Energetic conversion of organic fraction of municipal solid waste by anaerobic codigestion with sewage sludge

Ing. Valentina Cabbai

Supervisor Prof. Daniele Goi
Introduction:
The Anaerobic Digestion (AD) process
The AD process - microbiology

Organic Macro molecules

Hydrolysis

Soluble monomers

Acidogenesis

Organic Acids

Acetogenesis

Acetic Acid

H₂, CO₂

Methanogenesis

BIOGAS

Methane  55-65%

CO₂  35-45%
The sewage sludge AD in WWTP

Process aims:
- Substrate stabilization
- COD reduction
- Odour control

SEWAGE SLUDGE → BIOGAS → DIGESTATE

Liquid fraction: to WWTP

Solid fraction
The AD as renewable energy source

Process aims:
• Substrate stabilization
• COD reduction
• Odour control
• Energy recovery

Liquid fraction: to WWTP
Solid fraction: to agriculture
Available substrates to AD process

Typical organic substrates:
• Sewage sludge
• Manure

New organic substrates:
• Industrial wastewater
• Organic waste from industrial process
• Organic waste from agricultural production
• Organic fraction of municipal solid waste (OFMSW)
• Energy crops

**Anaerobic Codigestion (AcoD):** treatment of different organic substrates simultaneously
The PhD research project
The PhD research project

A new approach to optimize the anaerobic digesters up-grade by the design of an innovative protocol, based on biochemical process equations rather than on classical empirical methods

1. Organic substrates characterization
   Measure of classic chemical-physical parameters and AD key macromolecular compounds such as carbohydrates, proteins, lipids and VFA

2. BMP tests
   Biochemical methane potential to measure methane yields of organic substrates and their mixture at bench-top

3. Pilot plant test
   To investigate in a CSTR regime, the interaction between the substrates with increasing organic loading rates

4. Process simulation
   Anaerobic Digestion Model no°1 (ADM1, Batstone et al., 2006) implementation
Udine WWTP
AMGA(CAFC)
The AD unit inside AMGA (CAFC) WWTP

WASTEWATER LINE

PRIMARY CLARIFIER

AS REACTORS
SECONDARY CLARIFIER

SEWAGE SLUDGE LINE

SEWAGE SLUDGE

MESOPHILIC AD UNIT

THICKENER

Spare treatment capacity
The AcoD solution

Synergy between WWTP and the organic waste treatment

Biomethane
Fueling stations for vehicles or connection to gas grid

BIOGAS

OFMSW and sewage sludge

Electricity

Heat

AD process inside WWTP
Using existing reactors and operational facilities
The PhD research project

Phase 1

1. Organic substrates characterization
   - Measure of classic chemical-physical parameters and AD key macromolecular compounds such as carbohydrates, proteins, lipids and VFA

2. BMP tests
   - Biochemical methane potential to measure methane yields of organic substrates and their mixture at bench-top

3. Pilot plant test
   - To investigate in a CSTR regime, the interaction between the substrates with increasing organic loading rates

4. Process simulation
   - Anaerobic Digestion Model no°1 (ADM1, Batstone et al., 2006) implementation
Key AD parameters analysis

- TS, VS, COD$_{TOT}$, COD$_S$, TKN, NH$_4^+$, pH, ALK
- Carbohydrates (Dubois’s method)
- Proteins
- Lipids (gravimetric analysis)
- VFA (GC-MS)
Organic substrates characterization

1. Sewage sludge from thickener

AD unit monitoring

- Sewage sludge
  - Chemical-physical analysis
  - Macromolecular compounds analysis

- Digestate
  - Chemical-physical analysis

- Biogas
  - Biogas production and methane concentration
Source selected OFMSW samples

- Source selected OFMSW (SS-OFMSW): selection criterion was fixed to conciliate minor distance to WWTP and higher quality waste, to avoid AD unit maintenance problems and to obtain the maximum biogas production.
Substrates pre-treatment

- Grinding
- Dilution 5%TS
- Shredding
Characterization results

Substrates sampled:
- SwS
- Fruit&vegetable wastes (FVW1)
- Canteen1
- Fruit&vegetable wastes (FVW2)
- Supermarket1
- Household
- Supermarket2
- Bakery
- Restaurant
- Canteen2

VS mapping
1. Organic substrates characterization

Measure of classic chemical-physical parameters and AD key macromolecular compounds such as carbohydrates, proteins, lipids and VFA

2. BMP tests

Biochemical methane potential to measure methane yields of organic substrates and their mixture at bench-top

3. Pilot plant test

To investigate in a CSTR regime, the interaction between the substrates with increasing organic loading rates

4. Process simulation

Anaerobic Digestion Model no°1 (ADM1, Batstone et al., 2006) implementation
BMP tests

BMP tests are influenced by:
- inoculum characteristics (source, storage, activity);
- the gas measurement system (volumetric or manometric methods);
- the operational conditions (reactor volume, temperature, mixing system, trial duration);
- the chemical operational conditions (headspace gas, pH and alkalinity adjustment, mineral medium);
- the inoculum to substrate ratio (ISR)

BMP tests performed on:
- Sewage sludge at different ISR;
- SS-OFMSW (gVS/gVS);
- Sewage sludge and SS-OFMSW mix in codigestion regime.

BMP tests were carried out in triplicate.
BMP tests

1. SS-OFMSW at 5%TS
2. Sewage sludge
3. Inocula
BMP tests results

Specific Methane Rate Production (SMRP) of SwS at different ISR

![Graph showing SMRP over time for different ISR levels]

- **SMRP** [Nm³/gVS.h]
- **Hours**
- **Lines**:
  - **BLANK**
  - **ISR 3**
  - **ISR 2**
  - **ISR 1.5**
  - **ISR 1**
### BMP tests results

#### BMP of mono-substrates

<table>
<thead>
<tr>
<th>Organic substrates</th>
<th>BMP [mlCH(_4)/VS add]</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household waste</td>
<td>456</td>
<td>Zhang et al. 2012</td>
</tr>
<tr>
<td>FVW1</td>
<td>472</td>
<td>Cho et al., 1995</td>
</tr>
<tr>
<td>Restaurant waste</td>
<td>430</td>
<td>Liu et al., 2009</td>
</tr>
<tr>
<td>SwS</td>
<td>390</td>
<td>Neves et al. 2008</td>
</tr>
<tr>
<td>Canteen1</td>
<td>352</td>
<td>Jiang et al. 2012</td>
</tr>
<tr>
<td>Household</td>
<td>382</td>
<td>Ponsa et al. 2011</td>
</tr>
<tr>
<td>FVW2</td>
<td>300-570</td>
<td>Davidsson et al. 2007</td>
</tr>
<tr>
<td>Supermarket1</td>
<td>353</td>
<td>El-Mashad and Zhang, 2010</td>
</tr>
<tr>
<td>Supermarket2</td>
<td>186-222</td>
<td>Owens and Chynowet., 1993</td>
</tr>
<tr>
<td>Bakery</td>
<td>360</td>
<td>Shanmugam and Horan, 2009</td>
</tr>
<tr>
<td>SwS</td>
<td>525</td>
<td>Lissens et al., 2004</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Methane yields [Nm(lCH(_4)/gVS add]</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>248.77 (4.13)</td>
<td></td>
</tr>
<tr>
<td>338.37 (21.44)</td>
<td></td>
</tr>
<tr>
<td>571.16 (37.02)</td>
<td></td>
</tr>
<tr>
<td>363.00 (20.86)</td>
<td></td>
</tr>
<tr>
<td>99.08 (8.13)</td>
<td></td>
</tr>
<tr>
<td>364.88 (7.28)</td>
<td></td>
</tr>
<tr>
<td>233.85 (4.04)</td>
<td></td>
</tr>
<tr>
<td>476.28 (22.15)</td>
<td></td>
</tr>
<tr>
<td>675.22 (45.12)</td>
<td></td>
</tr>
<tr>
<td>644.64 (7.29)</td>
<td></td>
</tr>
</tbody>
</table>

**References**

- Zhang et al. 2012
- Cho et al., 1995
- Liu et al., 2009
- Neves et al. 2008
- Jiang et al. 2012
- Ponsa et al. 2011
- Davidsson et al. 2007
- El-Mashad and Zhang, 2010
- Owens and Chynowet., 1993
- Shanmugam and Horan, 2009
- Lissens et al., 2004
BMP tests results

BMP of mixed substrates in AcoD regime

Methane yields [Nml/gVS add]

Days

Methane [NmlCH₄/gVS]

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO-DIG1</td>
<td>293.03 (12.28)</td>
</tr>
<tr>
<td>CO-DIG2</td>
<td>365.49 (30.17)</td>
</tr>
<tr>
<td>OFMSW-MIX</td>
<td>491.00 (8.79)</td>
</tr>
</tbody>
</table>

+18% +47%

22/46
1. Organic substrates characterization
   Measure of classic chemical-physical parameters and AD key macromolecular compounds such as carbohydrates, proteins, lipids and VFA

2. BMP tests
   Biochemical methane potential to measure methane yields of organic substrates and their mixture at bench-top

3. Pilot plant test
   To investigate in a CSTR regime, the interaction between the substrates with increasing organic loading rates

4. Process simulation
   Anaerobic Digestion Model no°1 (ADM1, Batstone et al., 2006) implementation
Pilot plant test

3. Design and building of the pilot plant of 2.3 m³

The pilot plant is designed to implement the AD process in a 1:1000 scale respect the AD existing unit in Udine WWTP. The pilot plant is formed by 3 sections:

- Substrates pre-treatment;
- AD unit;
- Biogas line.
Pilot plant configuration

Substrates pre-treatment

Biogas line

AD reactor

Feeding tank
The experiment was conducted through six different stages with an increasing organic load.

- **Pilot plant start-up**: pilot plant digester was inoculated with 1.8 m³ of biomass.
- **Phase 1**: sewage sludge digestion HRT=24.3d;
- **Phase 2 to 6**: AcoD of sewage sludge and SS-OFMSW increasing OLR and decreasing HRT to 20 days.
Experimental procedure

- OLR ramp

<table>
<thead>
<tr>
<th>Phase</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>SwS</td>
<td>100%</td>
<td>90,9%</td>
<td>90,9%</td>
<td>66,7%</td>
<td>66,7%</td>
<td>41,3%</td>
</tr>
<tr>
<td>SS-OFMSW</td>
<td>-</td>
<td>1,5%</td>
<td>3,0%</td>
<td>11,1%</td>
<td>16,7%</td>
<td>29,3%</td>
</tr>
<tr>
<td>Treated wastewater</td>
<td>-</td>
<td>7,6%</td>
<td>6,1%</td>
<td>22,2%</td>
<td>16,6%</td>
<td>29,4%</td>
</tr>
</tbody>
</table>

Substrates percentages (weight based) in the feed during the experimental phases.

- Parameters monitoring

The experimental pilot plant test was characterized by intensive parameters monitoring in order to control the process and establish its efficiency.

Chemical-physical parameters analysed in each sample point.

<table>
<thead>
<tr>
<th>Sample point</th>
<th>Feeding tank</th>
<th>AD reactor</th>
<th>Discharging pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>pH</td>
<td>pH</td>
<td>pH</td>
</tr>
<tr>
<td></td>
<td>TS,VS</td>
<td>Alkalinity</td>
<td>TS,VS</td>
</tr>
<tr>
<td>Soluble COD</td>
<td>FOS/TAC</td>
<td>Soluble COD</td>
<td></td>
</tr>
<tr>
<td>TKN</td>
<td>VFA</td>
<td>TKN</td>
<td></td>
</tr>
<tr>
<td>Ammonia</td>
<td></td>
<td></td>
<td>Ammonia</td>
</tr>
<tr>
<td>Sulphates</td>
<td></td>
<td></td>
<td>Sulphates</td>
</tr>
<tr>
<td>Phosphorus</td>
<td></td>
<td></td>
<td>Phosphorus</td>
</tr>
<tr>
<td>C,N</td>
<td></td>
<td></td>
<td>Heavy metals</td>
</tr>
</tbody>
</table>
Pilot plant results

Parameters for substrates characterization

- **VS/TS [%]**
  - Phase 1: 60.9%
  - Phase 2: 66.8%
  - Phase 3: 68.6%
  - Phase 4: 73.8%
  - Phase 5: 81.4%
  - Phase 6: 85.4%

- **CODs [mg/L]**
  - Phase 1: 5000 mg/L
  - Phase 2: 10000 mg/L
  - Phase 3: 15000 mg/L
  - Phase 4: 20000 mg/L
  - Phase 5: 25000 mg/L
  - Phase 6: 30000 mg/L

- **Ammonia [mgNH4+/l]**
  - Phase 1: 2 mg/L
  - Phase 2: 4 mg/L
  - Phase 3: 6 mg/L
  - Phase 4: 8 mg/L
  - Phase 5: 10 mg/L
  - Phase 6: 12 mg/L

- **C/N [-]**
  - Phase 1: 10
  - Phase 2: 12
  - Phase 3: 14
  - Phase 4: 16
  - Phase 5: 18
  - Phase 6: 20

- **Ammonia [mgNH4+/l]**
  - Phase 1: 400 mg/L
  - Phase 2: 600 mg/L
  - Phase 3: 800 mg/L
  - Phase 4: 1000 mg/L
  - Phase 5: 1200 mg/L
  - Phase 6: 1400 mg/L
Pilot plant results

Control parameters

Sample point | Phase |
--- | ---
AD reactor
ALK [mgCaCO₃/l] | 1447,9 | 1578,6 | 1453,4 | 1323,3 | 2088,5 | 2764,7 |
(289,5) | (145,9) | (133,8) | (253,3) | (600,5) | (161,3) |
VFA [mgCOD/l] | 21,8 | 30,2 | 11,5 | 3,0 | 5,1 | 4,1 |
(8,2) | (16,7) | (5,1) | (2,8) | (4,8) | (2,7) |
Pilot plant results

Efficiency parameters

![Graphs showing biogas and methane efficiency parameters across different phases.](image-url)
1. **Organic substrates characterization**

Measure of classic chemical-physical parameters and AD key macromolecular compounds such as carbohydrates, proteins, lipids and VFA

2. **BMP tests**

Biochemical methane potential to measure methane yields of organic substrates and their mixture at bench-top

3. **Pilot plant test**

To investigate in a CSTR regime, the interaction between the substrates with increasing organic loading rates

4. **Process simulation**

Anaerobic Digestion Model no°1 (ADM1, Batstone et al., 2006) implementation
Process simulation

Mathematical modeling of the anaerobic digestion process by ADM1

Mathematical model
ADM1 _Anaerobic Digestion Model no°1 (2002, IWA)

Equations to describe biochemical and chemical-physical process

Simulation of behaviour of biomass inside the AD reactor in different scenarios

Optimize digesters design and the operative conditions
Experimental procedure

ADM no° 1 (Batstone et al. 2002) Implementation

A. ADM1 with Copp interface for ASM1

B. ADM1 modified (without Xc parameter)


MS=monosaccarides; AA=amminoacids; LCFA=long chain fatty acids; Hva=valeric acid; Hbu=butyric acid
Simulation results for full-scale AD unit with sewage sludge

ADM 1 (A)

Error 11.5%

Error 2.3%

Error 17.8% [0.3÷40.2]

Error 35.5% [0.2÷227.9]
Simulation results for full-scale AD unit with sewage sludge

ADM 1 (B)

Err 5.0% [0.1÷12.5]

Err 13.0% [0.4÷71.8]
Simulation of pilot plant and full-scale up-grade to AcoD

Pilot Plant: Simulation of the experimental phase

Full scale reactor: Simulation of SwS and up-grade to AcoD
Feasibility study of AcoD plant up-grade
Two scenarios were hypothesized:

- **Scenario 1**: AcoD of SwS and SS-OFMSW in AD WWTP reactor to deplete the spare treatment capacity;

- **Scenario 2**: AcoD of SwS and OFMSW in AD WWTP unit in existing reactor and in a new one, to treat the amount of OFMSW received by the Udine waste treatment plant.

**Sinergy between WWTP and waste treatment plant**
SCENARIO 1

**SS-OFMSW** 16.7 ton/d → **PRE-TREATMENT**
- SS-OFMSW 15.0 ton/d
- **HYDROPULPER**
- FORSU 30%TS 25 m3/d
- **BUFFER TANK** 115 m3/d → 140 m3/d
- **AD REACTOR**
- **THICKENER** V=2800 m3
- **BELTPRESS**
- **DIGESTATE** 52 m3/d + **GREEN WASTE** 52 ton/d → **COMPOSTING**
- **INERTS** 1.6 ton/d 10%
- **WASTEWATER LINE**
- **CHEMICAL PHYSICAL TREATMENT**
- **LIQUID FRACTION** 81.3 m3/d
- **BIOGAS**
- **SwS** 0.4 m3/d
- **= new unit**
- **= revamping**
### Operative conditions

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HRT</td>
<td>20</td>
<td>[d]</td>
</tr>
<tr>
<td>Volume</td>
<td>2800</td>
<td>[m³]</td>
</tr>
<tr>
<td>Qin</td>
<td>140</td>
<td>[m³/d]</td>
</tr>
<tr>
<td>Qin_SwS</td>
<td>115</td>
<td>[m³/d]</td>
</tr>
<tr>
<td>Qin_OFMSW</td>
<td>25</td>
<td>[m³/d]</td>
</tr>
<tr>
<td>TS_in</td>
<td>7,8</td>
<td>[%]</td>
</tr>
<tr>
<td>OLR</td>
<td>3,3</td>
<td>[KgVS/m³d]</td>
</tr>
<tr>
<td>Q Biogas</td>
<td>3640</td>
<td>[m³/d]</td>
</tr>
</tbody>
</table>

### Energetic Balance [MWh/y]

- **District heating system** 2097,5 MWh
- **AD UNIT** 960 MWh
- **EE** 1965,5 MWh
- **Composting** 1075,4 MWh
- **Waste pre-treatment** 335 MWh
- **WWTP** 557,1
Scenario 2

Sinergy between WWTP and waste treatment plant
**SCENARIO Integrated waste and wastewater treatment hub**

- **OFMSW** 90 ton/d

  - **PRE-TREATMENT**
    - OFMSW 72 ton/d
    - **HYDROPULPER**
      - H2O tec.

  - **INERTS** 18 ton/d

- **HYDROPULPER**
  - **OFMSW** 150 m3/d
  - **BUFFER TANK**
    - SwS 115 m3/d
    - AcoD REACTORS
      - 130 m3/d
    - 140 m3/d
    - V=2800m3

- **THICKENER**

- **BELTPRESS**

- **BIOGAS**
  - **DIGESTATE** 104 m3/d
  - + **GREEN WASTE** 100 ton/d

- **WASTEWATER LINE**
  - **COMPOSTING**
    - SwS 1 m3/d
  - **CHEMICAL PHYSICAL TREATMENT**

---

- **= nuove unità**
- **= revamping**
Scenario 2

OLR conditions tested in simulation for digester 1 and digester 2

Simulated biogas production for the whole AD unit
## Scenario 2

### Operative conditions

<table>
<thead>
<tr>
<th></th>
<th>DIG 1</th>
<th>DIG 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HRT</strong></td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Volume</strong></td>
<td>2800</td>
<td>2600</td>
</tr>
<tr>
<td><strong>Qin</strong></td>
<td>140</td>
<td>130</td>
</tr>
<tr>
<td><strong>Qin_SwS</strong></td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td><strong>Qin_OFMSW</strong></td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td><strong>TS_in</strong></td>
<td>7,2</td>
<td>12,2</td>
</tr>
<tr>
<td><strong>OLR</strong></td>
<td>3,3</td>
<td>5,4</td>
</tr>
<tr>
<td><strong>Q Biogas</strong></td>
<td>3420</td>
<td>5265</td>
</tr>
</tbody>
</table>

### Energetic Balance [MWh/y]

- District heating system: 5375,4 MWh
- AD unit 1920 MWh
- Integrated treatment hub: 3076,6 MWh
- AD unit 1613,3 MWh
- ET: 7295,4 MWh
- EE: 4689,9 MWh
## Scenarios comparison

<table>
<thead>
<tr>
<th>Scenario n°1</th>
<th>Scenario n°2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>3960,00</td>
</tr>
<tr>
<td>Expenses</td>
<td>436,42</td>
</tr>
<tr>
<td>Revenues</td>
<td>1537,01÷1773,89</td>
</tr>
<tr>
<td>NPV</td>
<td>4735,47÷6477,98</td>
</tr>
<tr>
<td>PB</td>
<td>7÷5</td>
</tr>
<tr>
<td>IRR</td>
<td>20÷25</td>
</tr>
</tbody>
</table>

### Graph

- **Scenario n°2 85-50**: Blue line
- **Scenario n°1 85-50**: Red line
- **Scenario n°2 75-35**: Green line
- **Scenario n°1 75-35**: Purple line

**Y-axis**: [€] 0, 5,000,000, 10,000,000, 15,000,000, 20,000,000

**X-axis**: [Years] 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20
This protocol can be defined as follow:

- **Deep substrate characterization** has to be focalized on macromolecular compounds analysis (carbohydrates, proteins, lipids and VFA) and chemical-physical parameters analysis are mandatory to evaluate the substrate for AD process. This step implies high lab efforts and a standardized methodology for complex substrate is necessary.

- **BMP tests** allow to understand the biomass performance in substrates degradation and to highlight potential inhibition phenomena. The operative conditions of BMP trials are still under discussion in the scientific community. However, complying with the most recent guidelines, comparable results can be obtained.

- **Pilot plant experimentation** is fundamental to understand the AD process performance under dynamic organic loading conditions. In case of non-conventional substrates or non-conventional operative conditions, pilot plant test is mandatory.

- **ADM1 modeling** allows to test different HRT and OLR scenarios and to define the best operative conditions. ADM1 requires a lot of experimental data and the quality results are strictly linked to substrate characterization. When the ADM1 is calibrated, it can be used in a very wide field of operations: numerous operative scenarios can be tested.
The project

“Energetic conversion of organic fraction of municipal solid waste by anaerobic codigestion with sewage sludge”

POR FESR 2007-2013
OBIETTIVO COMPETITIVITA’ REGIONALE E OCCUPAZIONE
Friuli Venezia Giulia

RISAs.r.l. Ricerca Sviluppo Ingegneria Ambiente

Net

Spin-off dell’Università degli Studi di Udine

Dipartimento di Chimica, Fisica e Ambiente
Thanks for attention