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Jan F.M. Van Impe, Grégoire Léonard, Satyajeet S. Bhonsale,
Monika E. Polańska, Filip Logist (Eds.)

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Valorization of suspended solids from wine effluents through hydrothermal liquefaction: a sustainable solution for residual sludge management

Carlos E. Guzmán Martínez [a], Sergio I. Martínez Guido [a], Valeria Caltzontzin Rabell [a], Salvador Hernández [b], and Claudia Gutiérrez Antonio [a]*

[a] Universidad Autónoma de Querétaro, Facultad de Ingeniería, Querétaro, Querétaro, México
[b] Universidad de Guanajuato, Departamento de Ingeniería Química, Guanajuato, Guanajuato, México
* Corresponding Author: claudia.gutierrez@uaq.mx

ABSTRACT

The growing concern over the environmental impacts of the wine industry has driven the search for sustainable technologies to manage its waste, particularly the residual sludge generated during effluent treatment. This sludge, rich in organic matter, represents a significant source of pollution if not properly treated. However, their energy content allows them to turn this environmental liability into an asset through innovative valorization. Hydrothermal liquefaction (HTL) emerges as a promising technology in this context. This process allows the direct conversion of residual sludge into high-energy-value liquid biofuels. Unlike other treatment methods, HTL can process wet biomass without needing prior drying, making it particularly suitable for managing sludge from wine effluents. Thus, this research aims to evaluate the conversion of residual sludge derived from wine effluent treatment into biofuels through a hydrothermal liquefaction simulation, integrating this process into a sustainable biorefinery for levulinic acid and bioethanol production. The methodology considers the determination of the composition and treatment of the wine effluent to define a case study. The biorefinery processes, as well as the HTL, are designed and simulated in Aspen Plus V.14, and also they are evaluated technically and economically. As a result, levulinic acid, sustainable aviation fuel, bioethanol, propylene glycol, and electrical energy are produced. In addition, the biorefinery reduces the effluent's Chemical Oxygen Demand (COD) by 99%. In conclusion, valorizing suspended solids from wine effluents through HTL is technically and economically feasible.

Keywords: Hydrothermal liquefaction, Biorefinery, Wine effluents, Sludge valorization, Aspen Plus V.14.

INTRODUCTION

The winemaking industry releases large quantities of waste, being wine effluents between them. According to Buitron et al. (2019) [1], the ratio of wastewater per liter of wine produced is 2-4. Due to its features, the effluent is treated by using biological processes, such as anaerobic fermentation [1]; unfortunately, the organic material remotion in wastewater generates considerable quantities of sludge, which represents a significant source of pollution if it is not adequately treated [2]. Sludge derived from effluent treatment can be valorized to generate new products. In the literature, several alternative processes for treating sludge are reported. These processes are feasible from a technical point of view, but they fail to reach economic viability. In this context, the concept of biorefinery arises. A biorefinery is an implemented process involving unit operations aiming to transform raw materials, mainly biological ones, into a wide range of value-added products, biofuels, energy, or renewable materials [3].

Among the value-added products, levulinic acid is highlighted. The National Renewable Energy Laboratory identifies 12 essential chemical compounds, which are value-added products that can be produced from sugars through biological or chemical conversions; among these

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compounds is levulinic acid. This component presents enormous economic potential because it is a raw material of various industrially important chemicals, such as methyl-tetrahydrofuran [4]. Besides, levulinic acid is a value-added product used in producing nylon, synthetic rubbers, plastics, and pharmaceuticals.

On the other hand, biofuels and chemicals, bioethanol, sustainable aviation fuel, and propylene glycol are of interest due to their wide applications in the industrial sectors. Bioethanol is a liquid biofuel from renewable biomass sources such as agricultural waste, winery effluent, and lignocellulosic residues. Its increasing use in the energy matrix addresses the need to reduce dependence on fossil fuels and lower greenhouse gas emissions, thereby contributing to climate change mitigation and energy sustainability [5]. Moreover, propylene glycol and dipropylene glycol are used as an antifreeze liquid in airplane engines. Employing ethylene oxide hydration and propylene oxide hydration can produce a mixture of glycols that have an industrial value [5]. Finally, sustainable aviation fuel is the best alternative for decarbonizing the aviation sector.

Therefore, this work proposes using sludge derived from wine effluent treatment to produce levulinic acid, bioethanol, propylene glycol, and sustainable aviation fuel. To the authors' knowledge, this approach has not been reported in the literature. For this, a biorefinery is modeled and simulated, considering hydrothermal liquefaction; this last technology is a promising solution to transform wet biomass, such as sludge, into valuable bio-oil, offering advantages like waste volume reduction, energy recovery, and decrement of greenhouse gas emission [6].

METHODOLOGY

The research is divided into six stages:

1. Definition of a case study. It consists of considering a calculous base that represents an actual situation; according to that, the process feed stream is chemically characterized using literature searching.
2. Development of a conceptual design for biorefinery. It proposes the products obtained from the raw material stream and the unit operations needed to reach them.
3. Compilation of thermodynamic and chemical kinetic data. Through a literature search, chemical kinetic parameters and equations are joined to describe reactors' behavior. In addition, thermodynamic parameters are taken to guarantee a close approach to actual process performance. Carlson algorithm has been employed to define thermodynamic models in each unit operation [7].
4. Aspen Plus V.14 simulation. Using rigorous models, the conceptual design of biorefinery is simulated in Aspen Plus V.14.
5. Parametric analysis. Sensitivity analyses are carried out for each unit operation to define the final values of manipulated variables.
6. Technical and economic evaluation. Technic and economic parameters are calculated to evaluate the biorefinery performance. These are described by equations (1 - 12). Equipment costs are estimated by using the Guthrie method [8]. In addition, chemical oxygen demand (COD) is calculated using Aspen Plus V. 14 as a technical and environmental indicator.

$$rec = \frac{oms}{fms} \tag{1}$$

$$cv = \frac{r_{in} - r_{out}}{r_{in}} \tag{2}$$

$$Yd = \frac{pmf}{tpm} \tag{3}$$

$$pmr = \frac{mp}{rmm} \tag{4}$$

$$PFT = (Ah)(psale - rmc - UC_T) - (\mathrm{k})(\mathrm{EC}) \tag{5}$$

$$psale = \sum_1^j \left((mp_j)(pp_j)\right) \tag{6}$$

$$rmc = \sum_1^g \left((rmm_g)(prmm_g)\right) \tag{7}$$

$$UC_T = \sum_1^i UC_i \tag{8}$$

$$k = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{9}$$

$$EC = C_2 = C_1\left(\frac{I_2}{I_1}\right) \tag{10}$$

$$C_{BM} = C_P^{\circ}(B_1 + B_2 F_M F_P) \tag{11}$$

$$Log_{10} C_P^{\circ} = K_1 + K_2 Log_{10}(\mathrm{A}) + K_3 (Log_{10}(\mathrm{A}))^2 \tag{12}$$

Where: rec = component recuperation, oms = output mass flow (kg/h), fms = feed mass flow (kg/h), cv =conversion, r_{in} = reactant input to process (mol/h), r_{out} = reactant output to process (mol/h), Yd = Yield, pmf = moles of desired product formed (mol), tpm = theoretical product moles (mol), pmr = product mass ratio, mp = product mass flow (kg/h), rmm = raw material mass flow (kg/h), PFT= Annual profit (USD/y), Ah = hours per year (8,766 h/y), PSALE = product sale (USD/h), RMC = raw material cost (USD/h), UCT = Utilities total cost (USD/h), k = annualization factor, EC = Equipment cost (USD), pp = product price (USD/kg), prmm = raw material price (USD/kg), UC = Utility cost, i = interest rate (10 %), n = project life period (20 years), C°_{p} = Equipment base cost (USD), A = capacity or measurement parameter for the equipment, (K_1, K_2, K_3, B_1, B_2,) = Guthrie's constants, F_M = material factor, F_P = pressure factor, C_{BM} = module cost (USD), C_1 = Equipment cost at reference time (USD), C_2 =

Cost of equipment in the desired time (USD), I_1 = Reference time cost index, I_2 = Desired Time Cost Index. Subscripts: j = product stream, g = raw material stream, i = utility. It is important to mention that utility costs are calculated by using Aspen Plus V.14 software.

Table 1 shows the wine effluent composition. The solids, which are considered the sludge's main components, are represented by cellulose ($C_6H_{10}O_5$), hemicellulose ($C_5H_8O_4$), lignin ($C_{7.3}H_{13.9}O_{1.3}$), and lees (dead yeast, $CH_{1.83}O_{0.56}N_{0.17}$) [9].

Table 1: Comparison between wine effluent and treated water.

Parameter	Wine effluent	Treated water
Mass Flow (kg/h)	10,000	4,333.16
Water (% mass)	71.76	99.99
Ethanol (% mass)	7.39	0
Glucose(% mass)	5.26	0
Solid (% mass)	15.59	0
COD (PPM)	210,052	32.19

Figure 1 represents the conceptual biorefinery. Wine effluent is fed to process through a decanter tank (DCT-01), where some solids are separated from the liquid matrix. NRTL is employed as a thermodynamic model for this unit operation. The remaining solids in the liquid phase are sent to the centrifuge (CN-01). This equipment uses NRTL as thermodynamic model. Liquid flow coming from CN-01 goes to reactive distillation column # 1 (RD-01); on the other side, the solids from CN-01 are mixed with those coming from DCT-01 to be pumped and heated for reaching the operational conditions in hydrothermal liquefaction reactor (R-01).

The liquid phase of water, ethanol, and glucose feeds RD-01. Inside the reactive column reactions (1) and (2), are carried out, Table 2. The kinetic parameters are taken from the literature [4]. Glucose is transformed to 5-Hydroximetilfurfural, then converted to levulinic acid and formic acid. For RD-01 modeling, the Rad Frac block and NRTL thermodynamic model are employed. The RD-01 top releases ethanol and water to a conventional distillation column (DC-03). Moreover, the stream coming from the RD-01 bottom is constituted by levulinic, formic, and sulphuric acids; this stream is fed to DC-01, a conventional distillation column that separates formic acid from the acid mixture.

DC-01 is modeled by Rad Frac block and uses NRTL as a thermodynamic model. DC-01 bottoms are directed to DC-02, where levulinic acid is separated from the mixture that contains the catalyst, H_2SO_4. DC-02 is simulated with the same rigorous models as DC-01. The catalyst is recirculated to RD-01.

DC-03 purifies the water by releasing all the organic compounds, mainly ethanol and traces of formic acid, from its top. From the DC-03 bottom, treated water is obtained. The thermodynamic model employed is Wilson, and Rad Frac block is used.

RD-02 receives the diluted ethanol, 53.94 % mass from DC-03, and propylene oxide as raw material. Inside this reactive column, reactions (3) and (4) are carried out [5], Table 2. The water reacts with propylene oxide to get propylene glycol. In addition, propylene oxide reacts with propylene glycol to produce dipropylene glycol. Rad frac block and NRTL thermodynamic model are used. Kinetic parameters are obtained from the literature [5]. On the RD-02 top, bioethanol production is reached, while glycols are released on the RD-02 bottom. It is important to mention that the glycol stream is coupled to the organic Rankine cycle, which uses R235FA as a working fluid to get electrical power; this aims to reduce electrical utility consumption.

Table 2: Reactions carried out in reactive distillation columns.

Reaction	#
$C_6H_{12}O_6 \xrightarrow{H_2SO_4} C_6H_6O_3 + 3H_2O$	(1)
$C_6H_6O_3 + 2H_2O \rightarrow C_5H_8O_3 + CH_2O_2$	(2)
$C_3H_6O + H_2O \rightarrow C_3H_8O_2$	(3)
$C_3H_6O + C_3H_8O_2 \rightarrow C_6H_{14}O_3$	(4)

R-01 is represented by the RBatch block and Peng-Robinson thermodynamic model. The solid compounds are transformed into biogas, bio-oil, and aqueous phase [10-11]. Operational conditions reached by R-01 are 400 °C and 220 bar. Reactions are described in Table 3. The kinetic parameters are taken from the literature [12].

Once products are obtained from R-01, they are separated using Flash Tank #1 (FL-01). FL-01 is modeled through a Sep block and NRTL thermodynamic model. Operational conditions are 20 °C and 1 bar.

The biogas and aqueous phases are considered by-products. The bio-oil is sent to the up-grading process in reactor #2 (R-02), the hydrotreatment. R-02 is a batch reactor, represented by RBatch block and Peng-Robinson thermodynamic model. It operates at 450 °C and 20 MPa. The reactions involved are those shown in Table 4. Kinetic parameters are taken from the literature [13]. At the end of this unit operation, residual gas (mainly H_2), biofuel, and aqueous phase are obtained. The mixture goes to Flash Tank #2 (FL-02).

A Sep block represents FL-02 and uses the NRTL thermodynamic model. Operation conditions are 30 °C and 1.52 bar. The biofuel stream is fed to conventional distillation column #4 (DC-04). DC-04 separates naphtha from the top and sustainable aviation fuel (biojet fuel) by the column bottoms. This column uses a Rad frac block and BK-10 as thermodynamic models.

Table 3: Reactions carried out in hydrothermal liquefaction reactor.

Reaction	#
$C_{7.3}H_{13.9}O_{1.3} \rightarrow 0.4475C_{12}H_{10}O + 0.8525H_2O + 1.93CH_4$	(5)
$C_{7.3}H_{13.9}O_{1.3} \rightarrow 0.4068C_{14}H_{12} + 1.3H_2O + 1.6045CH_4$	(6)
$C_{7.3}H_{13.9}O_{1.3} \rightarrow 0.3729C_{15}H_{14}O + 0.9271H_2O + 1.7063CH_4$	(7)
$C_{7.3}H_{13.9}O_{1.3} \rightarrow 0.6885C_8H_8O + 0.6115H_2O + 1.7923CH_4$	(8)
$C_{7.3}H_{13.9}O_{1.3} \rightarrow C_6H_6 + 3.95H_2 + 1.3CO$	(9)
$C_{7.3}H_{13.9}O_{1.3} \rightarrow 0.7417C_6H_6O + 0.1397C_6H_{10}O_4 + 2.0138CH_4$	(10)
$C_6H_{10}O_5 \rightarrow C_5H_4O_2 + CO + 2H_2O + H_2$	(11)
$C_6H_{10}O_5 \rightarrow C_5H_8O_3 + CO_2 + H_2$	(12)
$C_6H_{10}O_5 \rightarrow 0.48C_8H_{18} + 2.16CO_2 + 0.68H_2O$	(13)
$C_6H_{10}O_5 \rightarrow 0.4286C_9H_{20} + 2.1429CO_2 + 0.7143H_2O$	(14)
$C_6H_{10}O_5 \rightarrow 0.3871C_{10}H_{22} + 2.129CO_2 + 0.7419H_2O$	(15)
$C_6H_{10}O_5 \rightarrow C_2H_6O + C_2H_4O + CO + CO_2$	(16)
$C_6H_{10}O_5 + 3H_2O \rightarrow 2CH_2O_2 + 2C_2H_4O_2 + 2H_2$	(17)
$C_5H_8O_4 \rightarrow C_5H_4O_2 + 2H_2O$	(18)
$C_5H_8O_4 \rightarrow C_5H_8O_3 + O_2$	(19)
$C_5H_8O_4 \rightarrow 0.4C_8H_{18} + 1.8CO_2 + 0.4H_2O$	(20)
$C_5H_8O_4 \rightarrow 0.3571C_9H_{20} + 1.7857CO_2 + 0.4286H_2O$	(21)
$C_5H_8O_4 \rightarrow 0.3226C_{10}H_{22} + 1.7742CO_2 + 0.4516H_2O$	(22)
$C_5H_8O_4 \rightarrow 2C_2H_4O + CO_2$	(23)
$C_5H_8O_4 \rightarrow C_2H_6O + 3CO + H_2$	(24)
$C_5H_8O_4 + 2H_2O \rightarrow CH_2O_2 + 2C_2H_4O_2 + H_2$	(25)
$CH_{1.83}O_{0.56}N_{0.17} \rightarrow 0.09C_4H_5N + 0.49H_2 + 0.48CO + 0.08C_2H_5ON$	(26)
$CH_{1.83}O_{0.56}N_{0.17} \rightarrow 0.06C_4H_4N_2 + 0.05C_4H_9N + 0.57H_2 + 0.56CO$	(27)
$CH_{1.83}O_{0.56}N_{0.17} + 0.34H_2O \rightarrow 0.2667C_3H_6O_3 + 0.17NH_3 + 0.1C_2H_4O$	(28)
$CH_{1.83}O_{0.56}N_{0.17} \rightarrow 0.0647C_8H_{18} + 0.4824CO + 0.0776H_2O + 0.17NH_3$	(29)
$CH_{1.83}O_{0.56}N_{0.17} \rightarrow 0.0579C_9H_{20} + 0.4789CO + 0.0811H_2O + 0.17NH_3$	(30)
$C_6H_{12}O_6 \rightarrow C_5H_4O_2 + CO + 3H_2O + H_2$	(31)
$C_6H_{12}O_6 \rightarrow C_5H_8O_3 + CH_2O_2 + H_2O$	(32)
$C_6H_{12}O_6 \rightarrow 0.48C_8H_{18} + 2.16CO_2 + 1.68H_2O$	(33)
$C_6H_{12}O_6 \rightarrow 0.4286C_9H_{20} + 2.1429CO_2 + 1.7143H_2O$	(34)
$C_6H_{12}O_6 \rightarrow 0.3871C_{10}H_{22} + 2.129CO_2 + 1.7419H_2O$	(35)
$C_6H_{12}O_6 \rightarrow C_2H_6O + C_2H_4O + H_2 + 2CO_2$	(36)

RESULTS

As the study case, the wine effluent generated in a year by the Baja, California, Mexico wine industry is considered because this Mexican State generates 80% of national production [14,15]. Table 1 shows the study case's effluent characterization and the mass flow rates. Moreover, Table 5 shows the obtained products through the biorefinery scheme.

According to Table 5, water, glycols, bioethanol, biogas, and levulinic acid represent 58.12%, 23.9%, 6.5%, 3.89%, and 2.94% of the total production, respectively. These results are consistent with the inputs; the most abundant compound in wine effluents is water, which justifies that water has the highest value. The percentage of glycols comes from the reaction between the attached water in the diluted ethanol stream at the DC-03 dome outlet and the supplied propylene oxide. Although the solid presence is higher than ethanol and glucose in wine effluent, bioethanol and levulinic acid production are more significant than the biofuels (naphtha and sustainable aviation fuel) from sludge hydrothermal liquefaction. The cause is that not all solids produce bio-oil to upgrade to biofuels because they have both aqueous phase and biogas production; thus, bioethanol and levulinic acid production are more significant than liquid biofuels.

Table 4: Reactions carried out in bio-oil hydrotreatment reactor.

Reaction	#
$C_{12}H_{10}O + 9H_2 \rightarrow C_{12}H_{26} + H_2O$	(37)
$C_{12}H_{10}O + 8H_2 \rightarrow C_{12}H_{24} + H_2O$	(38)
$C_{14}H_{12} + 9H_2 \rightarrow C_{14}H_{30}$	(39)
$C_{14}H_{12} + 10H_2 \rightarrow 2C_7H_{16}$	(40)
$C_6H_6 + 4H_2 \rightarrow C_6H_{14}$	(41)
$C_6H_6 + 3H_2 \rightarrow C_6H_{12}$	(42)
$C_8H_8O + 6H_2 \rightarrow C_8H_{18} + H_2O$	(43)
$C_8H_8O + 5H_2 \rightarrow C_8H_{16} + H_2O$	(44)
$C_{15}H_{14}O + 10H_2 \rightarrow C_{15}H_{32} + H_2O$	(45)
$C_{15}H_{14}O + 9H_2 \rightarrow C_{15}H_{30} + H_2O$	(46)
$C_4H_5N + 4H_2 \rightarrow C_4H_{10} + NH_3$	(47)
$C_4H_5N + 3H_2 \rightarrow C_4H_8 + NH_3$	(48)
$C_4H_4N_2 + 6H_2 \rightarrow C_4H_{10} + 2NH_3$	(49)
$C_4H_4N_2 + 5H_2 \rightarrow C_4H_8 + 2NH_3$	(50)
$C_4H_9N + 2H_2 \rightarrow C_4H_{10} + NH_3$	(51)
$C_4H_9N + H_2 \rightarrow C_4H_8 + NH_3$	(52)
$C_5H_4O_2 + 6H_2 \rightarrow C_5H_{12} + 2H_2O$	(53)
$C_5H_4O_2 + 5H_2 \rightarrow C_5H_{10} + 2H_2O$	(54)
$C_5H_8O_3 + 5H_2 \rightarrow C_5H_{12} + 3H_2O$	(55)
$C_5H_8O_3 + 4H_2 \rightarrow C_5H_{10} + 3H_2O$	(56)

Table 5: Product mass flow

Product	Mass flow (kg/h)
Biogas	290.32
Naphtha	90.14
Sustainable aviation fuel	158.22
Levulinic acid	219.05
Bioethanol	485
Water	4,333.16
Glycols	1,781.68
Formic acid	93.5
Residual gas	5.03

Table 6 shows the technical indicators obtained. It is essential to highlight the conversion of solids and glucose that reach 100%. This means finding a sustainable solution for managing all residual sludge in treating wine effluents is possible. Water recuperation seems to have a low value; however, a water mass flow is consumed in glycol production, and another part goes to the aqueous phase, with the mass balance of ethanol, in the sludge hydrothermal liquefaction. The glycol yield is attractive because it is greater than 95 %. The levulinic acid yield may not seem good enough. However, it has to be highlighted that the reaction to obtain levulinic acid involved the production of formic acid, so it represents an attractive yield for reaching a value higher than 50%.

The ratios obtained in Table 6 give the impression that they are too small, though as shown in Table 1, the mass flow of wine effluent is several times greater than the obtained products. In addition, water is the main component of wine effluent, and it does not directly contribute to almost all products except glycol production; it

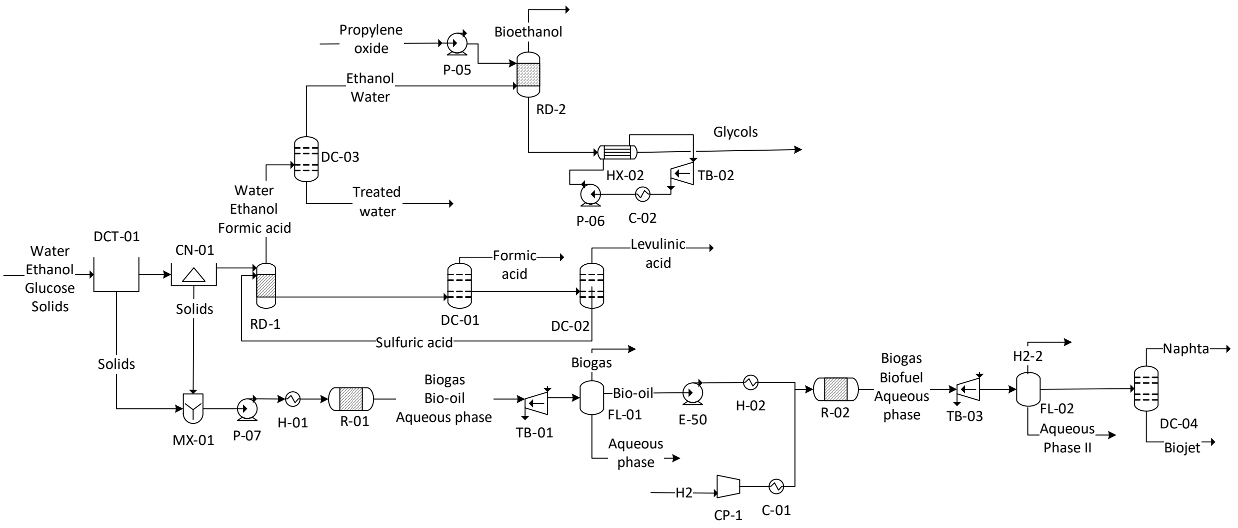

Figure 1: Biorefinery scheme. Where DCT=Decanter tank, CN= Centrifuge, RD= Reactive distillation column, DC= Distillation column, R= reactor, FT= Flash tank, MX= Mixer, TB=Turbine, C= condenser, P= Pump, CP= Compressor, HX= Heat exchanger, MX= Mixer.

provokes ratios that seem too insignificant. It does not happen with glycol production, where water is a reactant.

Table 6: Technical indicators

Parameter	Value
rec_{Water}	60.38 %
$rec_{Ethanol}$	65.63 %
$cv_{Glucose}$	100 %
cv_{Solids}	100 %
$Yd_{Levulinic\ acid}$	64.63 %
Yd_{Glycol}	97.21 %
pmr_{Biogas}	0.029
$pmr_{Naphtha}$	0.009
pmr_{Biojet}	0.0158
$pmr_{Levulinic\ acid}$	0.0219
$pmr_{Bioethanol}$	0.0485
pmr_{Water}	0.4333
$pmr_{Glycols}$	0.1782
$pmr_{Formic\ acid}$	0.0093
$pmr_{Residual\ gas}$	0.0005
COD removed	99.99%

For finishing the technical parameters, the COD reduction in treated water is so attractive because it is under the Official Mexican Standards (NOM-001-SEMARNAT-2021 and NOM-127-SSA1- 2021) that stipulate a COD level lower than 75 ppm is adequate to human use.

On the other hand, Table 7 shows the economic indicators. Regarding raw material cost, H_2 constitutes 50.2 % of the total, and the propylene oxide cost completes the balance. In product sales, levulinic acid gives the 86.89 % of the total, glycols the 8.86%, and bioethanol the 1.89%. Considering utility cost, the reboiler in RD-01 spent 91.52 % of the total; it is due to there being a large quantity of water and ethanol mass that has to be evaporated to separate it from the matrix with glucose, sulphuric acid, and formic acid; besides, it presents a higher reflux ratio, 20. these features consume too much energy, 136,043.28 kW.

Table 7: Economic indicators

Parameter	Value
Raw material cost (USD/h)	$129.75
Product sale (USD/h)	$31,010.08
Levulinic acid (USD/kg)	$123
Glycols (USD/kg)	$1.76
Bioethanol (USD/Kg)	$1.21
SAF (USD/kg)	$2.44
Naphtha (USD/kg)	$1.56
Biogas (USD/kg)	$1.39
Utilities cost (USD/h)	$1,507.88
Equipment cost (USD)	$51,335,863.95
Annual equipment cost (USD/y)	$6,029,891.32
Total annual cost (USD/y)	$20,385,357.23
Profit (USD/y)	$251,449,023.39

Regarding equipment cost, RD-01 represents the most expensive by using 41.45 % of the total, followed by R-01, the hydrothermal liquefaction reactor, with 23.51%, and R-02, the bio-oil hydrotreatment reactor. RD-01 has the highest cost due to its size and operational pressure, contributing to a more considerable equipment thickness.

CONCLUSIONS

This research presents the technical and economic feasibility of obtaining biofuels and value-added molecules through a biorefinery scheme. Different products, such as levulinic acid, bioethanol, biogas, glycols, naphtha, sustainable aviation fuel, and formic acid, are obtained from this biorefinery. This shows that the valuation of wine effluents and their sludge is possible using a biorefinery scheme.

Regarding the economic analysis, it is clear that levulinic acid production is essential in reaching the economic feasibility of wine effluent and its sludge valorization. However, expanding the range of generated products enhances the economic condition of the process, particularly when including biofuels, whose market price is lower than other higher-value-added products.

The presented strategy provides an efficient solution for waste management in the wine industry. However, a similar approach can be implemented for other sludge types. Moreover, this strategy contributes to the transition toward a circular economy by turning waste into energy-rich and value-added products.

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