ANALYSIS OF POSSIBILITIES OF OBTAINING POSITIVE ENERGY BALANCE IN ANAEROBIC DIGESTION SYSTEMS WITH HYDRODYNAMIC DISINTEGRATION

Monika Żubrowska-Sudoł, Katarzyna Sytek-Szmeichel, Justyna Walczak, Agnieszka Garlicka, Katarzyna Umiejewska

Warsaw University of Technology
POLAND’S NATIONAL ENERGY AND CLIMATE PLAN FOR THE YEARS 2021-2030

-7% reduction of CO2 emissions in non-ETS sectors by 2030 (compared to 2005)

14% renewable energy in transport in 2030

21-23% RES in gross final energy consumption in 2030

RES increase in heating and cooling by an average of 1.1 percentage point per year

23% increase in energy efficiency by 2030 (23% reduction of primary energy consumption comparing to PRIMES2007 forecasts)

Poland’s climate and energy targets until 2030
POLAND’S NATIONAL ENERGY AND CLIMATE PLAN FOR THE YEARS 2021-2030

Renewable Sources development

The five dimensions of the Energy Union

- Decarbonisation
- Energy efficiency
- Energy security
- Research, innovation and competitiveness
- Internal energy market

Graph showing renewable energy sources development from 2005 to 2040:
- Gross final energy consumption from renewable sources in electricity
- Gross final energy consumption from renewable sources in heating and cooling
- Gross final energy consumption from renewable sources in transport
- Share of energy from renewable sources in gross final energy consumption

Legend:
- Green line: Gross final energy consumption from renewable sources in electricity
- Dark green line: Gross final energy consumption from renewable sources in heating and cooling
- Light green line: Gross final energy consumption from renewable sources in transport
- Black line: Share of energy from renewable sources in gross final energy consumption

Key milestones:
- 2005: 6.9%
- 2010: 9.3%
- 2015: 11.9%
- 2020: 15.0%
- 2022: 16.4%
- 2025: 18.4%
- 2027: 20.2%
- 2029: 23.0%
- 2035: 25.8%
- 2040: 28.5%
POLAND’S NATIONAL ENERGY AND CLIMATE PLAN FOR THE YEARS 2021-2030

Structure of electricity production

The five dimensions of the Energy Union

- Decarbonisation
- Energy efficiency
- Energy security
- Internal energy market
- Research, innovation and competitiveness

<table>
<thead>
<tr>
<th>Year</th>
<th>Lignite</th>
<th>Gas Fuels</th>
<th>Hard Coal</th>
<th>Heating Oil</th>
<th>Solar Energy</th>
<th>Biogas</th>
<th>Nuclear Energy</th>
<th>Onshore Wind Energy</th>
<th>Biomass</th>
<th>Hydropower</th>
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</tbody>
</table>

Legend:
- Lignite
- Gas Fuels
- Hard Coal
- Heating Oil
- Solar Energy
- Biogas
- Nuclear Energy
- Onshore Wind Energy
- Biomass
- Hydropower
- Municipal and Industrial Waste
RESEARCH PROBLEM
How to increase biogas production?

**Pretreatment**
- e.g. disintegration process

ENERGY
(mechanical, thermal, chemical)

increasing the availability of the substrate for microorganisms involved in the anaerobic digestion process

**Co-digestion process**
- Co-substrate characterized by a high methane production potential

Substrate
(e.g. sewage sludge)

increase of calorific value of substrates entering the anaerobic digester

ENERGY
**Article**

**Energy-Positive Disinfection of Waste Activated Sludge—Full Scale Study**

Monika Zubrowska-Sudol 1,*, Katarzyna Sytka-Szmeichel 1, Piotr Krawczyk 2 and Agnieszka Bisak 1

1 Faculty of Building Services, Hydro and Environmental Technology, Warsaw University of Technology, Warsaw, Poland; katarzyna.szymczuk@pwr.edu.pl; Piotr.Krawczyk@pwr.edu.pl
2 Faculty of Power and Aeronautical Engineering, Warsaw University of Technology, Nowowiejskia 20, 00-653 Warsaw, Poland; katarzyna.szymczuk@pwr.edu.pl

**Abstract**

This study aimed to evaluate the effect of mechanical disinfection of waste activated sludge (WAS) on full scale anaerobic digestion, considering the possibility of obtaining a positive energy balance. The results showed that an increase in energy density (ε) used in disinfection was accompanied by an increase in the release of organic compounds from sludge (SCOD) increased from 211 ± 125 mg O2/L for ε = 0 kJ/L to 6292 ± 2860 mgO2/L for ε = 180 kJ/L. Some of these were volatile fatty acids. The percentage share of WAS subject to disinfection was also documented as a crucial parameter affecting the efficiency of biogas production. An increase in this parameter from 25% to 100%, even at much lower εL used in disinfection (therefore with smaller amounts of organic compounds released from sludge flow) resulted in an increase in biogas production.

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**Article**

**Effect of hydrodynamic disintegration on the solubilisation and bioavailability of thickened excess sludge**

Agnieszka Garlicka, Monika Zubrowska-Sudol

Department of Water Supply and Wastewater Treatment, Faculty of Building Services, Hydro and Environmental Engineering, Warsaw University of Technology, Nowowiejska 20, 00-653 Warsaw, Poland

**Abstract**

The main objective of the study was to verify whether conducting the hydrodynamics of thickened excess sludge (TES) before the anaerobic hydrolysis (AH) can cause an increase in the hydrolysis process, and therefore a reduction in its duration, or allow for complete hydrolysis before the anaerobic digestion (AD). For this purpose, the HD (conducted in five levels of 140, 280, 420, 560 and 790 kJ/L of TES was carried out and then all sludges (before and after HD) were subjected to AD. The obtained results confirmed that the process of HD can be a useful method to increase the solubilisation of organic matter in excess sludge. The impact of HD on the hydrolysis process before the anaerobic digestion is presented in the paper.

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**Article**

**Disintegration of waste sludge as an element bio-circular economy in waste water treatment plant towards carbon recovery for biological nutrient removal**

Monika Zubrowska-Sudol 1,*, Jozefina Wierzchak 2, Gregorius Pichora 3

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2 Department of Research and Analysis, A. Czumaja-Wołoszyn, Przysieka 18, 87-110 Toruń, Poland
3 Division of Environmental Engineering, Faculty of Civil Engineering, Warsaw University of Technology, Nowowiejska 20, 00-653 Warsaw, Poland

**Graphical Abstract**

- Bioremediation of waste sludge via disintegration process for nutrient recovery
- Disintegration of waste sludge as a source of biogas and organic matter
- Bilateral recovery of biomass and energy from which C and O were obtained
- Increase of biodegradable and fermentable content at 128 kJ and 256 kJ
- Biodegradability of organic matter is increased by 25% and 50% respectively

**Highlights**

- Biodegradable fraction of waste sludge via disintegration process for nutrient recovery
- Disintegration of waste sludge as a source of biogas and organic matter
- Bilateral recovery of biomass and energy from which C and O were obtained
- Increase of biodegradable and fermentable content at 128 kJ and 256 kJ
- Biodegradability of organic matter is increased by 25% and 50% respectively

**Article**

**Influence of Hydrodynamic Disintegration on the Release of Organic and Nutrient Compounds From Activated Sludge**

Justyna Welczek 1, Monika Zubrowska-Sudol 1, and Paulina Pichora 2

1 Faculty of Building Services, Hydro and Environmental Engineering, Warsaw University of Technology, Nowowiejska 20, 00-653 Warsaw, Poland
2 Division of Environmental Engineering, Faculty of Civil Engineering, Warsaw University of Technology, Nowowiejska 20, 00-653 Warsaw, Poland

**Graphical Abstract**

- Enhanced release of organic and nutrient compounds from activated sludge
- Hydrodynamic disintegration improves sludge degradation
- Increased solubilisation and bioavailability of organic compounds

**Highlights**

- Enhanced release of organic and nutrient compounds from activated sludge
- Hydrodynamic disintegration improves sludge degradation
- Increased solubilisation and bioavailability of organic compounds

**Article**

**Effects of Thickened Excess Sludge Pre-Treatment Using Hydrodynamic Cavitation for Anaerobic Digestion**

Agnieszka Garlicka 1,*, Monika Zubrowska-Sudol 1, Katarzyna Umiejska 1, Otokon Kounoë 1, Jack Taddeo 1 and Andrzej Chiwieksi 1

1 Faculty of Building Services, Hydro and Environmental Engineering, Warsaw University of Technology, Nowowiejska 20, 00-653 Warsaw, Poland

**Graphical Abstract**

- Enhanced release of organic and nutrient compounds from activated sludge
- Hydrodynamic disintegration improves sludge degradation
- Increased solubilisation and bioavailability of organic compounds

**Highlights**

- Enhanced release of organic and nutrient compounds from activated sludge
- Hydrodynamic disintegration improves sludge degradation
- Increased solubilisation and bioavailability of organic compounds
excess biogas obtained due to the disintegration process would allow for producing an amount of electricity higher than that used for pre-treatment method
Research challenge

Project idea

“Development of a technology for preparation substrates used in methane co-fermentation by disintegration methods” (DEZMETAN) No.: POIR.04.01.02-00-0022/17
Project idea

Research challenge

- biogas powered engine
  - electricity
  - heat

CO-SUBSTRATE

- hydrodynamic disintegration

anaerobic digestion

biogas

“Development of a technology for preparation substrates used in methane co-fermentation by disintegration methods” (DEZMETAN) No.: POIR.04.01.02-00-0022/17
AIM

Analysis of the possibility of increasing the methane potential of selected co-substrates and obtaining a positive energy balance via hydrodynamic disintegration pre-treatment.
METHODS
<table>
<thead>
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<th>Co-substrate</th>
<th>TS Range</th>
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<tr>
<td>Cow manure CM</td>
<td>6.91 – 8.21 %</td>
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<tr>
<td>Pig manure PM</td>
<td>2.87 - 10.8 %</td>
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<tr>
<td>Maize silage MS</td>
<td>8.72 – 10.9 %</td>
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<tr>
<td>Remains of fruits RF</td>
<td>22.7 – 30.9 %</td>
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<tr>
<td>Beetroot pulp BP</td>
<td>9.16 – 19.4 %</td>
</tr>
<tr>
<td>Beetroot pulp in the form of pellets BPP</td>
<td>87.6 – 94.0 %</td>
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</tbody>
</table>
HYDRODYNAMIC DISINTEGRATION
Disintegration apparatus

- Motor power: 5.5 kW
- Rotor revolution: 3000/min
- Volume of tank: 13 L

hydrodynamic disintegrator
(patent application WP-84/JW 13766118)
Biochemical Methane Potential Test (BMP test)

Specific Methane Production (SMP)

Biochemical Methane Potential Test (BMP test)

Specific Methane Production (SMP)
CO-SUBSTRATE before DISINTEGRATION

Biochemical Methane Potential Test (BMP test)

Specific Methane Production (SMP)

Biochemical Methane Potential Test (BMP test)

Specific Methane Production (SMP)

diluted to TS ≈ 5 % (MS, RF, BP, BPP)
diluted to $\text{TS} \approx 5\%$ (MS, RF, BP, BPP)

Biochemical Methane Potential Test (BMP test)

Specific Methane Production (SMP)

SERIES 1

Energy density $\varepsilon_L$: 35 – 140 kJ/L

BMP test

SMP

SERIES 2

Energy density $\varepsilon_L$: 10 – 35 kJ/L

BMP test

SMP
Biochemical methane potential tests (BMP)

- constant temperature of 37°C
- initial organic loading rate 5 gVTS of introduced substrate/L
- each assay was performed in three repetitions

Automatic Methane Potential Test System (AMPTS II - Bioprocess Control Sweden)

Specific Methane Production (SMP)


RESULTS
**Biochemical methane potential (BMP) test**

**SPECIFIC METHANE PRODUCTION – SERIES I**

![Graphs showing specific methane production across different conditions with energy density (kJ/L) on the x-axis and SMP (NmL CH₄/g VTS) on the y-axis for CM, PM, MS, RF, BP, and BPP.]
Biochemical methane potential (BMP) test

SPECIFIC METHANE PRODUCTION – SERIES I

CM

PM

MS

RF

BP

RPP
Biochemical methane potential (BMP) test

SPECIFIC METHANE PRODUCTION – SERIES 1

CM

PM

MS

RF

BP

RPP

SMP [NmL CH₄ / g VTS]

εₑ - energy density [kJ/L]

SMP [NmL CH₄ / g VTS]

εₑ - energy density [kJ/L]

SMP [NmL CH₄ / g VTS]

εₑ - energy density [kJ/L]

SMP [NmL CH₄ / g VTS]

εₑ - energy density [kJ/L]

SMP [NmL CH₄ / g VTS]

εₑ - energy density [kJ/L]
Biochemical methane potential (BMP) test

**SPECIFIC METHANE PRODUCTION – SERIES I**

- **CM**
- **PM**
- **MS**
- **RF**
- **BP**
- **BPP**
Biochemical methane potential (BMP) test

SPECIFIC METHANE PRODUCTION – SERIES 1

CM

PM

MS

RF

BP

BPP
SPECIFIC METHANE PRODUCTION – SERIES 1

Biochemical methane potential (BMP) test

CM

PM

MS

RF

BP

BPP
Biochemical methane potential (BMP) test

SPECIFIC METHANE PRODUCTION – SERIES 1

CM

PM

MS

RF

BP

BPP

SPECIFIC METHANE PRODUCTION – SERIES 1
Biochemical methane potential (BMP) test

SPECIFIC METHANE PRODUCTION – SERIES I

CM

PM

MS

RF

BP

BPP

SMP \([ \text{NmL CH}_4 / \text{g VTS} ]\)

\(\varepsilon_L\) - energy density \([\text{kJ/L}]\)

- 35
- 70
- 140

SMP \([ \text{NmL CH}_4 / \text{g VTS} ]\)

\(\varepsilon_L\) - energy density \([\text{kJ/L}]\)

- 35
- 70
- 140
SPECIFIC METHANE PRODUCTION – SERIES I

Biochemical methane potential (BMP) test

CM

PM

MS

RF

BP

BPP
Biochemical methane potential (BMP) test

SPECIFIC METHANE PRODUCTION – SERIES 2

CM

RF

MS

BPP
Biochemical methane potential (BMP) test

SPECIFIC METHANE PRODUCTION – SERIES 2

CM

RF

MS

BPP
Biochemical methane potential (BMP) test

SPECIFIC METHANE PRODUCTION – SERIES 2

CM

RF

MS

BPP

SMP [NmL CH₄/g VTS]

ε_L - energy density [kJ/L]
Biochemical methane potential (BMP) test

SPECIFIC METHANE PRODUCTION – SERIES 2

CM

RF

MS

BPP

SMP [NmL CH₄/g VTS]

$\epsilon_L$ - energy density [kJ/L]
SPECIFIC METHANE PRODUCTION – SERIES 2

- **CM**
- **RF**
- **MS**
- **BPP**
Biochemical methane potential (BMP) test

SPECIFIC METHANE PRODUCTION – SERIES 2

CM

RF

MS

BPP
Effect of hydrodynamic disintegration on the Specific Methane Production (SMP)

SERIES I

SERIES II

increase in SMP relative to untreated sample [%]
Effect of hydrodynamic disintegration on the Specific Methane Production (SMP)

SERIES I

SERIES II

increase in SMP relative to untreated sample [%]

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Energy balance

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<th>MS - Mazie Silage</th>
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<td>Extra electricity³</td>
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<td>Relative energy profit</td>
<td>%</td>
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| Parameter                        | unit   | RF - Remains of Fruits |           | BPP - Beetroot Pulp in the form of Pellets |           |
|----------------------------------|--------|                        | Series 1  | Series 2            |           |
|                                  |        | Series 1                | Series 2  |系列 1                | Series 2  |
| Methane energy content¹         | Wh     | 2,48                     | 2,70      | 2,63                | 2,52      |
|                                  |        | 2,52                     |           | 6,12                | 6,17      |
|                                  |        | 6,17                     |           | 5,92                | 6,25      |
|                                  |        | 6,25                     |           | 6,51                | 9,61      |
|                                  |        | 9,61                     |           | 6,65                | 6,65      |
|                                  |        | 6,65                     |           | 5,60                | 6,65      |
|                                  |        | 5,60                     |           | 6,65                | 6,65      |
|                                  |        | 6,65                     |           | 4,60                | 4,60      |
|                                  |        | 4,60                     |           | 5,21                |           |
| Electricity²                     | Wh     | 0,99                     | 1,08      | 1,05                | 1,01      |
|                                  |        | 1,01                     |           | 2,45                | 2,47      |
|                                  |        | 2,47                     |           | 2,37                | 2,50      |
|                                  |        | 2,50                     |           | 2,60                | 3,84      |
|                                  |        | 3,84                     |           | 2,66                | 2,24      |
|                                  |        | 2,66                     |           | 2,66                | 2,66      |
|                                  |        | 2,66                     |           | 2,66                | 2,66      |
| Extra electricity³               | Wh     | 0,09                     | 0,06      | 0,02                | 0,02      |
|                                  |        | 0,02                     |           | -0,08               | 0,05      |
| Energy applied for HD           | Wh     | 0,20                     | 0,39      | 0,78                | 0,10      |
|                                  |        | 0,10                     |           | 0,38                | 0,41      |
| Net energy production           | Wh     | -0,11                    |           | -0,33               | -0,09     |
|                                  |        | -0,09                    |           | -0,33               | 0,83      |
| Relative energy profit          | %      |                          |           | 303                 |           |

¹Methane energy content calculated by assuming methane calorific value equal to 36 MJ/m³;
²Electricity calculated by assuming electrical efficiency of engine equal to 40%;
³Extra electricity = electricity dez.—electricity untreated, (Wh): Electricity dez., amount of electricity produced in a disintegrated sample at a predefined energy density level (Wh); Electricity untreated, amount of electricity produced in an untreated sample (Wh).
### Energy balance

<table>
<thead>
<tr>
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</tr>
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>RF - Remains of Fruits</th>
<th></th>
<th>BPP - Beetroot Pulp in the form of Pellets</th>
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<td>Series 1</td>
<td>Series 2</td>
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<td>0,06</td>
<td>0,02</td>
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<td>Relative energy profit</td>
<td>%</td>
<td>303</td>
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</table>

¹Methane energy content calculated by assuming methane calorific value equal to 36 MJ/m³;  
²Electricity calculated by assuming electrical efficiency of engine equal to 40%;  
³Extra electricity = electricity dez.—electricity untreated, (Wh): Electricity dez., amount of electricity produced in a disintegrated sample at a predefined energy density level (Wh); Electricity untreated, amount of electricity produced in an untreated sample (Wh).
### Energy balance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>CM - Cow Manure</th>
<th></th>
<th></th>
<th></th>
<th>MS - Mazie Silage</th>
<th></th>
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<tbody>
<tr>
<td></td>
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<td>Series 1</td>
<td>Series 2</td>
<td></td>
<td>Series 1</td>
<td></td>
<td>Series 2</td>
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<td>Wh</td>
<td>3,86</td>
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<td>3,79</td>
<td>3,95</td>
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<td>4,25</td>
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<td>Electricity²</td>
<td>Wh</td>
<td>1,54</td>
<td>1,64</td>
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<td>1,58</td>
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<td>1,70</td>
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<td>Wh</td>
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<td>0,04</td>
<td>-0,03</td>
<td>0,06</td>
<td>0,12</td>
<td>0,02</td>
<td>0,13</td>
</tr>
<tr>
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<td>0,09</td>
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<td>-0,16</td>
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<td>-0,03</td>
<td>-0,05</td>
<td>-0,30</td>
<td>-0,10</td>
<td>-0,42</td>
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</table>

| RF - Remains of Fruits          |       | Series 1        | Series 2 |          | Series 1 |          | Series 2 |          |
|                                  |       |                 |          |          |          |          |          |          |
| Methane energy content¹         | Wh    | 2,48            | 2,70     | 2,63     | 2,52     | 6,12              | 6,17     | 5,92     | 6,25     |
| Electricity²                    | Wh    | 0,99            | 1,08     | 1,05     | 1,01     | 2,45              | 2,47     | 2,37     | 2,50     |
| Extra electricity³              | Wh    | 0,09            | 0,06     | 0,02     | 0,02     | -0,08             | 0,05     | 1,24     | 0,06     |
| Energy applied for HD            | Wh    | 0,20            | 0,39     | 0,78     | 0,10     | 0,38              | 0,41     | 0,82     |
| Net energy production            | Wh    | -0,11           | -0,33    | -0,77    | -0,09    | -0,33             | 0,83     | -0,76    |

1Methane energy content calculated by assuming methane calorific value equal to 36 MJ/m³;
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<td>Series 2</td>
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<td>Series 2</td>
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</tr>
<tr>
<td></td>
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<td>35 kJ/L</td>
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<td>0,83</td>
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<tr>
<td>Relative energy profit</td>
<td>%</td>
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CONCLUSIONS

Hydrodynamic disintegration as pre-treatment of substrates subject to the anaerobic digestion process allows for increasing the amount of produced methane while obtaining a positive energy balance.

Implementation works should be preceded with tests aimed at the selection of:
- substrate/substrates subject to pre-treatment
  - cow manure  pig manure  maize silage  remains of fruits
  - beetroot pulp  beetroot pulp in the form of pellets
- parameters of the disintegration process (including the amount of energy supplied in the process)
  - 10 kJ/L  20 kJ/L  35 kJ/L  70 kJ/L  140 kJ/L
ANALYSIS OF POSSIBILITIES
OF OBTAINING POSITIVE ENERGY BALANCE
IN ANAEROBIC DIGESTION SYSTEMS WITH
HYDRODYNAMIC DISINTEGRATION

Development of a technology for preparation substrates used in methane co-fermentation by disintegration methods (DEZMETAN) No.: POIR.04.01.02-00-0022/17

katarzyna.szmeichel@pw.edu.pl
Rys. 4.4.27. Wartość rozpuszczonego ChZT gnojowicy bydlęcej w zależności od gęstości energii zużytej w procesie hydrodynamicznej dezintegracji.

Rys. 4.4.28. Wartość rozpuszczonego ChZT gnojowicy świńskiej w zależności od gęstości energii zużytej w procesie hydrodynamicznej dezintegracji.
Rys. 4.4.30. Wartość rozpuszczonego ChZT kiszonki kukurydzy w zależności od gęstości energii zużytej w procesie hydrodynamicznej dezintegracji.

Rys. 4.4.31. Wartość rozpuszczonego ChZT wysłodków buraczanych w zależności od gęstości energii zużytej w procesie hydrodynamicznej dezintegracji.