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

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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)

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. Introduction

Anaerobic digestion

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

Operating conditions variation

Main products
- Biogas
- Digestate
- Volatile fatty acids (VFA)
- Electricity and heat
- Biomethane

Intermediaries in the acidogenic stage
- Acetic acid
- Butyric acid

pH
Time
C/N ratio

Inoculum
- Wastewater
- Organic biological waste
- Animal manure

Depending on the feedstock, there might be representative VFA.

Applications

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.

1. Experimental procedure
   - OKFW characterization
   - Biogas VFA
   - Experimental scenarios

2. Process simulation
   - Biogas
     - Electricity
     - Biomethane
   - VFA
     - Recovery of individuals VFA
     - Butyric acid
     - Acetic acid

3. Technical and economic assessment
2. Methodology

2.1. Experimental procedure

2.1.1. Raw material composition model

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

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

\[
FV_{\text{42\%}} = 20\%(\text{tomato peel}) + 16\%(\text{onion peel}) + 10\%(\text{bean residues}) \\
+ 1\%(\text{pumpkin peel}) + 4\%(\text{lettuce residues}) \\
+ 3\%(\text{cabbage residues}) + 1\%(\text{beetroot peel}) \\
+ 1\%(\text{celery residues}) + 10\%(\text{citric peel and seed}) \\
+ 5\%(\text{banana peel}) + 5\%(\text{mango peel and seed}) \\
+ 5\%(\text{guava seeds}) + 5\%(\text{tree tomato peel and pulp}) \\
+ 4\%(\text{spent blackberry pulp}) \\
+ 3\%(\text{passion fruit peel and pulp}) + 1\%(\text{strawberry residues}) \\
+ 3\%(\text{avocado peel and seed}) + 1\%(\text{papaya peel and seed}) \\
+ 1\%(\text{apple residues}) + 1\%(\text{lulo peel and pulp})
\]

\[
RT_{\text{25\%}} = 60\%(\text{potato peel}) + 30\%(\text{cassava peel}) + 10\%(\text{carrot peel})
\]

\[
MP_{\text{9\%}} = 50\%(\text{beef bone}) + 45\%(\text{chicken bone}) + 5\%(\text{meat waste}) \\
FS_{\text{15\%}} = 20\%(\text{fish bone}) + 80\%(\text{egg shells})
\]

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

Raw material characterization

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

- Chemical, proximate and solid analysis
- Homogenized
- International standards methods, triplicate testing

2. Methodology

2.1. Experimental procedure

2.1.2. Biogas and VFA production

Biogas and VFA production were performed using three experimental scenarios.

### Biogas production

**Standard method VDI 4630 [6]**

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

![Gasboard analyzer](Figure 2)

**VFA production**

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

![SpectraMax® ABS microplate spectrophotometer](Figure 3)

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

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

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

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2. Methodology

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>
<thead>
<tr>
<th>Scenario</th>
<th>Process</th>
<th>Product</th>
<th>Sub products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>Biogas production</td>
<td>Biomethane</td>
<td>Digestate</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Biogas production</td>
<td>Electricity</td>
<td>Digestate</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>VFA production</td>
<td>Acetic and butyric acid</td>
<td>Digestate</td>
</tr>
</tbody>
</table>
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].

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].

![Process flow diagram](image)

**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.


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**
  \[ Y_P = \frac{\dot{m}_{\text{Product}, i}}{\dot{m}_{\text{in}}} \]

- **Process mass intensity index (PMI)**
  \[ Y_P = \frac{\sum_{i=1}^{n} \dot{m}_{\text{in}, i} - \dot{m}_{\text{product}}}{\dot{m}_{\text{product}}} \]

**Mass indicators**

- **Specific energy consumption (SEC)**
  \[ S_{EC} = \frac{\dot{Q}_{\text{Total}} + \dot{W}_{\text{Total}}}{\dot{m}_{\text{Raw material}}} \]

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

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>31.96 ± 0.03</td>
<td>19.71</td>
<td>49.6</td>
<td>52.2</td>
<td>50.6</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>9.84 ± 0.15</td>
<td>5.12</td>
<td>49.6</td>
<td>52.2</td>
<td></td>
</tr>
<tr>
<td>Lignin</td>
<td>15.47 ± 0.11</td>
<td>13.69</td>
<td>49.6</td>
<td>52.2</td>
<td></td>
</tr>
<tr>
<td>Extractives</td>
<td>26.3 ± 0.08</td>
<td>20.92</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ash</td>
<td>4.79 ± 0.51</td>
<td>3.23</td>
<td>1.25</td>
<td>5.51</td>
<td>8.28</td>
</tr>
<tr>
<td>Fats</td>
<td>11.64 ± 0.42</td>
<td>6.34</td>
<td>3.1</td>
<td>16.2</td>
<td>15.4</td>
</tr>
</tbody>
</table>

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.


3. Results and analysis

3.2. Biogas and VFA production

**Biogas production**

- **CH\textsubscript{4}:** 53.4 % vol
- **CO\textsubscript{2}:** 40.8 % vol
- **H\textsubscript{2}S:** 50 ppm

Biogas increases by 23.59 %

**VFA production**

31 g/L

VFA increases by 14.4 %

**Figure 5.** Biogas production for the scenarios.

**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.


3. Results and analysis

3.3. Techno-economic assessment

Table 3. Techno-economic results of the proposed scenarios

<table>
<thead>
<tr>
<th>Scheme type</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>0.124 m³/kg of OKFW</td>
<td>222.45 kWh/day</td>
<td>0.09^a</td>
</tr>
<tr>
<td>SEC MJ/kg of OKFW</td>
<td>4.16</td>
<td>4.89</td>
<td>11.2</td>
</tr>
<tr>
<td>CapEx (mUSD)</td>
<td>0.437</td>
<td>0.409</td>
<td>3.27</td>
</tr>
<tr>
<td>PBP (year)</td>
<td>7.17</td>
<td>5.84</td>
<td>4.32</td>
</tr>
<tr>
<td>NPV (mUSD)</td>
<td>0.104</td>
<td>0.175</td>
<td>2.51</td>
</tr>
<tr>
<td>Revenue (USD/year)</td>
<td>0.11</td>
<td>0.20</td>
<td>0.15^a</td>
</tr>
</tbody>
</table>

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.

The costs distribution of the proposed scenarios is shown in Figure 7.

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

✓ 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.

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.
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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