

Design of a Recovery System for Organic Acids in a Banana Freezing Process

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Abstract– 3.5 million liters of water are used and disposed of during the treatment process, and to sum up, 54000 kg of acids have been used and reported from this study's food company. This research evaluates the viability of implementing a recovery system of organic acids to reduce costs of acquiring raw material and minimize its disposal to the environment. For the design, the acid solution used in the process was studied, and a series of unit operations and chemical reactions were proposed. After this, the process was simulated using an engineering software (Pro/II®) to obtain the material and energy balance to be used in cost calculations. Finally, the research estimates the cost of investment based on Ecuadorian banks' norms and laws and the Microsoft Excel macro-enabled file Capcost. The design system was able to recover 19.2 kg of solid acids for every 632 kg of acid in the solution in the process.

Keywords-- Organic acids, Pro/II®, recovery system, unit operations, material, and energy balance.

I. INTRODUCTION

For this research, the information provided was obtained from a company dedicated to frozen banana production and exportation. This food company disposes of approximately 3800 kg/day of acid solution. From this, 180 kg/day from a mix of ascorbic and citric acid is also discarded to the environment. As it is seen, this is a risk to the environment and high losses in cost for the company.

The freezing industry uses organic acids in solution to reduce the enzymatic activity from the polyphenols in the banana. The ascorbic acid reduces 92% of the enzyme polyphenol oxidase activity [1]; on the other hand, citric acid is used as a pH regulator, and malic acid is used as an inhibitory effect for other enzymes. Another important parameter that helps control enzyme activity is the temperature. At low temperatures, the enzymatic activity reduces to 98%, for instance, for the peroxidase enzyme [2].

Nowadays, agroindustry uses large volumes of acid solutions to prevent fruit oxidation; this is done before exportation [3]. The acid solution is used for hours until it saturates; after this, it is disposed of and replaced with a new solution. In a day, approximately 3800 liters of a solution are used, which is also contaminated with small banana pieces. In addition to all the negative environmental issues, the company infrastructure is getting destroyed. There have been traces of problems in pipes containing the disposal solutions.

The organizations seek continuous improvements in all their processes, and implementation of a recovery system to reduce consumption of water, energy, and raw materials is in their scope. For instance, a wastewater treatment plant is an option for better water use in a company.

This research aims to design a system to treat these acids in the water for the banana freezing process and recuperate as much acid as possible to decrease the use of the new acid solution, reducing the cost of new material for the process. A technical study is done to evaluate the feasibility of the proposed system.

II. MATERIAL AND METHODS

The method used to evaluate the system design for the recovery of the organic acids is based on three steps, as shown in Fig. 1. For all chemical processes, as the first step, it is essential to characterize the immersed solution or input of the process; this was done by an external laboratory using chromatographic and spectrophotometry analysis.

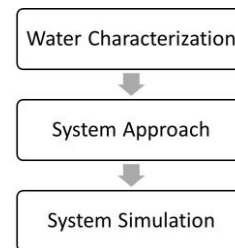


Fig. 1 Methodology used for the proposed system

The second step was done using a literature review. A series of flow process diagrams (PFD) was built to select the best option based on the company's performance and requirements. After the PFD was established, the process was inserted in an engineering simulator Pro/II® in which equipment capacities were evaluated. Finally, using Excel®, a rough estimate of investment was elaborated based on required equipment and implementation feasibility.

A. Separation System

An evaluation of the unit operations used in the process was done for the recovery system proposed. Several stages were considered, raw material treatment, reactor, and purification stage. These three stages were going to allow the recovery of solid acids from the residual water of acid solutions from the process. The first stage is the raw material

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which is the output of the banana freezing process. In this stage, a large volume of suspended solids from the banana was removed. The second stage is the reaction in which large volumes of clots are formed, and finally, the purification stage in which the solid acids were obtained with small amounts of water in its composition. These three stages were evaluated using the algorithm shown in Fig. 2.

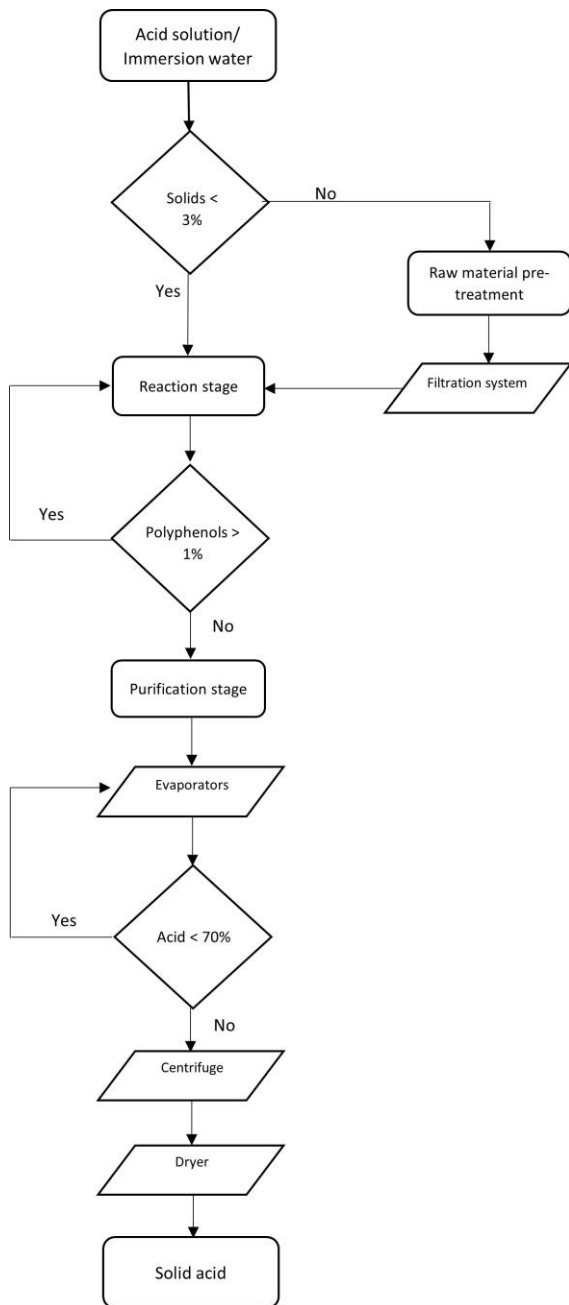


Fig. 2 Decision-making algorithm for the proposed system

B. Precipitating Reactant

For the separation of the polyphenols in the solution, the use of protein was evaluated and carbohydrate as a precipitant reactant. B-Cyclodextrin, serum albumin, and gelatin were compared to select the appropriate use of the reaction. The reactant had to satisfy the following conditions: capacity to precipitate tannins, and due to the company, the reactant must be approved by the organization Food and Drug Administration (FDA) and by the Organic Regulations EE.UU.

C. Simulation

For the simulation of the recovery process, an engineering software was used, Pro/II®. The simulation was done after the PFD was built, according to Fig. 2. The unit operations most representative in the process were simulated by using the requirements that the software asked for; this way, it resulted in meaningful information for the company and the proposed process.

D. Thermodynamic and unit operations

For selecting the thermodynamics in the simulation, the algorithms described in Fig. 3 and 4 are used.

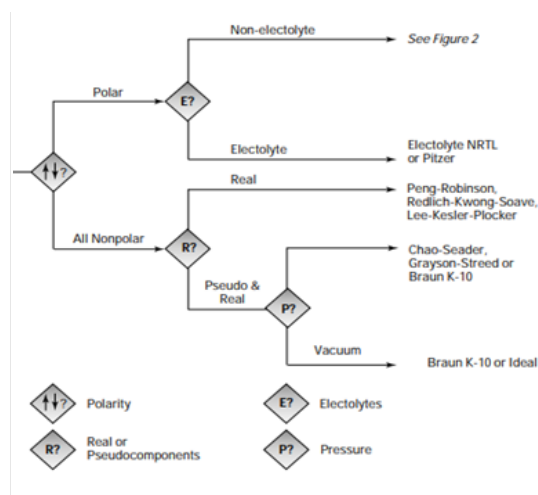


Fig. 3 Steps for the selection thermodynamic method based on physical properties [4]

III. RESULTS AND DISCUSSION

RECOVERY SYSTEM

A. Water characterization

Liquid chromatography and mass spectrometry were done to determine concentrations of acids and polyphenol (tannins) in the immersion water. This experimental analysis was done by an external laboratory, which reported the results used as inputs for the simulation (see Table II).

B. Selected process

Many advantages were found comparing them to the evaporation process; for instance, *acid-base reactions*, including *membranes*, had higher operations costs [5]. Thus, including recovery acid capacities, the evaporation process was selected as an important unit operation in the process flow.

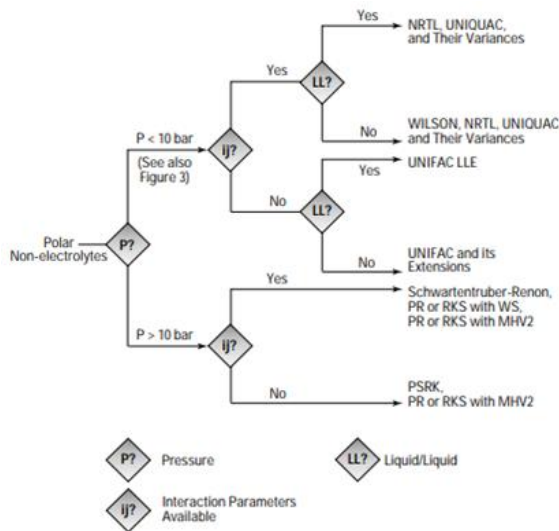


Fig. 4 Procedure for polar and non-electrolyte compounds [4]

Based on Carlson (1996) [3], the first step is to know the polarity of each component on the mixture, followed by the determination of the capacity to conduct electricity (electrolyte and no electrolyte). After this, the pressure of each unit operation of the recovery system is determined, considering whether it is more or less than ten absolute bar. Finally, the input data was calculated for the simulation (binary interaction parameters) and the mixture's equilibrium point.

After selecting the correct thermodynamics for the simulations, the conditions for each operation unit were determined. As seen in Table 1, a list of process unit names and specifications were selected based on the company and literature studies' needs. These were some of the process units used to elaborate the PFD.

TABLE I
PROCESS UNITS USED IN PRO/II®





Process Units	Name	Specifications Required
	Conversion Reactor	Temperature Increase. Reaction order: Reaction and conversion constants Product phase: Output phase
	Pump	Pressure Secondary units: Pump efficiency Mechanical efficiency
	Evaporator	Pressure Temperature
	Solid Dryer	Pressure Temperature

TABLE II
WATER CHARACTERIZATION

Chemical compositions (wt%)	Type of analysis
Citric Acid	22.66
Ascorbic Acid	28.67
Polyphenols	0.85
Organoleptic appearance	
Color	Yellow
Odor	Banana

The proposed system allows the recovery of solid acids in the process [6]. Furthermore, the recovery system does not require high fuel consumption for vapor production or expensive equipment than other processes, resulting in increased acid concentrations.

For the system of study, the unit operations selected are shown in Table III.

TABLE III
SELECTED EQUIPMENT AND UNIT OPERATION FOR THE PROPOSED SYSTEM

Units	Items	Type
Filter	1	Mesh
Pump	3	Centrifuge
Storage Tank	1	Cylinder
Reactor	1	Batch
Evaporator	2	Forced circulation
Centrifuge	1	For filtration
Dryer	1	Rotatory

C. Precipitating reagent

The protein selected to eliminate and extract the polyphenol was the gelatin due to its high capacity to form clots compared to cyclodextrin. In addition to this, it has a relation of 1:4 tannins/precipitating reagent, which indicates

that for 1 gram of tannin in the solution, it requires 4 grams of gelatin. This relation is less in comparison to the cyclodextrin that is 1: 6,667. On the other hand, the gelatin cost is \$12/kg, based on market reports less than the other reagents mentioned, information based on Ecuadorian markets.

The pH was also studied for both proteins, and it was determined that the gelatin becomes stable and can form clots at pH 4.5, which matches with the pH of the immersion water at ambient conditions in the actual process.

D. Flow process diagram of the evaporation system

The PFD of the evaporation system was elaborated using the selected operation units mentioned in Table III.

The acid solution is fed into the process; this feed contains banana waste on its composition, which will be extracted using the filter S-101, as seen in Fig. 5. The outflow of the filter will be divided into banana waste (current (2)) and liquid waste (current (3)), which is part of the process. This liquid is pumped to the tank TK-101 to control the liquid process volume to start its operation. The outflow of TK-101 passes through an automatic valve that will have a sensor connected to the tank's level control.

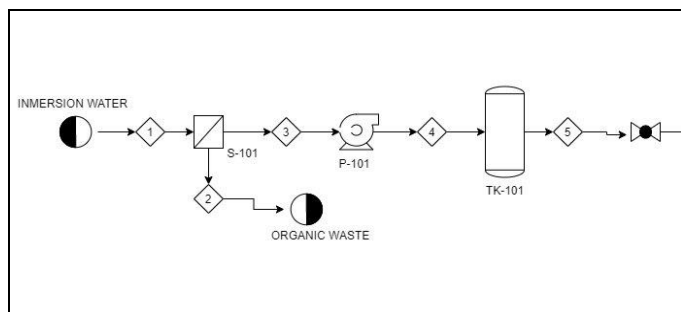


Fig. 5. Part 3 PFD of the evaporation system

The precipitating reagent (gelatin) was added to the reactor R-101, as seen in Fig. 6, in which clots were formed to precipitate the polyphenols (tannins) that were pumped using pump P-102 from TK – 101 (current (7)). Two phases were created in the reactor, an aqueous phase (current (10)) and an organic phase (current (9)); these were separated using decantation and level control in the reactor.

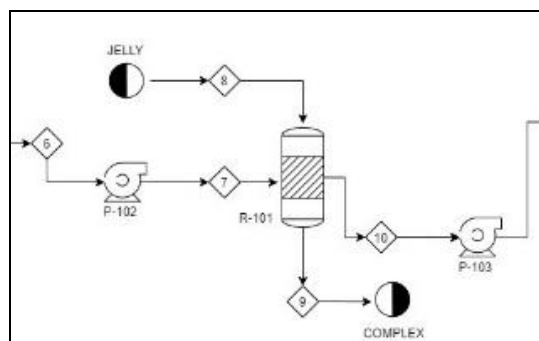


Fig. 6. Part 2 PFD of the evaporation system

The last part of the process flow diagram, Fig. 7, consists of the feed from the outflow of the reactor R-101 (current (10)). This process line is pumped to the first evaporator chamber, E-101. This first chamber operates with a pressure lower than the atmospheric pressure, which helps increase the solid acid concentrations. The outflow (current (12)) of the first chamber is fed to the second chamber evaporator, which operates with atmospheric pressure. This system is known as a double effect evaporator.

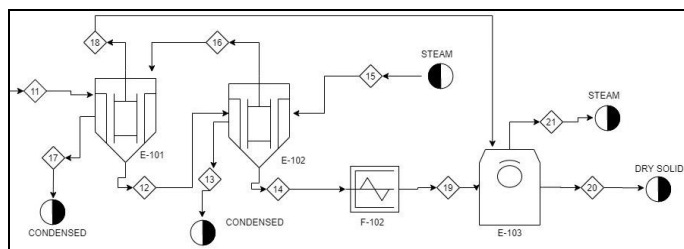


Fig. 7. Part 3 PFD of the evaporation system

This evaporation with double effect uses for heat exchange, vapor that comes from a steam boiler (current (15)) that operates at 786 kPa of pressure. This condition satisfies the energy requirement for the evaporator and the pumps of the process. Afterward, this vapor becomes the inflow to the first chamber (current (16)), it heats the first chamber, and then it is used for the following unit operation.

The outflow of the double effect evaporator, as shown in Fig. 7, passes through a centrifuge system F-102, which concentrates, even more, the solid acids but with a small percentage of water in its composition. This mixture of water and solid acid (current (19)) becomes the inflow to a rotary dryer E-103, which operates using the recycle vapor from the evaporation system (current (18)). The rotary dryer leads to the outflow of the process with solid acids (current (20)) and vapor (current (21)).

D.1. Evaporator

As said before, the evaporator is the heart of this process. Therefore, a material balance was done to assure that the information obtained from the simulation will be correct. With

the information collected from the company, a material and energy balance was performed, see Fig. 8.

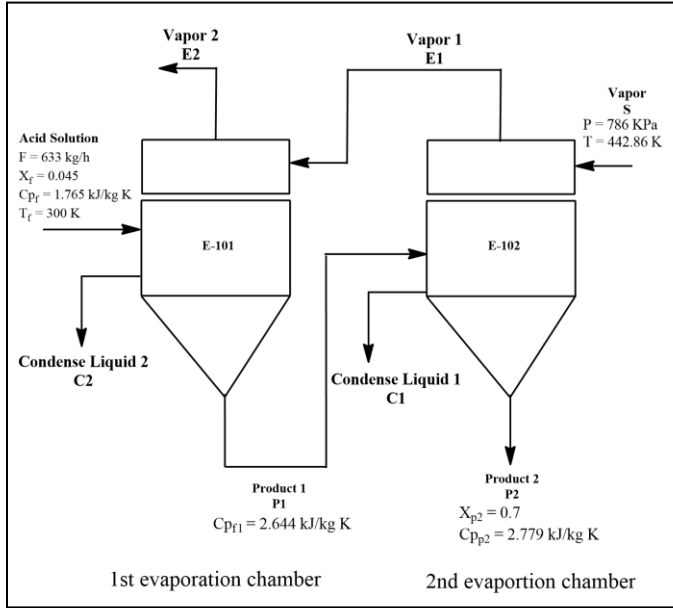


Fig. 8. Zoom in material balance for the double effect evaporator

All variables shown from (1) to (10) are defined in Fig. 8.

Solid global material balance

F : Feed mass flow

X_{F1} : mass fraction of the feed

X_{P2} : mass fraction of Product 2

$$F * x_F = P2 * x_{p2} \quad (1)$$

$$P2 = 40.69 \text{ Kg/h}$$

Assume that mass saturated vapor flow is $E1 = E2 = E$

$$E_1 = E_2 = E \quad (2)$$

$$F = 2 * E + P$$

$$633 = 2 * E + 40.69$$

$$E = 296 \text{ Kg/h}$$

Material balance E-101

$$F = P_1 + E_2 \quad (3)$$

$$633 = P_1 + 296$$

$$F_1 = 337 \text{ Kg/h}$$

Solid Material Balance E-101

$$F * x_F = P_1 * x_{F1} \quad (4)$$

$$633 * 0.045 = 337 * x_{F1}$$

$$x_{P1} = 0.085$$

After the material balance was done, an energy balance was required for the simulation. Some information was obtained, for instance, temperature, heat transfer coefficients, characteristics from vapor and water. All this information led to enthalpies, specific heat determination, and, most importantly, heat transfer area.

Information from the company, heat transfer coefficient

$$U_1 = 2838.98 \text{ W/m}^2\text{K}$$

$$U_2 = 3974.57 \text{ W/m}^2\text{K}$$

$\Delta T1$ y $\Delta T2$ calculus

$$\sum \Delta T = T_s - T_2 \quad (5)$$

$$\sum \Delta T = 442.68 - 311$$

$$\sum \Delta T = 131.68 \text{ K}$$

$$\Delta T_1 = \sum \Delta T * \frac{\frac{1}{U_1}}{\frac{1}{U_1} + \frac{1}{U_2}} = 76.81 \text{ K} \quad (6)$$

$$\Delta T_2 = \sum \Delta T * \frac{\frac{1}{U_2}}{\frac{1}{U_1} + \frac{1}{U_2}} = 54.87 \text{ K} \quad (7)$$

Enthalpies

C_{pf} : Feeds heat capacity

$$H_f = C_{pf} * (T - T_{ref}) = 1.765 * (298 - 273) = 44.125 \text{ kJ/Kg}$$

$$H_{f1} = C_{pf1} * (T - T_{ref}) = 2.644 * (311 - 273) = 100.472 \text{ kJ/Kg}$$

$$H_p = C_{pp} * (T - T_{ref}) = 2.779 * (365.87 - 273) = 258.086 \text{ kJ/Kg}$$

Energy balance E-101

$$FH_F + E_1H_{E1} = E_2H_{E2} + C_2H_{C2} + F_1H_{F1} \quad (8)$$

From $E1 = C2$

$C2$: Condense liquid mass flow

$$E_1(H_{E1} - H_{C2}) = E_2H_{E2} + F_1H_{F1} - FH_F$$

Using (2)

$$E_1(2664.18 - 389.1) = 296(2578.96) + 337(100.472) - 633(44.125)$$

$$E_1 = 339.623 \text{ Kg/h}$$

$$F = E_1 + E_2 + P_2 \quad (9)$$

$$E_2 = F - P - E_1 = 633 - 40.69 - 339.623 = 252.687 \frac{\text{Kg}}{\text{h}}$$

Energy balance E-102

S: Vapor mass flow

$$SH_S + F_1H_{F1} = E_1H_{E1} + C_1H_{C1} + PH_P \quad (10)$$

From $S = C1$

C1: Condense liquid mass flow

$$S(H_S - H_{C1}) = E_1H_{E1} + PH_P - F_1H_{F1}$$

$$S(2767.58 - 717.82) = 339.623(2664.18) + 40.69(258.086) - 337(100.472)$$

$$S = 430 \frac{\text{Kg}}{\text{h}}$$

A heat transfer area was determined within all these calculations that satisfied the simulation's conditions and the other operation units used in Pro/II®.

TABLE IV
EVAPORATOR'S DESIGN AREA

	Chamber 1	Chamber 2
Heat generated from vapor (kW)	244.83	214.63
Heat transfer area (m ²)	1.1	0.98

E. Simulating the system

Pro/II® simulator was used to gain information for the research. The thermodynamic method selected for the simulation was NRTL. This method was selected based on the water's characterization, which consists mostly of polar substances and less non-electrolytic substances; the system's pressure is less than 10 bar. The simulator also considers parameters with binary interactions.

The entry specifications to each unit's operations were based on bibliographic information, experimental systems, and similar simulations, as seen in Table V.

TABLE V
SPECIFICATIONS OF THE PROCESS UNITS USED IN PRO/II®

Process Unit	Specifications	Author
Conversion Reactor	ΔT: 2 K. Product currents(s): Liquid Solid	[7]
Pump	P = 101 325 Pa Secondary: η _p =0.8 † η _m =0.8 ‡	Authors
Evaporator	P = 101 325 Pa T = 383 K	[8]
Solid Dryer	P = 101 325 Pa T = 308 K	

† pump efficiency

‡ mechanic efficiency

F. Equipment design

Material and energy balance were obtained from the simulation done in Pro/II® (see Annex A. Table VII). These results helped determine the design parameters of the process unit operations in the recovery system. The design data was also carried out using heuristic methods and considering the critical points in each operation. Table VI shows the design parameters based on costs and material balance using Turton (2009) [9] heuristic methods and Capcost (CAPITAL COST).

TABLE VI
DESIGN PARAMETERS FOR THE UNIT OPERATIONS USED IN THE SEPARATION SYSTEM

Process Unit	Design Parameter	Value
Filter	Area	0.5 m ²
Reactor	Volume	0.71 m ³
Pump 1	Power	2.24 KW
Storage Tank	Volume	2 m ³
Pump 2	Power	6.62 KW
Pump 3	Power	6.62 kW
Vacuum evaporator	Area	1.12 m ²
Atmospheric evaporator	Area	0.98 m ²
Centrifuge	Diameter	0.50 m
Rotatory dryer	Area	4 m ²

IV. CONCLUSIONS

The design of an evaporation recovery system for organic acids consists of 3 parts: the pre-treatment of raw materials, which includes pumps, storage tanks, and filters; the reaction

part, which includes fluid pumps and the reactor and finally the purification part, which has the double effect evaporator, centrifuge, and the dryer.

The simulation of the system was developed with compiled information from the literature review and scientific articles. This simulation led to the understanding of the precipitant reagent used for the tannins and the process units' specifications. The thermodynamic method used was NRTL due to physical chemistry properties in the study's solution in the raw material and heuristic methods for the heat transfer area calculation of the evaporator.

The operating conditions: Pressure (101.325 kPa – 724.27 kPa) due to the double effect evaporator, temperature (293 K – 442 K), the lowest temperature is used to void precipitation in undesired compounds and the maximum temperature used for the evaporators.

Finally, this project's implementation is considered economically feasible with a cost indicator of 64.02%, which indicates the annual saving in the purchase of acids, allowing the company to save in raw material and recirculate its acids in their process. On the other hand, the project's investment was \$ 226,364.00 and a TIR of 90%. This information is provided from Capcost and the companies indicators.

ACKNOWLEDGMENT

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ANNEX A

TABLE VII
MATERIAL AND ENERGY BALANCE FROM THE PROPOSED RECOVERY SYSTEM

CURRENT	1	2	3	4	5	6	7	8	9	10
From	Feed	S-101	S-101	P-101	TK-101	V-101	P-102	Feed	R-101	R-101
To	S-101	Residual	P-101	TK-101	V-101	P-102	R-101	R-101	Residual	P-103
Phase	S-L	S	L	L	L	L	L	S	S	L
Pressure (atm)	1	1	1	1.003	1.003	1.003	1.006	1	1.003	1.003
Temperatura (K)	295	295	295	295.03	22.03	22.03	22.06	297	298	25
Density (Kg/m3)	1016	1320	1020.14	1020.14	1020.14	1020.14	1020.14	1134	1058.33	1020.85
Mass Flow (Kg/h)	221.86	6.6558	215.2042	215.2042	632.633	632.633	632.633	3	3.183	632.45
Enthalpy (KJ/Kg)	91.82	90.52666667	91.86	100.064	100.064	100.064	100.398	1175.53	1179.48	44.125
Mass Composition										
Water (% m/m)	0.8190	-	0.8444	0.8444	0.8444	0.8444	0.8444	-	-	0.9470
Ascorbic Acid (%m/m)	0.0856	-	0.0882	0.0882	0.0882	0.0882	0.0882	-	-	0.0300
Citric Acid (%m/m)	0.0428	-	0.0441	0.0441	0.0441	0.0441	0.0441	-	-	0.0150
Polyphenols (%m/m)	0.0225	-	0.0232	0.0232	0.0232	0.0232	0.0232	-	0.1298	0.0075
Protein (%m/m)	--	-	-	-	-	-	-	1.0000	0.8702	0.0004
Inerts (%m/m)	0.0300	1.0000	-	-	-	-	-	-	-	-

CURRENT	11	12	13	14	15	16	17	18	19	20	21
From	P-102	E-101	E-102	E-102	Feed Vapor	E-102	E-101	E-101	F-102	E-103	E-103
To	E-101	E-102	Cond 1 *	F-102	E-102	E-101	Cond 2 **	E-103	E-103	Product	Vapor
Phase	L	L-S	L	L-S	V	V	L	V	S-L	S	V
Pressure (atm)	1.006	0.065	1.04	1.04	7.15	1.05	0.065	0.065	1	1	1
Temperatura (K)	25.03	311	638.87	365.87	442.68	365.87	311	311	311	358	313
Density (Kg/m3)	1020.85	1030.36	998	1360	1360	998	998	998	1585	1586	998.9
Mass Flow (Kg/h)	632.45	409.28	430	27.449	430	296	296	296	19.61	19.4	296
Enthalpy (KJ/Kg)	44.125	100.472	717.82	258.086	2767.58	2664.18	389.1	2578.96	869.556	1000.968	2406
Mass Composition											
Water (% m/m)	0.9470	0.9211	1.0000	0.3000	1.0000	1.0000	1.0000	1.0000	0.0200	0.0100	1.0000
Ascorbic Acid (%m/m)	0.0300	0.0445	-	0.4690	-	-	-	-	0.6600	0.6635	-
Citric Acid (%m/m)	0.0150	0.0224	-	0.2310	-	-	-	-	0.3200	0.3265	-
Polyphenols (%m/m)	0.0075	0.0112	-	-	-	-	-	-	-	-	-
Protein (%m/m)	0.0004	0.0008	-	-	-	-	-	-	-	-	-
Inerts (%m/m)	-	-	-	-	-	-	-	-	-	-	-