Prefeasibility Analysis of Different Anaerobic Digestion Upgrading Pathways Using Organic Kitchen Food Waste as Raw Material

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Content

1. Introduction

A person generates between 0.3 and 0.74 kg of **municipal solid waste daily** → 60% represents organic waste [1].

61% of organic waste comes from households (i.e., organic kitchen food waste - **OKFW**)

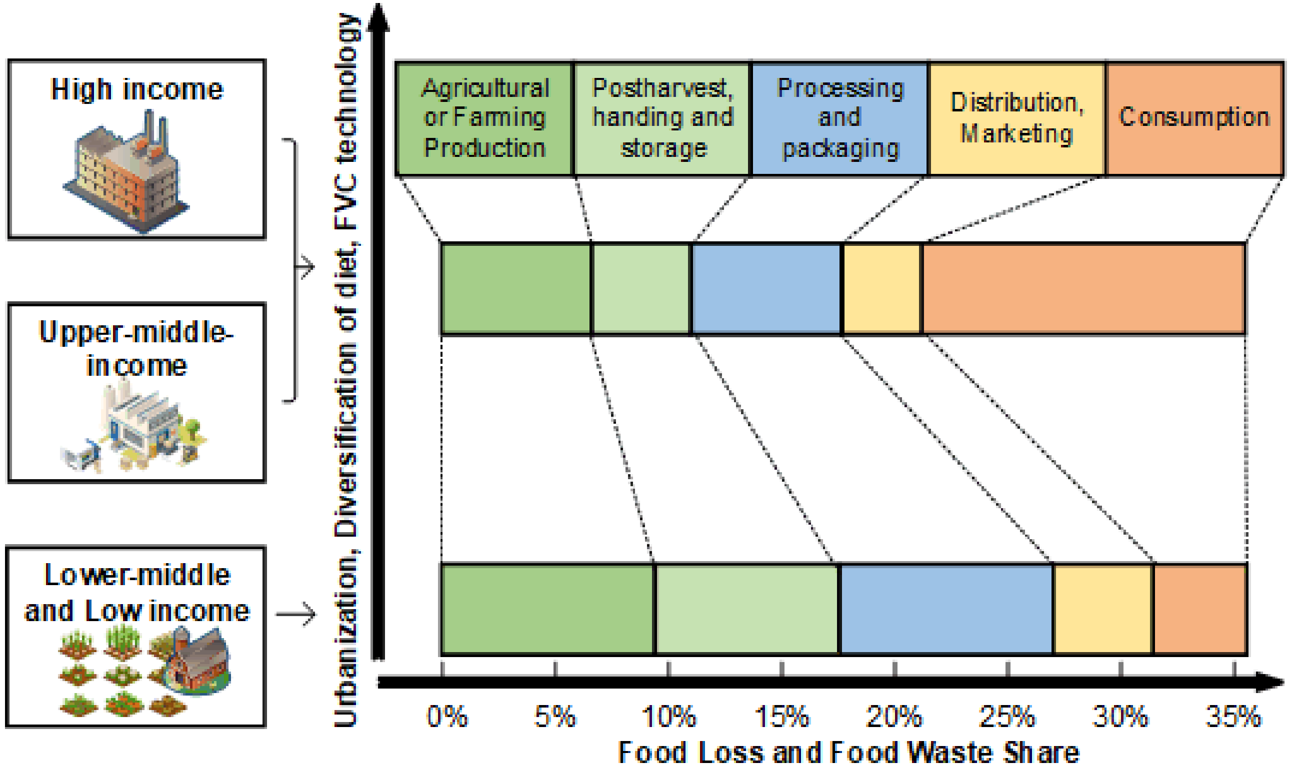
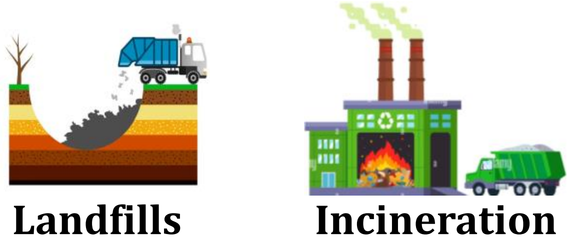


Figure 1. Trend of organic waste and losses in the food value chain.

OKFW have become a global problem associated to food safety factors and environmental impacts [2].



OKFW can be used to produce energy vectors or value-added products through easily applied technologies, such as anaerobic digestion (**AD**) processes [3].

[1] T. Getahun, M. Gebrehiwot, A. Ambelu, T. Van Gerven, and B. Van Der Bruggen, "The potential of biogas production from municipal solid waste in a tropical climate," *Environ. Monit. Assess.*, vol. 186, no. 7, pp. 4637–4646, 2014, doi: 10.1007/s10661-014-3727-4.
[2] United Nations Environment Programme, *Food Waste Index Report 2021*. 2021
[3] M. Blakeney, *Food loss and food waste: Causes and solutions.* 2019

1. Introduction

Anaerobic digestion

Degradation process of organic matter in the absence of oxygen from a microbial consortium [4].

Microbial consortium

Inoculum
- Wastewater
- Organic biological waste
- Animal manure

Operating conditions variation

pH
Time
C/N ratio

Main products

Biogas

Electricity and heat

Biomethane

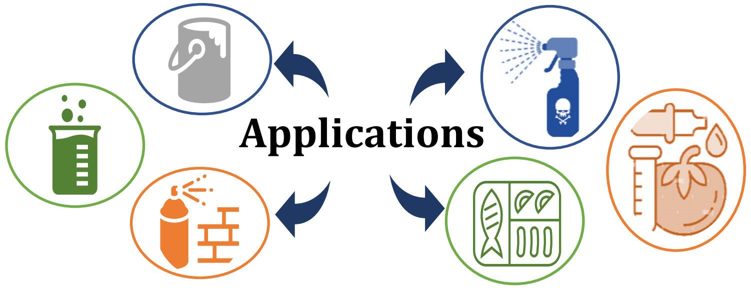
Digestate

Volatile fatty acids (VFA)

Intermediaries in the acidogenic stage

Depending on the feedstock, there might be representative **VFA.**

- Acetic acid
- Butyric acid

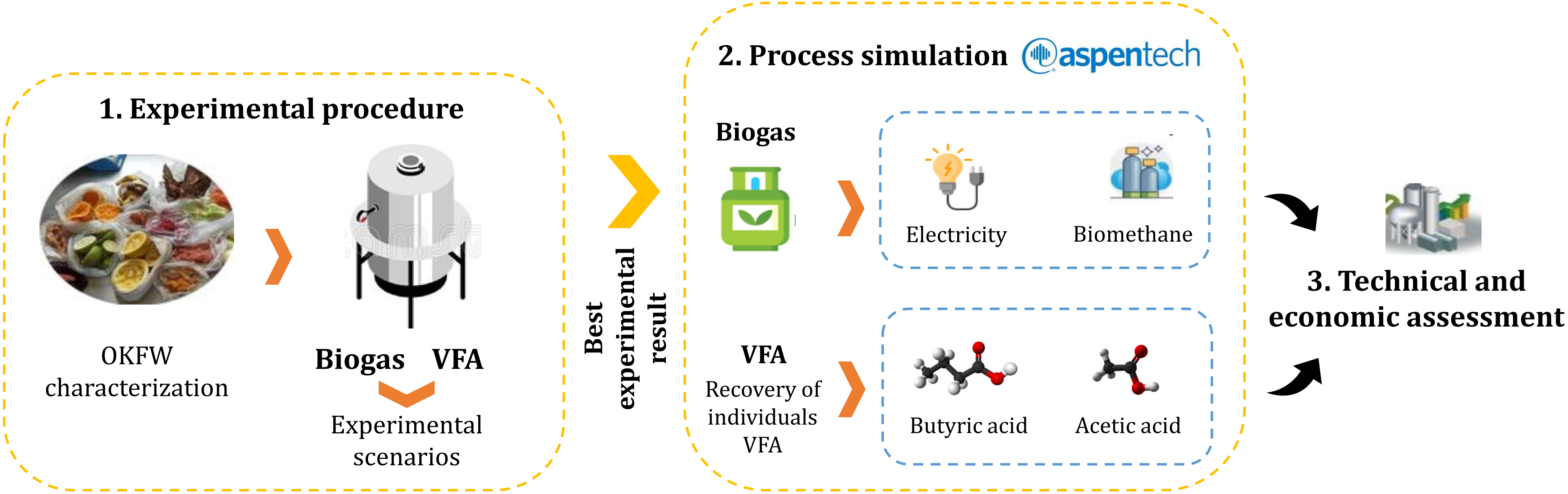


[4] Angelidaki *et al.*, "Defining the biomethane potential (BMP) of solid organic wastes and energy crops: A proposed protocol for batch assays," *Water Sci. Technol.*, vol. 59, no. 5, pp. 927–934, 2009, doi: 10.2166/wst.2009.040.

1. Introduction

Research objective

This work **aims to evaluate** the techno-economic feasibility of the anaerobic digestion upgrading pathways using organic kitchen food waste (OKFW) as raw material.



2. Methodology

2.1. Experimental procedure

2.1.1. Raw material composition model

A compositional model reported by previous studies was used. [5]

The methodology involves the use of the **most representative foods according to the basic family basket of Colombia**.

$$OKFW_{Model} = 0\%(DP) + 1\%(FS) + 3\%(MP) + 62\%(FV) + 1\%(OCP) + 25\%(RT) + 8\%(C)$$

$$FV_{62\%} = 20\%(tomato\ peel) + 16\%(onion\ peel) + 10\%(bean\ residues) + 1\%(pumpkin\ peel) + 4\%(lettuce\ residues) + 3\%(cabbage\ residues) + 1\%(beetroot\ peel) + 1\%(celery\ residues) + 10\%(citric\ peel\ and\ seed) + 5\%(banana\ peel) + 5\%(mango\ peel\ and\ seed) + 5\%(guava\ seeds) + 5\%(tree\ tomato\ peel\ and\ pulp) + 4\%(spent\ blackberry\ pulp) + 3\%(passion\ fruit\ peel\ and\ pulp) + 1\%(strawberry\ residues) + 3\%(avocado\ peel\ and\ seed) + 1\%(papaya\ peel\ and\ seed) + 1\%(apple\ residues) + 1\%(lulo\ peel\ and\ pulp)$$

$$RT_{25\%} = 60\%(patato\ peel) + 30\%(cassava\ peel) + 10\%(carrot\ peel)$$

$$MP_{3\%} = 50\%(beef\ bone) + 45\%(chicken\ bone) + 5\%(meat\ waste) \quad FS_{1\%} = 20\%(fish\ bone) + 80\%(egg\ shells)$$

The food groups share of the composition model was defined from reports of **government entities.**

Raw material characterization

The OKFW composition was handmade in the laboratory based on the composition model.

Homogenized

Chemical, proximate and solid analysis → **International standards methods, triplicate testing**

[5] Mariana Ortiz-Sanchez, Juan-Camilo Solarte-Toro, Carlos Ariel Cardona Alzate (2023). Food waste valorization applying the biorefinery concept in the Colombian context: Pre-feasibility analysis of the organic kitchen food waste processing

2. Methodology

2.1. Experimental procedure

2.1.2. Biogas and VFA production

Biogas and VFA production were performed using **three experimental scenarios.**

Scenarios

1
Dry feedstock:
Final moisture content 9.81%wt.
50°C, 24 hours

2
Fresh feedstock:
Moisture content 79 %wt.

3
Pretreated feedstock:
Liquid hot water (LHW) [7].
121°C, 1 bar , Liquid: Solid ratio 8.0

Biogas production

Standard method VDI 4630 [6]

Conditions:
T: 37 °C
I/S ratio: 0.4
pH: 7
Time: 26 days

Figure 2. Gasboard analyzer

VFA production

Conditions [7]:
T: 37 °C
I/S ratio: 1.2
pH: 5.5
Time: 10 days

Figure 3. SpectraMax® ABS microplate spectrophotometer.

VFA composition was determined by a colorimetric method described by Montgomery [8].

The inoculum was obtained from a coffee processing wastewater treatment plant.

I/S: Inoculum/Substrate

[6] Vdi 4630:2016-11fermentation of organic materials - characterization of the substrate, sampling, collection of material data, fermentation tests
[7] R. I. Iglesias, "Sustainable bioproduction of volatile fatty acids through fermentation of organic wastes," 2021
[8] H. A. C. Montgomery, J. F. Dymock, and N. S. Thom, "The rapid colorimetric determination of organic acids and their salts in sewage-sludge liquor," Analyst, vol. 87, no. 1041, pp. 949–955, 1962, doi: 10.1039/AN9628700949.

2.2. Simulation Procedure and Process Description

The simulation was performed using Aspen Plus v 9.0 software

Mass flow rate of **20.7 ton/day** of OKFW was performed. **Three** scenarios were proposed.

Mass balances of the best experimental results were provided as input data.

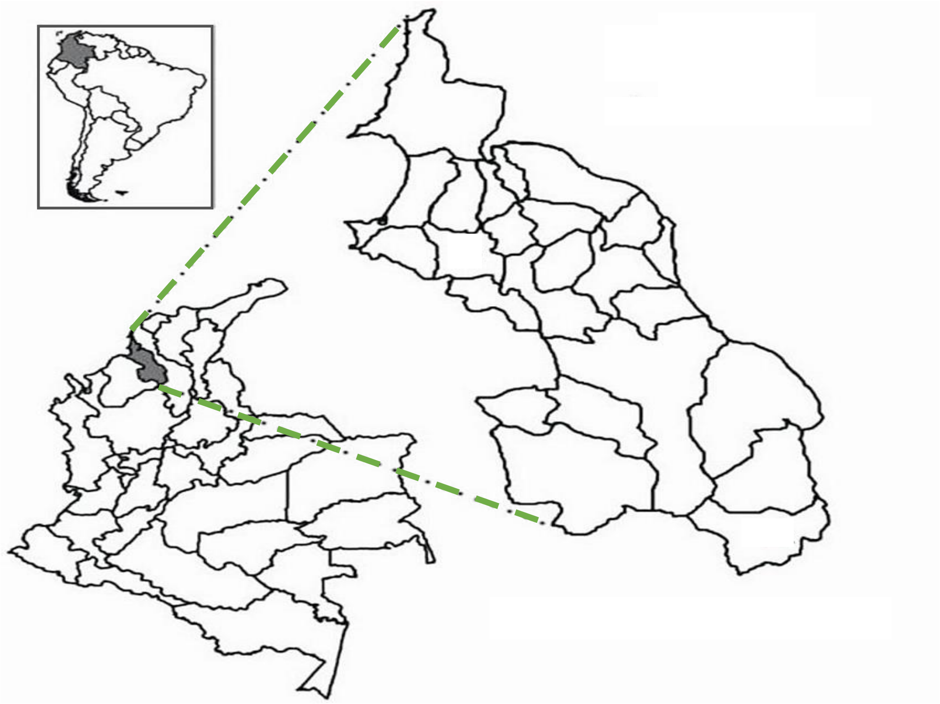


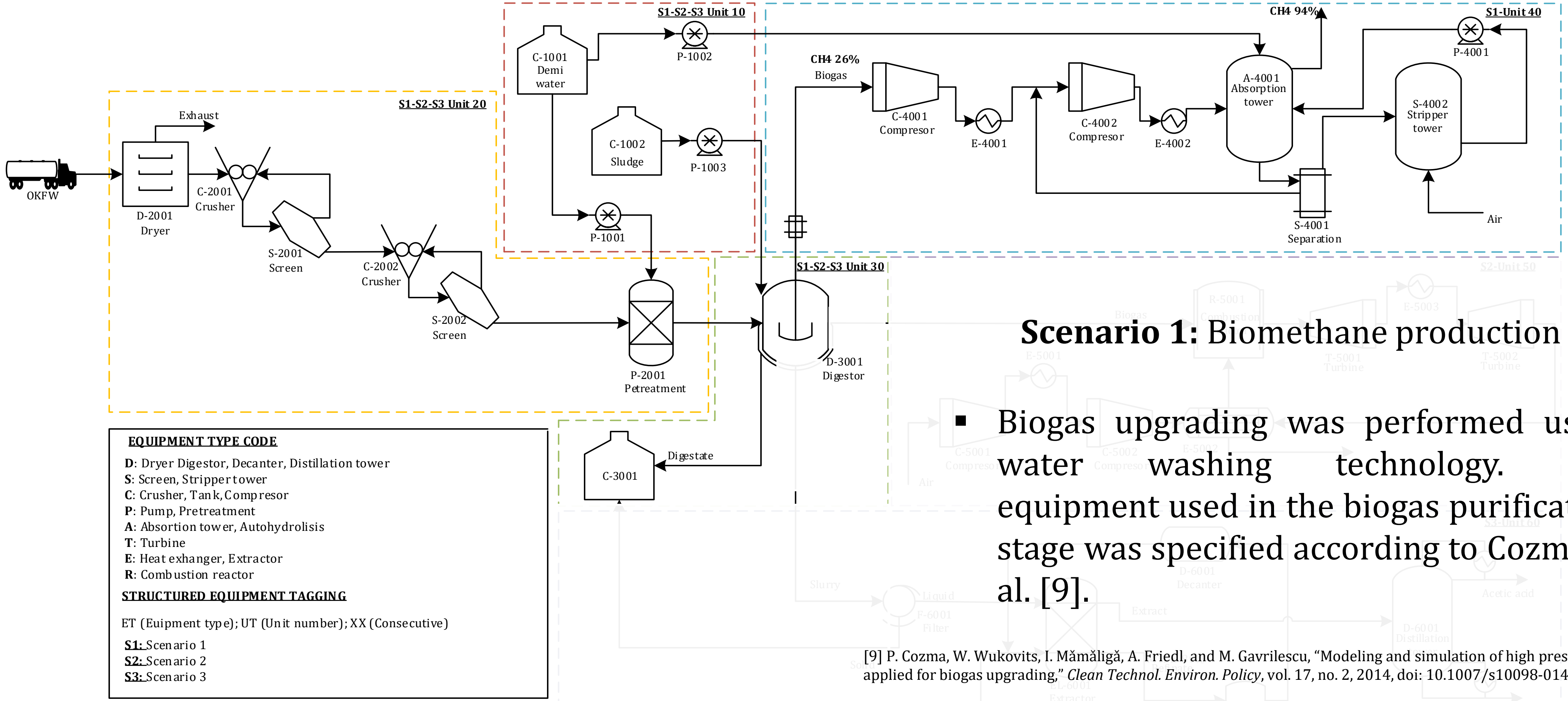
Table 1. Proposed valorization scenarios

Scenario	Process	Product	Sub products
Scenario 1	Biogas production	Biomethane	Digestate
Scenario 2	Biogas production	Electricity	Digestate
Scenario 3	VFA production	Acetic and butyric acid	Digestate

2. Methodology

2.2. Simulation Procedure and Process Description

The first three units (**Unit 10, Unit 20,** and **Unit 30**) are presented in the three proposed scenarios.



Scenario 1: Biomethane production

- Biogas upgrading was performed using water washing technology. The equipment used in the biogas purification stage was specified according to Cozma et al. [9].

[9] P. Cozma, W. Wukovits, I. Mămăligă, A. Friedl, and M. Gavrilescu, "Modeling and simulation of high pressure water scrubbing technology applied for biogas upgrading," *Clean Technol. Environ. Policy*, vol. 17, no. 2, 2014, doi: 10.1007/s10098-014-0787-7.

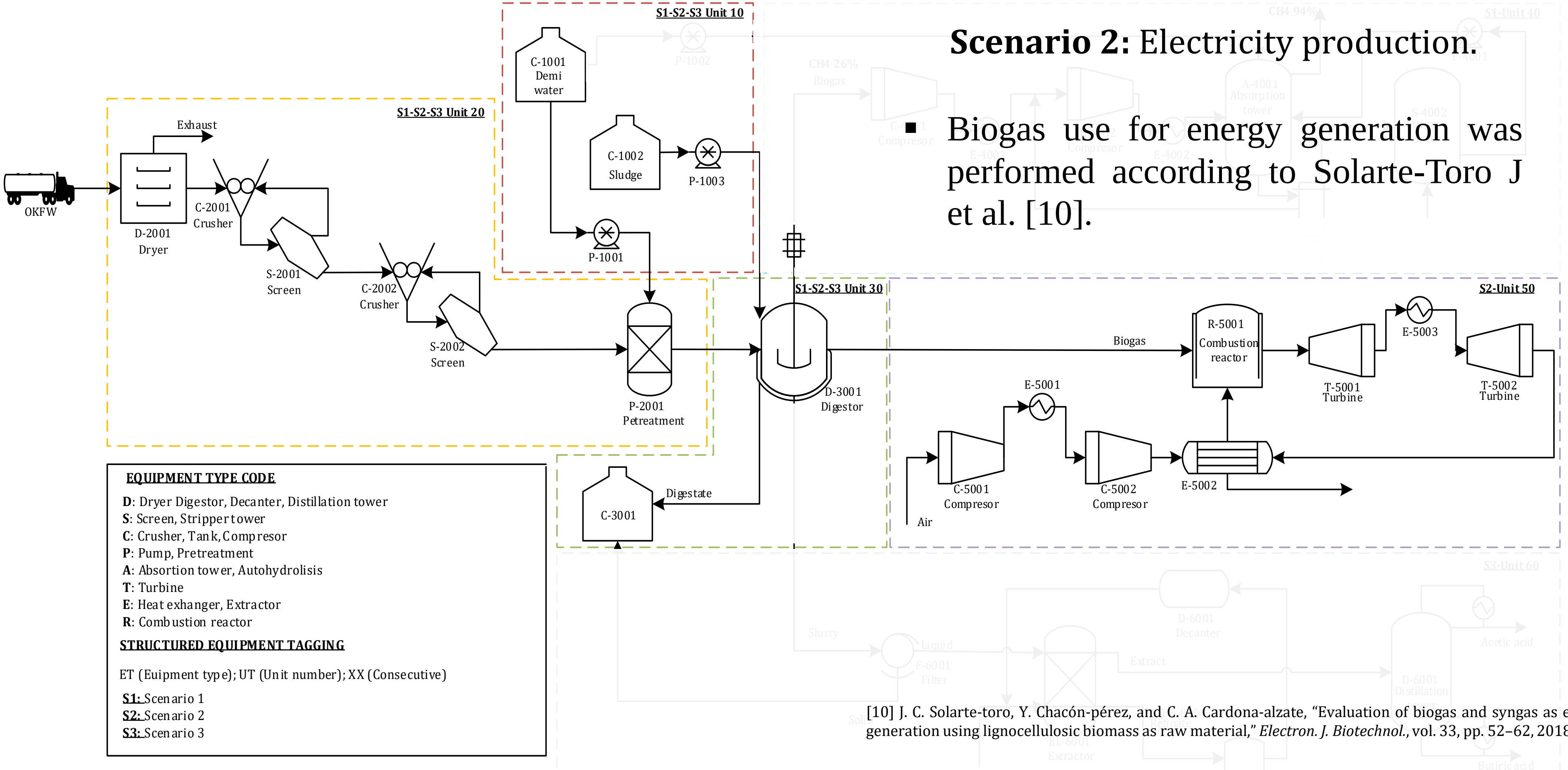
Figure 4. Process flow diagram of the methane (**Sc1**), electricity (**Sc2**) and VFA (**Sc3**) production process.

2. Methodology

2.2. Simulation Procedure and Process Description

Scenario 2: Electricity production.

- Biogas use for energy generation was performed according to Solarte-Toro J et al. [10].



[10] J. C. Solarte-toro, Y. Chacón-pérez, and C. A. Cardona-alzate, "Evaluation of biogas and syngas as energy vectors for heat and power generation using lignocellulosic biomass as raw material," *Electron. J. Biotechnol.*, vol. 33, pp. 52–62, 2018, doi: 10.1016/j.ejbt.2018.03.005.

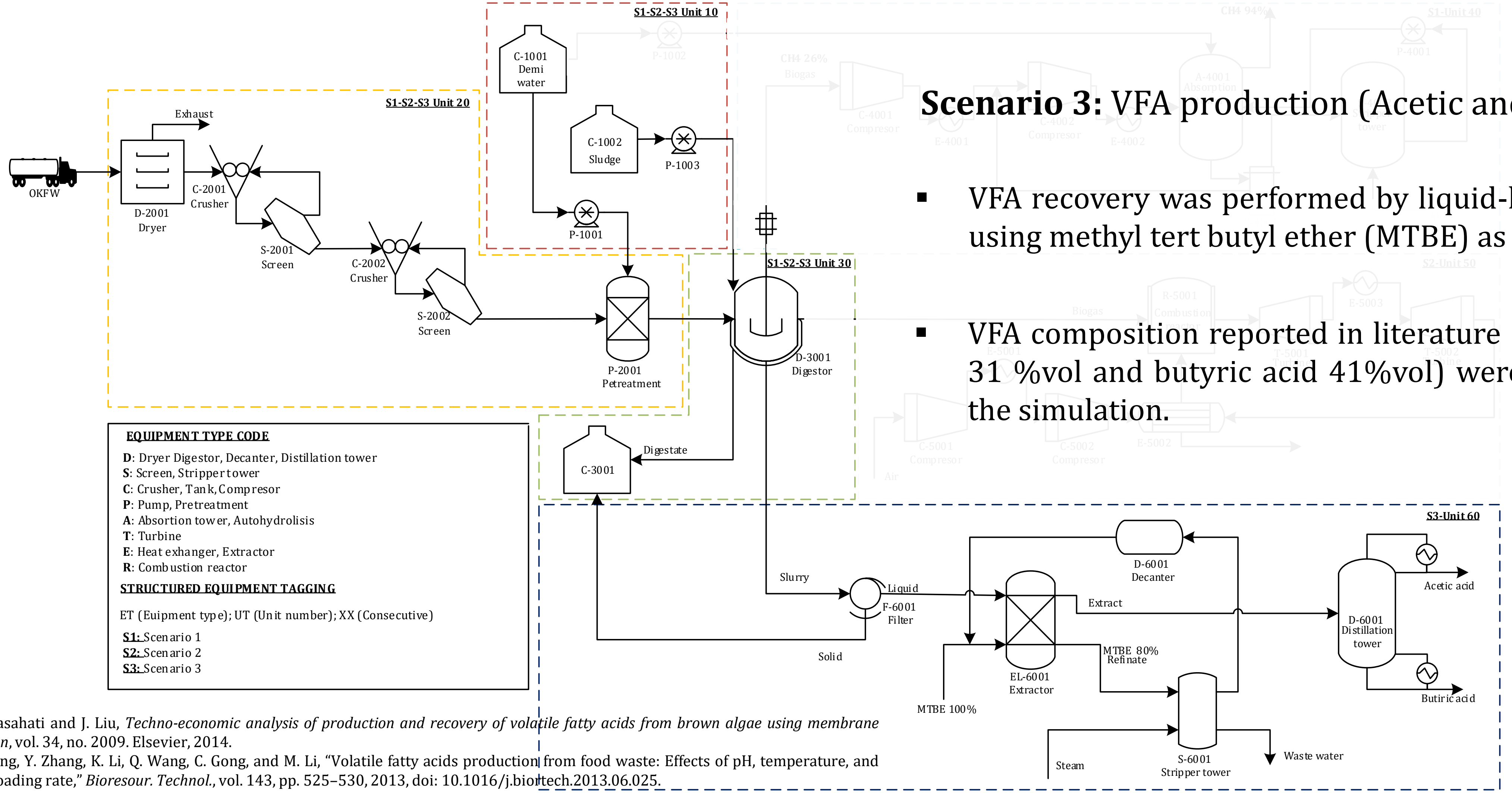
Figure 4. Process flow diagram of the methane (**Sc1**), electricity (**Sc2**) and VFA (**Sc3**) production process.

2. Methodology

2.2. Simulation Procedure and Process Description

Scenario 3: VFA production (Acetic and butyric acid)

- VFA recovery was performed by liquid-liquid extraction using methyl tert butyl ether (MTBE) as solvent [11].
- VFA composition reported in literature [12] (acetic acid 31 %vol and butyric acid 41%vol) were considered for the simulation.



[11] P. Fasahati and J. Liu, *Techno-economic analysis of production and recovery of volatile fatty acids from brown algae using membrane distillation*, vol. 34, no. 2009. Elsevier, 2014.

[12] J. Jiang, Y. Zhang, K. Li, Q. Wang, C. Gong, and M. Li, "Volatile fatty acids production from food waste: Effects of pH, temperature, and organic loading rate," *Bioresour. Technol.*, vol. 143, pp. 525–530, 2013, doi: 10.1016/j.biortech.2013.06.025.

Figure 4. Process flow diagram of the methane (**Sc1**), electricity (**Sc2**) and VFA (**Sc3**) production process.

2. Methodology

2.3. Technical and Economic Assessment

Technical assessment

The mass and energy requirements obtained from the simulation are considered. The technical assessment was determined with mass and energy indicators.

Product yield

$$Y_P = \frac{\dot{m}_{Product,\, i}}{\dot{m}_{in}}$$

Process mass intensity index (PMI)

$$Y_P = \frac{\sum_{i=1}^{n} \dot{m}_i^{in} - \dot{m}_{product}}{\dot{m}_{product}}$$

Mass indicators

Specific energy consumption (SEC)

$$S_{EC} = \frac{\dot{Q}_{Total} + \dot{W}_{Total}}{\dot{m}_{Raw\ material}}$$

Aspen Energy Analyzer v.9.0

Energy indicators

Economic assessment

Operating cost estimate (OpEx)

Operating costs, utilities, cost of supplies and raw material, labor costs.

Equipment cost estimation (CapEx)

Aspen Process Economic Analyzer v.9.0.

Colombian context

Tax rate: 35%
Interest rate: 13%
CEPCI: 815,98

3. Results and analysis

3.1. Raw material characterization

Table 2. Chemical characterization of raw material

Characterization	This work	OKFW [5]	Dinner shop food waste [13]	Food waste (restaurant) [14]	OKFW [15]
Chemical characterization					
Cellulose	31.96 ± 0.03	19.71			
Hemicellulose	9.84 ± 0.15	5.12	49.6	52.2	50.6
Lignin	15.47± 0.11	13.69			
Extractives	26.3 ± 0.08	20.92	-	-	-
Ash	4.79 ± 0.51	3.23	1.25	5.51	8.28
Fats	11.64 ± 0.42	6.34	3.1	16.2	15.4
Solid analysis					
Volatile solid	25.1 ± 0.10	20.54	-	35.4	-
Total solid	27± 0.36	21.67	-	39.1	-

The results present variations compared to other raw materials due to the compositional complexity.

These results show the potential of the raw material for anaerobic digestion processes due to its high carbohydrate content.

[5] Mariana Ortiz-Sanchez, Juan-Camilo Solarte-Toro, Carlos Ariel Cardona Alzate (2023). Food waste valorization applying the biorefinery concept in the Colombian context: Pre-feasibility analysis of the organic kitchen food waste processing
[13] C. Zhang, G. Xiao, L. Peng, H. Su, and T. Tan, "The anaerobic co-digestion of food waste and cattle manure," *Bioresour. Technol.*, vol. 129, pp. 170–176, 2013, doi: 10.1016/j.biortech.2012.10.138.
[14] X. Shi, X. Guo, J. Zuo, Y. Wang, and M. Zhang, "A comparative study of thermophilic and mesophilic anaerobic co-digestion of food waste and wheat straw: Process stability and microbial community structure shifts," *Waste Manag.*, vol. 75, pp. 261–269, 2018, doi: 10.1016/j.wasman.2018.02.004.
[15] K. S. Ho and L. M. Chu, "Characterization of food waste from different sources in Hong Kong," *J. Air Waste Manag. Assoc.*, vol. 69, no. 3, pp. 277–288, 2019, doi: 10.1080/10962247.2018.1526138.

3. Results and analysis

3.2. Biogas and VFA production

Biogas production

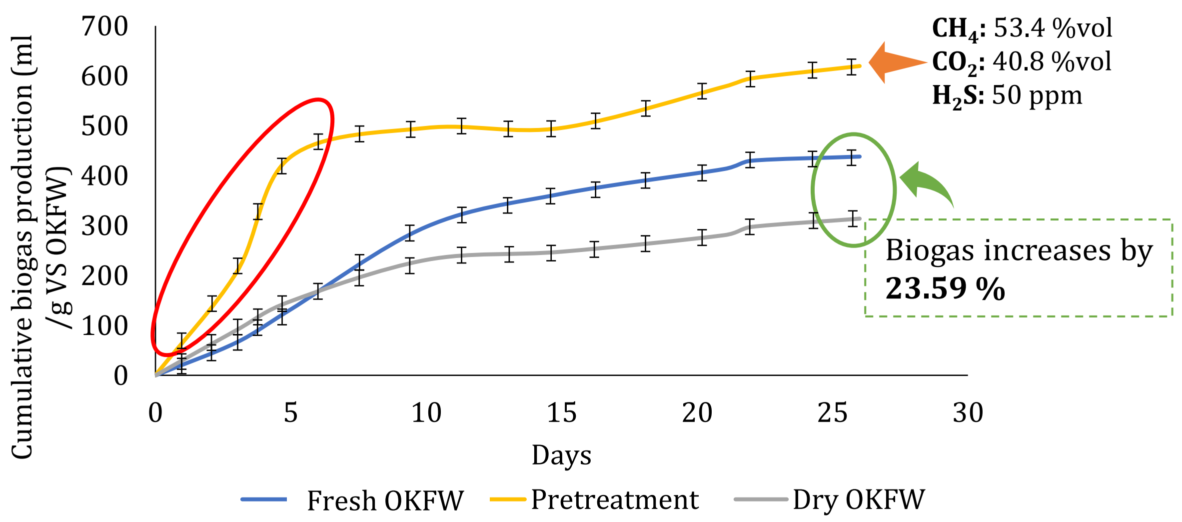


Figure 5. Biogas production for the scenarios.

VFA production

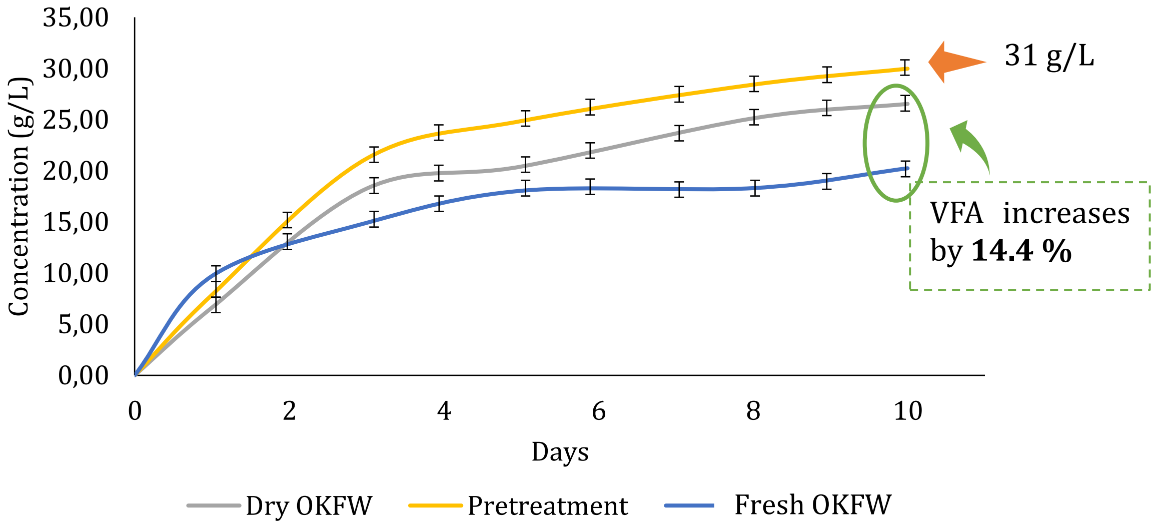


Figure 6. VFA production for the scenarios.

- ✓ **LHW** pretreatment was effective for the highest biogas and VFA production.
- ✓ **Moisture content** present in the feedstock directly affects the substrate consumption

Gandhi P et al. [16] → LHW pretreatment of food waste, biogas production increased by 40%.

Varjani, J et al., → For moisture content from 97% to 29%, methane yield decreased from 330 to 280 mL/g VS, respectively.

Nuo Liu [17] → 26.16 g VFA/L from food waste.

Liangwu et al. → 56.7 g VFA/L from activated sludge. Pretreatment with acid and alkali improved VFA production by 12.5 times.

[16] P. Gandhi *et al.*, "Multicriteria Decision Model and Thermal Pretreatment of Hotel Food Waste for Robust Output to Biogas : Case Study from City of Jaipur , India," vol. 2018, 2018.
[17] N. Liu *et al.*, "Enhancement of volatile fatty acid production and biogas yield from food waste following sonication pretreatment," *J. Environ. Manage.*, vol. 217, pp. 797–804, 2018, doi: 10.1016/j.jenvman.2018.03.135.

3. Results and analysis

3.3. Techno-economic assessment

Table 3. Techno-economic results of the proposed scenarios

Scheme type	Scenario 1	Scenario 2	Scenario 3
Yield	$0.124 m^3$/ kg of OKFW	222.45 kWh/day	0.09[a]
			0.102[b]
SEC MJ/kg of OKFW	4.16	4.89	11.2
CapEx (mUSD)	0.437	0.409	3.27
PBP (year)	7.17	5.84	4.32
NPV (mUSD)	0.104	0.175	2.51
Revenue (USD/year)	0.11	0.20	0.15[a]
			0.24[b]

kg/kg of OKFW, [a] Acetic acid, [b] Butyric acid

- The biogas upgrading unit (to biomethane) represented the unit with the highest energy consumption (35.3%).
- The liquid-liquid extraction technique accounted for 40% of the net energy consumption of the system.

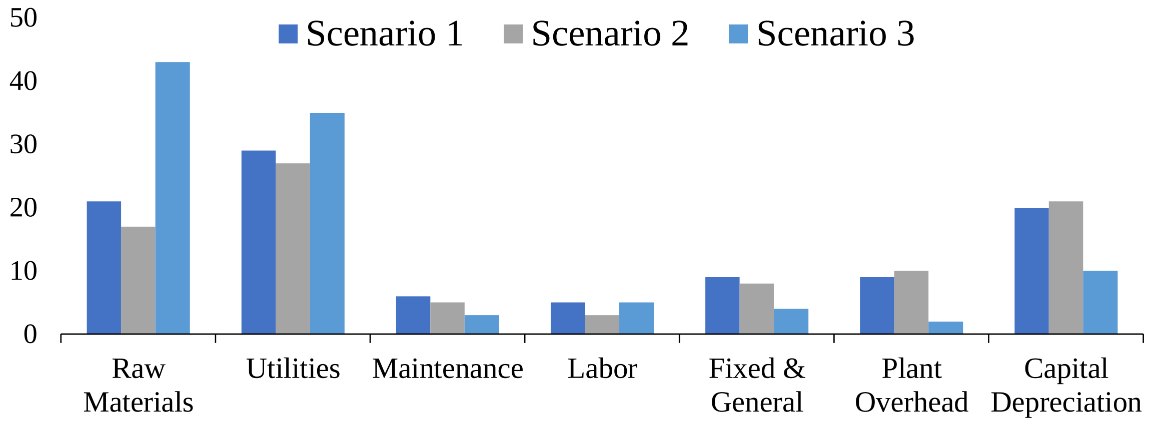


Figure 7. Costs distribution of the proposed scenarios

- Raw material and utility costs in **Scenario 3** represent the high share of operating costs due to the VFA recovery unit.
- Scenario 3 presents more than 80% increase in **CapEx** compared to scenario 1.

VFA production level and the high selling price amortize the process complexity, having a reduction of 27% and 39.7% of the PBP value compared to scenarios 1 and 2 respectively.

3. Results and analysis

3.3. Techno-economic assessment

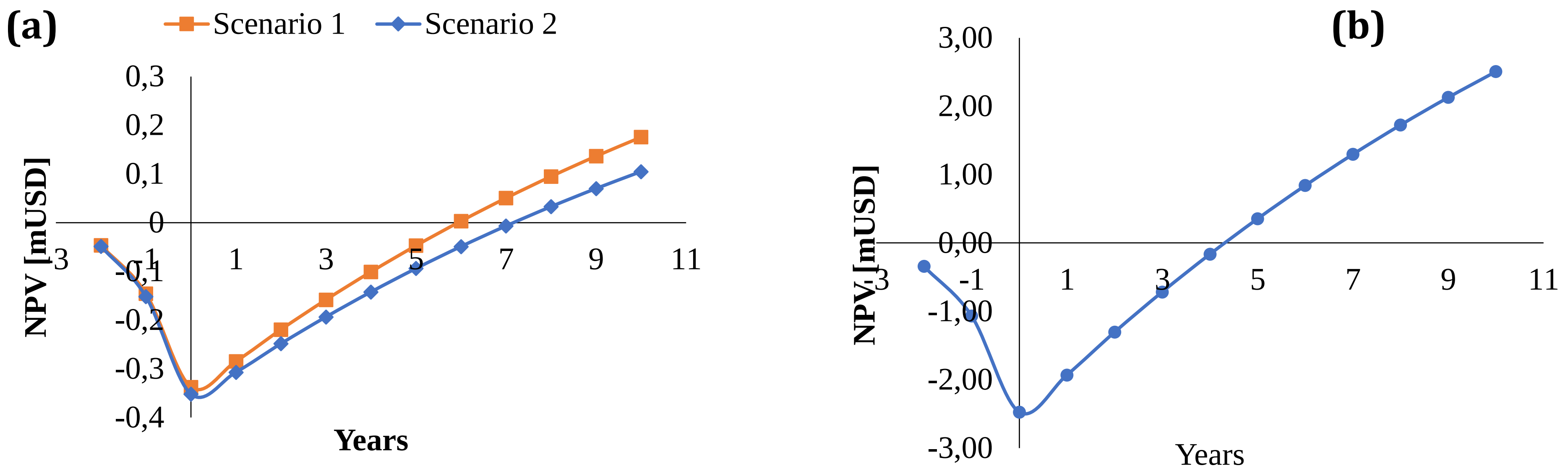


Figure 8. NPV of the project lifetime of the proposed scenarios. **(a)** scenario 1 and 2, **(b)** scenario 3 at a flowrate of 103.61 ton/day of OKFW.

- ✓ The three proposed scenarios demonstrate economic feasibility due to the positive trend of NPV at a flowrate of 20.7 ton/day of raw material.
- ✓ The minimum processing scales for economic feasibility (MPSEF) of scenarios 1, 2 and 3 were 0.51, 0.63 and 0.8 times the base case (20.7 ton/day), respectively.

4. Conclusions

- OKFW is a potential feedstock for energy production such as biogas and the generation of high-value products such as VFAs through AD. This is evidenced by the high carbohydrate content (e.g., cellulose, hemicellulose) of the feedstock as determined in the experimental characterization.

- The LHW pretreatment increases biogas and VFA production by 65% and 13%, respectively. In addition, it was determined that the initial moisture content of the feedstock positively affects biogas production. The opposite case was evidenced for VFA production.

- Methane and electricity production proved to be economically viable due to the simplicity of the process. VFA production increased capital and operating costs due to the VFA purification and recovery units and the additional use of solvents. However, the higher selling price of VFA compared to biogas resulted in a higher profit margin and payback period.

Acknowledgements

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Thank you

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