball Valve

To perform the mass balance, the goal of producing 1,000 tons of formic acid per year is the starting point. Following the methodology described in Section A.1 in the Appendix A: Methodologies, the raw material necessary to fulfill that annual production are presented in Table 7. In Figure 5, we can see that HPA-5, 1-Hexanol, TSA, Trichloroethylene and water are recirculated, with a purge of 3.15% to maintain an optimal purity and minimize the residues throughout all of the process. With the whole data, the sizing of the equipment can be done.

Table 7. Tons per year needed to produce 1,000 tons of formic acid

Raw Material	Tons/year needed
Coffee Husk	2,303.92
1-Hexanol	121.53
Water	14.29
TSA	34.14
HPA-5	36.82
Trichloroethylene	89.91

3.2 Equipment Sizing and Plant Design

Using the equipment list and the mass balance, the sizing of the equipment can be performed. A unique methodology will be used for each machine. In the first place, the milling machine will not be designed as it will be bought from a supplier; the only parameter that is needed is the mass flow of coffee husk per hour, which is 291 kg/h. Once the pretreatment is done, all this material must enter the reactor.

As mentioned before, three batch reactors will be designed so the whole process can be adapted as a steady state system. As the batch reactor will operate at 20 bar (Table 2), the wall thickness is calculated using as shown in Section A.2.2 (Appendix A: Methodologies). The volume of the reactor is 12.38 m^3. The wall thickness of each reactor will be of 20.2 mm and in Table 8 all the dimensions of the reactor are demonstrated supported by Figure 6. As the wall of the batch reactor is thick enough, the heating process would be performed using a heating coil whose area is calculated in Section B.2.2 in the Appendix B: Calculations. Another advantage of having three reactors is that the plant can continue operating normally while one of them is under maintenance.

Table 8. Dimension for tank sizing.

Dimension	Size	Units
Wall thickness	19.01	mm
Volume	10.14	m^3
Impeller Diameter (Da)	0.68	m
Tank Diameter (Dt)	2.05	m
Liquid Height (H)	2.05	m
Width of the deflectors (J)	0.17	m
Height from the bottom (E)	0.68	m
Height of the impellers (W)	0.14	m
Length of the impeller (L)	0.17	m

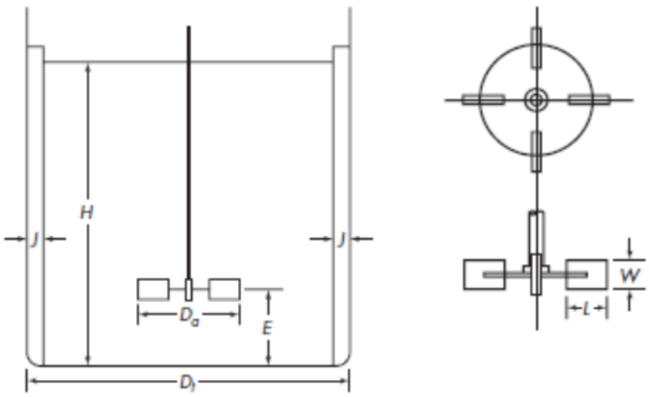

Figure 6. Impeller dimensions [16].

In the reactor, the organic and aqueous phases are separated; after this, a flash distillation and an extractive distillation should be done. For the sizing of the flash distillation equipment, the only data that is needed is the mass flow to be treated. From current number 6 in Table 30 on Appendix D: Mass Balance, the total mass that needs to be treated by the distillation equipment is 19.69 tons/day, which is equal to 0.83 tons/hour. Using this data, a simulation in Aspen Hysys is carried out to determine the size of the equipment.

After the flash distillations is conducted, formic acid and acetic acid are mixed with trichloroethylene, and the mixer sizing is carried out as shown in Section A.2.5 (Appendix A: Methodologies) and demonstrated in Section B.2.5 (Appendix B: Calculations). The extractive distillation equipment is also calculated in Aspen Hysys, using the molar flow and molar fraction of current number 10 in Appendix D: Mass Balance, Table 31. With 12 plates and 40 cm of separation between each plate, the distillation column has 75 cm of diameter and 4.8 m of height.

For the additional equipment such as pumps and globe valves, the sizing would not be performed as this equipment will be acquired from other suppliers. Finally, with all the equipment properly sized, the economic analysis can be performed.

3.3 Economic Analysis

With the sizing of the equipment done, the economic analysis can be carried out. The equipment costs and the operating costs of the plant can be calculated. First, the fixed capital investment that consist of ISBL (Inside Battery Limits) and OSBL (Outside Battery Limits) will be calculated, then variable COP (Costs of Production), fixed COP, and the work capital. Finally determine time of Return of Investment (ROI) defining if the project is feasible or not.

The fixed capital investment has four components, which involve the total cost of infrastructure of the plant, from the designing to the whole construction of the plant. The four components are: ISBL, the total cost of the equipment; OSBL, modifications or improvements made in the plant location; engineering and construction costs; and finally, a contingency charge. There are many ways to estimate the ISBL, in this work we would work with the Detailed Factorial Estimates [17].

First, the total costs of the equipment present in Table 6 were calculated as shown in Section 3.1 (Appendix A: Methodologies) and demonstrated in Section 3.1 (Appendix B: Calculations). The cost per equipment is presented in Table 32; using this data and the equations present in the methodology mentioned before, the total ISBL cost is calculated, resulting in an estimate total of $1,072,724.39. As OSBL, Engineering costs and contingency costs are calculated based on ISBL, the total cost of the Fixed Capital is $1,802,176.97, and the detail of this values are present in Table 20. With the fixed capital calculated, the Work Capital can be performed.

The Work Capital is divided in 6 parts: inventory of raw materials, inventory value, liquidity, receivable accounts, credits and maintenance inventory. These costs are crucial as they represent the debt of each month for the plant to continue producing. The total cost of the Work Capital is $ 993,306.64 and the detail of each part is demonstrated in Table 21.

Another important aspect of the economic analysis is the estimation of fixed and variable operation costs. The fixed operation costs refer to all the costs that do not depend on the production rate; for example, the salary of the employees or the land rental, meanwhile, the variable operation costs are the ones that change based on the amount of formic acid and acetic acid produced. In this case, raw materials are expensive, as detailed in Table 24, where the two most expensive ones are coffee husk and 1-hexanol. The cost per ton of 1-hexanol is nearly 15 times higher than for coffee husk, and represents one of the main challenges for future estimates, where it can be found that 1-hexanol price is lower will benefit the project implementation as a whole. On the other hand, fixed operation costs are 5 times lower than the variable operation costs, which represent an advantage for this process as the amount of employees needed for the plant is 12, 8 operatives and 4 supervisors, as demonstrated in Table 22. Finally, the sum of all costs is $3,143,733.41, and now the cash flow evaluation would be conducted to determine the project feasibility.

To define the return of investment time, the entire income must be calculated. The annual sales of the whole project consist of the total sales between acetic acid, 25 kg at 80% purity, and formic acid, 25 kg at 93% purity. As the presentation of formic acid has a high purity, the 25 kg will be sold at $91.75, meanwhile 25 kg of acetic acid would have a price of $53.75. The total production of formic acid is 990 tons/year and 528 tons/year of acetic acid, which represent $4,803,966.56 in annual sales.

Afterwards, the raw margin, which is the difference between the annual sales and the costs of raw materials, was calculated, leaving $1,598,032.40 as an estimate of the raw margin. The raw benefit is defined as the margin obtained after deducting the operation costs, variable and fixed, to the annual sales, obtaining $680,736.68 before taxes and $599,048.28 after taxes, which is the net benefit. A crucial parameter for determining the feasibility of the project is the estimated time of return of investment, which for projects in Ecuador, must be under 5 years, as the politic atmosphere is always changing and exist several uncertainties on future politic decisions. The estimate ROI time is calculated as the sum of the fixed capital and the work capital divided by the net benefit, which results in 4.67 years, demonstrating that the project could be certainly implemented. In Table 9, a summary of all the economic aspects that must be considered are shown, with a description of how these values were calculated.

Table 9. Economic Analysis for determining the project viability.

Item	Description	Value
Sale Price AA	for each (25 kg)	$ 53.75
Sale Price AF	for each (25 kg)	$ 91.75
Annual Sales	sale price per kg*annual production	$ 4,803,966.56
Raw Margin	sales-annual raw material	$ 1,598,032.40
Raw Benefit	sales-COP (fixed + var)	$ 680,736.68
Net Benefit	raw benefit-taxes (12%)	$ 599,048.28
ROI Time	Fixed C + Work C/Net Benefit	4.67
Linear Depreciation	Fixed C/ROI Time	$ 385,550.19
Interest Rate	Established by bank or investor	11%
NPV (Net Present Value)	VNA function - Fixed C	$ 2,030,140.73
IRR (Internal Rate of Return)	TIR function	34%

Two parameters that support the fact that the project is applicable are the NPV and IRR. The NPV demonstrates the economic viability of the project; if the NPV is negative, the project is not viable, while if it is positive, the project is feasible. On the other hand, IRR is the return rate, and it shows how much of the initial investment returns each cycle. If IRR is higher than the interest rates established by the bank or the investor, the project realization becomes a fact. As both of these conditions apply, the project's feasibility is proven.

4. CONCLUSIONS AND RECOMENDATIONS

The main objective of this project was to prove the feasibility of developing a formic acid production plant using agricultural residues. For this purpose, a novel and green biomass oxidation process was chosen, named “OxFA process”.

After a complete analysis of the process and its risks, coffee husks were chosen as a suitable raw material and el Oro Province as the proper location for the plant. From an economic analysis, considering the equipment, total investment and annual sales, the ROI time was determined in 4.67 years, which make the project viable.

Through the economic analysis, it was demonstrated that the return of investment time was lower than 5 years, which proves the feasibility of the project, with a sale price of $53.75 for 25 kg of Acetic Acid with 80% purity and $91.75 for 25 kg of Formic Acid 93% with purity. This statement is also supported by the fact that NPV value is positive and IRR percentage is higher than the interest rate proposed by the bank or the investor. This project offers almost $600,000 in net benefit annually, which shows that the cash flow would not be an impediment in this project. It also contributes to a future circular economy, as the agricultural wastes can upgrade their value as they can be used as raw materials for the chemical industry. The amount of agricultural wastes in Ecuador has the potential to be exploited with sights of developing the chemical industry while also reducing contamination and increasing the work force of the whole country.

When defining the necessary unit operations and raw materials, choosing three batch reactors with half capacity over one batch reactor with full capacity can give the versatility that can determine if the process can undergo maintenance without interrupting the production. The cost of raw materials is expensive, for the implementation of the plant, this aspect must be reviewed as there can be costs that can be reduced. A purge of 3.15% from all the recirculation currents is enough for the process to work at high standards and minimize wastes. As there are not many plants that perform this process, when implementing it and scaling up, a new economic analysis must be conducted to ensure that all the calculations made in this work are up to date.

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APPENDIX A: METHODOLOGIES

A.1 Methodology 1: Mass Balance

1) Establish the annual production
2) Perform the mass balance backwards throughout the process.
    1. Using Excel, the quantity of each component in each stream must be calculated based on the annual production
    2. In this case, it was calculated in concentration terms, kmol per year.
    3. The molar mass of Coffee Husk required was determined experimentally.
3) Using the molar mass of each component, calculate the mass of each component on each stream.
4) Calculate the molar fractions of each flow by dividing the individual molar flow of a component to the total flow of that stream.

A.2 Methodology 2: Equipment sizing

Based on the tables from "*Chemical Engineering Design*" of R.K. Sinnot [17]. Also, supported by Aspen Hysys**.**

A.2.1. Milling Machine

1. Determine the mass stream that is going to be needed in units of tons per hour.
2. With this data, conduct a research of a milling machine that can produce on average that stream and use those dimensions.

A.2.2. Batch Reactor

1. Review the operating conditions of the reactor.
    - In this case, as the operating pressure is 20 bar, the sizing of the equipment must be done as a pressure tank

2. Determine the volume of the reactor using the current 3 from Table 30 and the densities of each compound present in Table 10.
3. Use Equation 13.41 present in Sinnott, Chapter 13 for Cylinder and Spherical Shells to determine the wall thickness

$$e = \frac{P_i D_i}{2f - 1.2P_i} + 2$$

4. Calculate the wall thickness of the ellipsoidal heads using equation 13.45:

$$e = \frac{P_i D_i}{2SE - 0.2P_i} + 2$$

5. The height of the reactor must be 1.5 times the diameter.

A.2.3. Flash Distillation Equipment

1. The sizing of the distillation equipment was carried out using the stream of products that must be treated
    - In this case the products that enter this flash distillation equipment are formic acid, acetic acid, 1-hexanol and p-toluenesulfonic acid.
2. It is not necessary to introduce heat as the temperature at which the reactor is operating is enough for the separation to take place.

A.2.4. Extractive Distillation Equipment

1. The sizing of the extractive distillation equipment was made in Aspen Hysys.
2. Introduce all the components in Aspen Hysys. As TSA and Coffee Husk are not found in the component’s library, create these as hypothetical components.

3. Create the set of reactions, using coffee husk as the reactant and carbon dioxide, formic acid, and acetic acid in the selectivities presented in

4. Table **3**.

5. Create the material stream with the molar fractions and molar flows from stream 1 and 2 presented in Table 31.

6. Add the reactor, the flash distillation equipment and the extractive distillation equipment.

7. Connect the material stream to the reactor, then connect the products from the organic phase to the flash distillation equipment and finally mix the product stream from de condenser to the material stream of trichloroethylene.

8. Connect this material stream that consists mainly of formic acid, acetic acid, and trichloroethylene, enter the distillation column.

9. Install a 3-phasic separator to the product stream of the condenser, which will separate the formic acid from the trichloroethylene. Acetic Acid will be on the reboiler products stream.

10. In Figure 7, the whole process simulation in Aspen Hysys can be observed.

A.2.5. Mixer

1. As the operating pressure of the mixers is atmospheric, the capacity can be calculated using the flow rate per hour, assuming that the diameter of the mixer is going to be half of its height.

A.2.6. Decanter

3. With the mass of the stream, a relationship can be done, trichloroethylene and formic acid separate quite easily without an energy transfer.

A.3 Methodology 3: Economic Analysis

A.3.1. Fixed Capital

1. ISBL: Calculate the costs for the principal equipment

    - Detailed Factorial Method

$$C = C_{e,i,Cs}[(1 + f_p)f_m + (f_{er} + f_{el} + f_i + f_c + f_s + f_l)]$$

Where:

f_p is installation factor for piping

f_{er} is installation factor for equipment construction

f_{el} installation factor for electrical work

f_i installation factor for instrumentation and control

f_c installation factor for civil engineering work

f_s installation factor for structures

f_l installation factor for lagging

2. OSBL

    - 40% of ISBL

3. Design and Engineering (D&E)

    - 10% of ISBL and OSBL

4. Contingency (X)

    - 10% of ISBL + OSBL

A.3.2. Work Capital

1. Inventory raw materials

    - Based on 2 weeks of production

2. Inventory value

    - COP fixed and variable of 2 weeks

3. Liquidity

- Raw materials for 1 week

4. Accounts receivable

- Inventory value of 1 month

5. Credits

- Raw materials of 1 month

6. Maintenance inventory

- 1% of ISBL + OSBL

A.3.3. Variable and fixed operation costs

1. Fixed

- Operative jobs salary
- Supervisor job salary
- Direct salaries (40% oper + super)
- Maintenance (3% ISBL)
- Taxes (1% ISBL)
- Land rental (1% ISBL + OSBL)
- General costs (65% oper + super + direct salaries)

2. Variable

- Raw materials per month
- Electricity per month
- Vapor per month

A.3.4. Income

1. Sales

- Annual sales (sale price times annual production)

2. Margin

- Raw margin (difference between sales and annual raw material costs)

3. Benefits
   - Raw Benefit (difference between sales and total operating final costs)
   - Net Benefit (difference between Raw benefit and taxes)
4. Estimated time of ROI
   - Fixed Capital + Work Capital / Net Benefit
5. NPV
   - Use VAN function in Excel

APPENDIX B: CALCULATIONS

B.1 Mass Balance

Table A. 1. Molar mass of each component in the process.

Compound	MM [kg/kmol]
Coffee Husk	36.60351
1-Hexanol	102.162
Water	18.02
TSA	172.2
HPA-5	1857
CO2	44.01
Trichloroethylene	131.4
Acetic Acid	60.052
Formic Acid	46.03

Table 10. Density of different components and materials present in the process.

Compound	Density	
1-Hexanol	0.814	ton/m^3
TSA	1.24	ton/m^3
Water	0.965	ton/m^3
Trichloroethylene	1.46	ton/m^3
Acetic Acid	1.05	ton/m^3
Formic Acid	1.22	ton/m^3
SS 304	7896	kg/m^3

Table 11. Important relationships to perform the mass balance.

Parameter	Value
Per 100 kg of Coffee Husk	43.4 kg of Formic Acid 22.9 kg of Acetic Acid 33.7 kg of CO_2
Substrate to catalyst ratio	100:1
Substrate to additive ratio	10:1

B.2 Equipment Sizing

B.2.1. Milling Machine

$$6.98\ \frac{tons\ Coffee\ H}{day} * \frac{1\ day}{24\ hours} * \frac{1000\ kg}{1\ ton} = 290.9\ \frac{kg}{h}$$

B.2.2. Batch Reactor

$$Volume = \frac{Mass}{Density}$$

Using this formula to obtain the volume of 1-Hexanol, TSA and Water, using current 3 of Table 30 the total volume of the reactor is calculated.

Table 12. Data for determining the volume of the batch reactors.

Compound	Density [ton/m^3]	Volume [m^3]	Mass [ton]
1-Hexanol	0.814	14.36	11.69
TSA	1.24	2.65	3.28
Water	0.965	1.42	1.37
TOTAL	0.887	18.44	16.35
Security %	10%	**10.14**	

Volume of each batch reactor: 10.14 m^3.

With the volume, the diameter and the height of the cylindrical batch reactor can be calculated, assuming that the relationship between the height and the diameter is 1.5:1. Also, the wall thickness is calculated using the equation present on Use Equation 13.41 present in Sinnott, Chapter 13 for Cylinder and Spherical Shells to determine the wall thickness and presented below:

For the wall thickness:

$$e = \frac{P_i D_i}{2f - 1.2P_i} + 2$$

For the ellipsoidal heads:

$$e = \frac{P_i D_i}{2SE - 0.2P_i} + 2$$

Using the following data:

Table 13. Wall thickness for the batch reactor.

Dimension	Wall Thickness	
Pi	2.00	N/mm^2
Di	2049.36	mm
S	121.69	N/mm^2
t (wall)	19.01	mm
t (elips heads)	18.87	mm

Finally, the total volume of the reactor with the wall thickness is going to be used to calculate the equipment costs in the following section for the economic analysis.

Table 14. Dimensions of the batch reactors.

Parameter	Value	Units
Diameter	2.05	m
Height	3.07	m
Volume int	10.14	m^3
Volume out	**10.65**	m^3

B.2.3. Flash Distillation Equipment

For this equipment, the total volume needed is calculated using the densities and the mass flow from current 6 in **Table 30**.

Table 15. Data for determining the volume of flash distillation equipment.

Compound	Density [ton/m^3]	Volume [m^3]	Mass [ton]
1-Hexanol	0.814	0.60	0.49
TSA	1.24	0.11	0.14
Acetic Acid	1.05	0.06	0.07
Formic Acid	1.22	0.10	0.13
TOTAL	0.933	0.88	0.82
% seguridad	10%	**0.96**	

Volume of the Flash Distillation Equipment: 0.96 m^3

Using the same formula for calculating the wall thickness for the reactors, the wall thickness of the flash distillation equipment is calculated, this data is presented in Table 16.

Table 16. Dimensions of the flash distillation equipment.

Parameter	Value	Unit
Ratio between Height and Diameter	3.5:1	
Diameter	0.71	m
Height	2.47	m
t (wall)	7.16	mm
t (elips heads)	7.12	mm
Volume int	0.96	m^3
Volume out	1.01	m^3
Wall Volume	0.05	m^3
Shell Mass	358	kg

A simulation in Aspen Hysys was made to verify this data and that the components could really separate in an appropriate manner. The shell mass is calculated for determining the cost of the equipment in the following section.

B.2.4. Extractive Distillation Equipment

For this machinery, a simulation was conducted on Aspen Hysys following the process explained in Extractive Distillation Equipment. In Figure 7, the simulation of the OxFA Process is presented. T-103, which represents the extractive distillation equipment appear in yellow because in the condenser, two phases were found, one phase that contains high concentration of formic acid and the other of trichloroethylene.

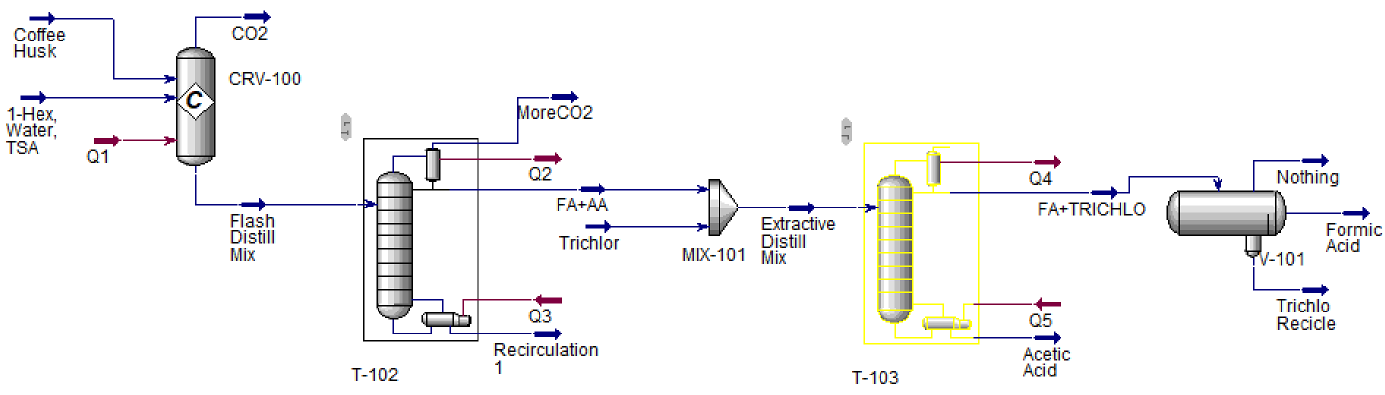

Figure 7. Process scheme simulation in Aspen Hysys.

The molar flows from the feed and the products are demonstrated in Figure 8, showing that the separation is feasible. In Figure 9, the molar fraction of the condenser product stream is shown, where two organic phases exist, one with 93% of formic acid and the other with 91% of trichloroethylene.

Feeds

	Distmix
Flow Rate (kgmole/h)	6.493
FormicAcid (kgmole/h)	2.665
1-Hexanol (kgmole/h)	0.1846
AceticAcid (kgmole/h)	0.8875
Cl3-C2= (kgmole/h)	2.743
H2O (kgmole/h)	0.0000
CO2 (kgmole/h)	1.372e-002
CoffeeHusk* (kgmole/h)	0.0000
TSA* (kgmole/h)	0.0000

Products

	FA+TRICLO	ACETICA
Flow Rate (kgmole/h)	5.6247	0.8686
FormicAcid (kgmole/h)	2.6348	0.0299
1-Hexanol (kgmole/h)	0.0450	0.1397
AceticAcid (kgmole/h)	0.1883	0.6991
Cl3-C2= (kgmole/h)	2.7428	0.0000
H2O (kgmole/h)	0.0000	0.0000
CO2 (kgmole/h)	0.0137	0.0000
CoffeeHusk* (kgmole/h)	0.0000	0.0000
TSA* (kgmole/h)	0.0000	0.0000

Figure 8. Molar flows of all the streams on the Extractive Distillation.

Material Stream: FA+TRICHLO

Worksheet | Attachments | Dynamics

Worksheet: Conditions, Properties, Composition, Oil & Gas Feed, Petroleum Assay, K Value, User Variables, Notes, Cost Parameters, Normalized Yields

	Mole Fractions	Liquid Phase	Liquid Phase
FormicAcid	0.4684	0.9279	0.0547
1-Hexanol	0.0081	0.0020	0.0136
AceticAcid	0.0334	0.0495	0.0188
Cl3-C2=	0.4877	0.0188	0.9099
H2O	0.0000	0.0000	0.0000
CO2	0.0024	0.0018	0.0030
CoffeeHusk*	0.0000	0.0000	0.0000
TSA*	0.0000	0.0000	0.0000

Figure 9. Molar fraction of products stream.

The appropriate number of plates was determined by the desired purity of formic acid, determining that there would be in total 12 plates, with a distance in each plate of 40 cm, the dimensions of the equipment are listed in Table 17.

Table 17. Dimensions of Extractive Distillation Column.

Dimension	Value	Units
Diameter	0.75	m
Height	4.8	m
Volume int	2.12	m^3

Volume out	**2.21**	m^3
Wall Volume	0.09	m^3
Shell Mass	730	kg

The shell mass is obtained as it is going to be used for determining the cost of the equipment in the following section.

B.2.5. Mixer

The flow rate for the mixer is determined by stream 10 from Table 30 and using the densities of formic acid, acetic acid and trichloroethylene.

$$Mixer_{Flow\ rate} = \left(\sum \frac{Daily\ Molar\ Flow_i}{Density_i}\right) * \frac{1\ day}{24\ h} * \frac{1\ h}{3600\ s} * \frac{1000\ L}{1\ m^3}$$

$$Mixer_{Flow\ rate} = 0.115\ \frac{L}{s}$$

With this data, the dimensions of the mixer are presented in Table 18.

Table 18. Dimensions of the mixer.

Parameter	Value	Unit
Diameter	0.84	m
Height	1.67	m

B.2.6. Decanter

The sizing of the decanter is performed using the molar flows of stream 11 from Table 30. Using this data, the dimensions of the decanter are presented in

Table 19. Dimensions of the Decanter.

Parameter	Value	Unit
Diameter	1.21	m
Height	1.82	m
Volume	2.10	m^3

B.3 Economic Analysis

B.3.1. Fixed Capital

For the Detailed Factorial Method, the cost of each equipment must be calculated in order to use the formula present in 38. The total cost of the equipment is $335,226.37 and the details for each equipment are presented in Appendix E: Economic A. All constants values were retrieved from Table 6.4 of the reference[17]. Using these values, the total ISBL cost is:

$$C = C_{e,i,Cs}\left[\left(1 + f_p\right)f_m + \left(f_{er} + f_{el} + f_i + f_c + f_s + f_l\right)\right]$$

$$ISBL = 335{,}226.37 * [(1 + 0.8) * 1 + (0.3 + 0.2 + 0.3 + 0.3 + 0.2 + 0.1)]$$

$$\boldsymbol{ISBL} = \$\mathbf{1,072,724.39}$$

As the OSBL is 40% of the ISBL

$$OSBL = 40\%\ ISBL$$

$$\boldsymbol{OSBL} = \$\mathbf{429,089.76}$$

The Design and Engineering (D&E) and the Contingency costs (X) are defined as 10% of the ISBL + OSBL costs, leading to:

$$D\&E = 10\%\ (ISBL + OSBL)$$

$$\boldsymbol{D\&E} = \$\mathbf{150,181.41}$$

$$\boldsymbol{X} = \$\mathbf{150,181.41}$$

With this data, the total Fixed Capital can be obtained as it is the sum of ISBL, OSBL, Design and Engineering and Contingency costs, with a total of $1,802,176.97 as demonstrated in .

Table 20. Fixed Capital costs detail.

Component	How is obtained	Value
ISBL	Detailed Factorial Method	$ 1,072,724.39
OSBL	40% ISBL	$ 429,089.76
Design & Engineering	10% (ISBL+OSBL)	$ 150,181.41
Contingency	10% (ISBL+OSBL)	$ 150,181.41
TOTAL		**$ 1,802,176.97**

B.3.2. Work Capital

The Work Capital has 6 components, which are listed in Table 21, next to each other, a description of where the value comes from is provided.

Table 21. Work Capital costs detail.

Component	How is calculated	Cost
Inventory Raw Material	Raw materials for 2 weeks	$ 133,580.59
Inventory Value	COP fixed+var of 2 weeks	$ 170,252.14
Liquidity	Raw materials for 1 week	$ 66,790.29
Accounts receivable	Inventory Value of 1 month	$ 340,504.29
Credit	Raw materials for 1 month	$ 267,161.18
Maintenance	1% (ISBL+OSBL)	$ 15,018.14
TOTAL		**$ 993,306.64**

B.3.3. Variable and fixed operation costs.

The fixed operational costs consist of 7 different parts, all of them are listed in Table 22 and how are estimated is described next to each component. With this information, the total fixed operation cost is estimated and the variable operation costs are calculated on Table 23. The variable operation costs consist of 3 groups, which are directly affected by how much products are produced per month. In Table 26, the total costs of the project are listed by each category, completing a total cost of $3,143,733.41.

Table 22. Fixed Operation Costs detail.

Component	How is calculated	Cost
Operative salary	8 at $600 each	$ 4,800.00
Supervisor salary	4 at $1200 each	$ 4,800.00
Direct salaries	40% (oper+superv)	$ 3,840.00
Maintenance	3% ISBL	$ 10,727.24
Taxes	1% ISBL	$ 10,727.24
Land rental	1% (ISBL+OSBL)	$ 15,018.14
General costs	65% (oper+superv+direct)	$ 8,736.00
TOTAL		**$ 58,648.63**

Table 23. Variable Operation Costs detail.

Component	How is calculated	Cost
Raw Materials	Details in Table 24	$ 267,161.18

Electricity	$ 0.04/kWh from Table 25	$ 15,334.84
Vapor	Details in Batch Reactor	$ 2,457.84
	TOTAL	**$ 281,855.66**

Table 24. Raw materials costs per month.

Raw Material	Tons/year needed	Tons/month	$/ton	$/month
Coffee Husk	2303.92	209.4472727	$ 500.00	$ 104,723.64
1-Hexanol	121.53	11.04848197	$ 7,300.00	$ 80,653.92
Water	14.29	1.299202216	$ 0.72	$ 0.94
TSA	34.14	3.103809955	$ 1,340.00	$ 4,159.11
HPA-5	36.82	3.347054015	$ 14,400.00	$ 48,197.58
Trichloroethylene	89.91	8.173890723	$ 3,600.00	$ 29,426.01
			TOTAL	$ 267,161.18

Table 25. Energy Balance for distillation equipment.

Energy Stream	kJ/h	kWh
Q2 Partial Condenser	272431.96	75.73608488
Q3 Reboiler	509892.7591	141.750187
Q4 Total Condenser	420489.8189	116.8961696
Q5 Reboiler	438890.6581	122.0116029
TOTAL (per month)	45967745.49	12779.03325

Table 26. Total costs of the project.

Cost	Value
Fixed Capital	$ 1,802,176.97
Variable COP	$ 284,953.86
Fixed COP	$ 58,648.63
Work Capital	$ 997,953.94
TOTAL	$ 3,143,733.41

B.3.4. Income

The annual sales are calculated by using the next equation:

$$Annual\ Sales = Sale\ Price_{1\ kg\ AA} * \dot{m}_{AA} + Sale\ Price_{1\ kg\ FA}\dot{m}_{FA}$$

$$Annual\ Sales = (\$2.15 * 5.28 * 10^5) + (\$3.67 * 9.99 * 10^5)$$

$$Annual\ Sales = \$4{,}803{,}966.56$$

The raw margin is the is the difference between sales and the annual raw material costs:

$$Raw\ margin = \$4{,}803{,}966.56 - (\$267{,}161.118 * 12)$$

$$Raw\ Margin = \$1{,}598{,}032.40$$

The raw benefit is the difference between sales and the total operating costs, including fixed and variable operation costs. Values were retrieved from **Table *22.*** Fixed Operation Costs detail.Table 22 and Table 23. Meanwhile, the net benefit is the raw benefit minus taxes, which are of 12%..

$$Raw\ Benefit = \$4{,}803{,}966.56 - [(\$284{,}953.86 + \$58{,}648.63) * 12]$$

$$Raw\ Benefit = \$680{,}736.68$$

$$Raw\ Benefit = \$680{,}736.68$$

$$Net\ Benefit = \$680{,}736.68 * (0.88)$$

$$Net\ Benefit = \$599{,}048.28$$

With this data, the ROI time is determined, and it is estimated using the next equation:

$$ROI\ time = \frac{Fixed\ Capital\ (FC) + Work\ Capital\ (WC)}{Net\ Benefit}$$

$$ROI\ time = 4.67$$

In Table 27, the whole economic analysis is described, including sales, benefit, the time of return of investment and the functions NPV and IRR. To calculate NPV and IRR, a Cash Flow table must be conducted, this table is presented in Appendix E: Economic A.

Table 27. Cost evaluation of each parameter.

Item	Description	Value	
Sale Price AA	for each (25 kg)	$	53.75
Sale Price AF	for each (25 kg)	$	91.75
Annual Sales	sale price per kg*annual production	$	4,803,966.56
Raw Margin	sales-annual raw material	$	1,598,032.40
Raw Benefit	sales-COP (fixed + var)	$	680,736.68
Net Benefit	raw benefit-taxes (12%)	$	599,048.28

ROI Time	Fixed C + Work C/Net Benefit	4.67
Linear Depreciation	Fixed C/ROI Time	$ 385,550.19
Interest Rate	Established by banc or investor	11%
VAN	VNA function - Fixed C	$ 2,030,140.73
IRR	TIR function	34%

APPENDIX C: TIMELINE OF THE REACTORS

Table 28. Schedule of Batch Reactors.

Reactor/Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Reactor 1																																					
Reactor 2																																					
Reactor 3																																					

Table 29. Legend of Process per color.

Process	Color
Cleaning & Heating	
Reaction	
Feeding Distillation	

APPENDIX D: MASS BALANCE

Table 30. Mass flow of each component in each current

Corriente	Mass flow (ton/day)									Mass flow [ton/day]
	Coffee Husk	1-Hexanol	Water	TSA	HPA-5	CO2	Trichloro -ethylene	Acetic Acid	Formic Acid	
1	6.98	-----	-----	-----	-----	-----	-----	-----	-----	6.98
2	-----	11.69	1.37	3.28	3.54	-----	-----	-----	-----	19.89
3	6.98	11.69	1.37	3.28	3.54	-----	-----	-----	-----	26.87
4	-----	-----	1.29	-----	3.54	-----	-----	-----	-----	4.83
5	-----	-----	-----	-----	-----	2.35	-----	-----	-----	2.35
6	-----	11.69	0.08	3.28	-----	-----	-----	1.60	3.03	19.69
7	-----	11.69	-----	3.28	-----	-----	-----	-----	-----	14.98
8	-----	-----	0.08	-----	-----	-----	-----	1.60	3.03	4.71
9	-----	11.69	1.29	3.28	3.54	-----	-----	-----	-----	19.81
10	-----	-----	0.08	-----	-----	-----	8.65	1.60	3.03	13.36
11	-----	-----	0.06	-----	-----	-----	8.65	-----	3.03	11.74
12	-----	-----	-----	-----	-----	-----	8.65	-----	-----	8.65
13	-----	-----	0.02	-----	-----	-----	-----	1.60	-----	1.62
14	-----	-----	0.06	-----	-----	-----	-----	-----	3.03	3.09

Table 31. Molar fraction in each current for each component.

Corriente	Molar Fraction									Molar Flow [mol/día]
	Coffee Husk	1-Hexanol	Water	TSA	HPA-5	CO2	Trichloro-ethylene	Acetic Acid	Formic Acid	
1	1.00	-----	-----	-----	-----	-----	-----	-----	-----	190.73
2	-----	0.54	0.36	0.09	0.01	-----	-----	-----	-----	211.72
3	0.47	0.28	0.19	0.05	0.00	-----	-----	-----	-----	402.45
4	-----	-----	0.97	-----	0.03	-----	-----	-----	-----	73.58
5	-----	-----	-----	-----	-----	1.00	-----	-----	-----	53.46
6	-----	0.50	0.02	0.08	-----	-----	-----	0.12	0.29	230.59
7	-----	0.86	-----	0.14	-----	-----	-----	-----	-----	133.51
8	-----	-----	0.05	-----	-----	-----	-----	0.27	0.68	97.07
9	-----	0.55	0.35	0.09	0.01	-----	-----	-----	-----	207.09
10	-----	-----	0.03	-----	-----	-----	0.40	0.16	0.40	162.90
11	-----	-----	0.02	-----	-----	-----	0.49	-----	0.49	134.94
12	-----	-----	-----	-----	-----	-----	1.00	-----	-----	65.83
13	-----	-----	0.05	-----	-----	-----	-----	0.95	-----	27.95
14	-----	-----	0.05	-----	-----	-----	-----	-----	0.95	69.12

APPENDIX E: ECONOMIC ANALYSIS

Table 32. Cost of each equipment.

Quantity	Equipment	Eq. Table 6.6	Specification	Value (S)	a	b	n	Equipment Cost	Ce (Total Eq. Cost)
1	Milling Machine	Pulverizer	kg/h	290.899	3000	390	0.5	$ 9,651.74	$ 9,651.74
1	Mixer	Static Mixer	Liters/s	0.115	780	62	0.8	$ 790.98	$ 790.98
3	Batch Reactor	Jacketed, agitated	Capacity, m^3	10.650	14000	15400	0.7	$ 94,660.29	$ 283,980.86
1	Flash Distillation Equipment	Pressure vessel, vertical 304 ss	Shell Mass, kg	357.965	-10000	600	0.6	$ 10,438.82	$ 10,438.82
3		Sieve trays	Diameter, m	0.71	100	120	2.0	$ 159.65	$ 478.94
1	Extractive Distillation Equipment	Pressure vessel, vertical 304 ss	Shell Mass, kg	729.583	-10000	600	0.6	$ 21,332.58	$ 21,332.58
10		Sieve trays	Diameter, m	0.750	100	120	2.0	$ 167.50	$ 1,675.00
1	Decanter	Tank	Capacity, m^3	2.102	5700.00	700	0.7	$ 6,877.45	$ 6,877.45
								TOTAL	$ 335,226.37

Table 33. Cash Flow projection for 10 years.

Year	Raw Benefit	Depreciation	Taxable Income	Taxes	Cash Flow	Cumulative Flow	Balance
	Raw Benefit	Fixed Capital / ROI time	Raw Benefit - Depreciation	12% Taxes	Raw Benefit - Taxes	Fixed Capital + Net Benefit	Total costs + Net Benefit
0	0	0	0	0	$ (1,802,176.97)	$ (1,802,176.97)	$ (3,604,353.95)
1	$ 680,736.68	$ 385,550.19	$ 295,186.49	$ -	$ 680,736.68	$ (1,121,440.29)	$ (2,923,617.27)
2	$ 680,736.68	$ 385,550.19	$ 295,186.49	$ 35,422.38	$ 645,314.30	$ (476,125.99)	$ (2,278,302.96)
3	$ 680,736.68	$ 385,550.19	$ 295,186.49	$ 35,422.38	$ 645,314.30	$ 169,188.31	$ (1,632,988.66)
4	$ 680,736.68	$ 385,550.19	$ 295,186.49	$ 35,422.38	$ 645,314.30	$ 814,502.62	$ (987,674.36)
5	$ 680,736.68	$ 385,550.19	$ 295,186.49	$ 35,422.38	$ 645,314.30	$ 1,459,816.92	$ (342,360.05)
6	$ 680,736.68	$ 385,550.19	$ 295,186.49	$ 35,422.38	$ 645,314.30	$ 2,105,131.22	$ 302,954.25
7	$ 680,736.68	$ 385,550.19	$ 295,186.49	$ 35,422.38	$ 645,314.30	$ 2,750,445.53	$ 948,268.55
8	$ 680,736.68	$ 385,550.19	$ 295,186.49	$ 35,422.38	$ 645,314.30	$ 3,395,759.83	$ 1,593,582.86
9	$ 680,736.68	$ 385,550.19	$ 295,186.49	$ 35,422.38	$ 645,314.30	$ 4,041,074.13	$ 2,238,897.16
10	$ 680,736.68	$ 385,550.19	$ 295,186.49	$ 35,422.38	$ 645,314.30	$ 4,686,388.44	$ 2,884,211.46