Cradle-to-Cradle Approach for Bioeconomy Scale-up: Best Practices

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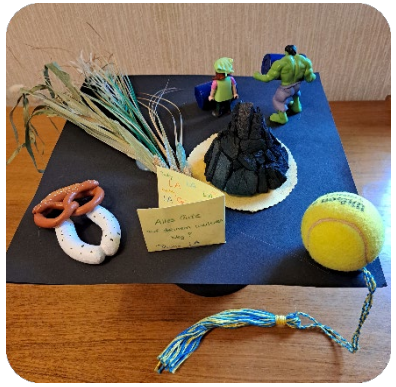

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MOTIVATION

On a Global Basis:[1, 2, 3]

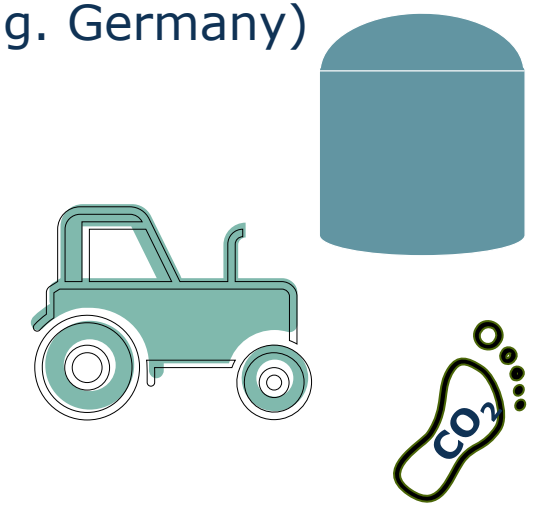
- Recycling of waste & agricultural residues, at least partly
- Environmentally friendly use of remaining waste
- 'Fit for 55' package: 55% emissions reduction in EU by 2030
- Zero net emissions of GHG by 2050
- Self-sufficient energy supply through renewables
- Switching to organic farming by applying organic fertilizers
- Sustainable soil management (SDG 12: Responsible consumption & production)
- Biodiversity

[1] Bioeconomy Summit (2015): Communique´ of the global bioeconomy summit 2015.
[2] Nagothu, U.S. (Ed.), 2020. The Bioeconomy Approach: Constraints and Opportunities for Sustainable Development.
[3] Directive (EU) 2023/2413, 18 October 2023: Renewable Energy Directive.

MOTIVATION

Western Europe[1, 2]

- Nutrient surpluses due to excessive livestock in certain areas (e.g. Germany)
- The Nitrate Directive: max. 170 $kg_N ha^{-1}$ (EU, Germany)
- Inefficient N fertilisation:
  - Nitrate in groundwater, ammonia emission, soil acidification
- German Renewable Energy Sources Act:
  - Maize cap ("Maisdeckel“)
  - Slurry / Excrement Bonus („Güllebonus“), min. 30% animal excrement used
- Emissions during storage, transportation & application of animal excrements
- Biogas production in EU can be increased more than 6 times (from 18 to 114 Mtoe)



[1] Thrän, Daniela; Moesenfechtel, Urs (Ed.) (2020): The Bioeconomy System.
[2] International Energy Agency, 2020. Outlook for Biogas and Biomethane: Prospects for organic growth.

MOTIVATION

Eastern Europe

- To be independent on imported energy carriers
- Limited / min. amount of animal waste, except for poultry (e.g. Ukraine)
- Large agricultural potentials for growing bioenergy crops w/o harming food security
- Lacking data on methane yields of bioenergy crops in these countries
- Necessity to reduce the usage of pesticides & mineral fertilizers
- Phytoremediation

a) b) c) d)

Figure. Bioenergy crops (Ukraine): a) sugar beet; b) sweet sorghum; c) maize; d) miscanthus

SUSTAINABLE CRADLE-TO-CRADLE APPROACH

3 Approach Elements:

1. Substrate supply

- ✓ Case study in Ukraine
- ✓ > 100 samples of bioenergy plants analysed
- ✓ Best practices for biogas production

2. Biogas production process optimization

- ✓ Nitrogen-rich substrates
- ✓ Effect of ammonia increase in the feedstock
- ✓ Recommendations on operation for the AD-process stability and efficiency

3. Valorization of the solid fraction of digestate

- ✓ Digestate pretreatment (laboratory & full-scale trials)
- ✓ Testing of innovative biocoal-based additives
- ✓ Pretreatment with additives under different scenarios
- ✓ Best performance additive and pretreatment

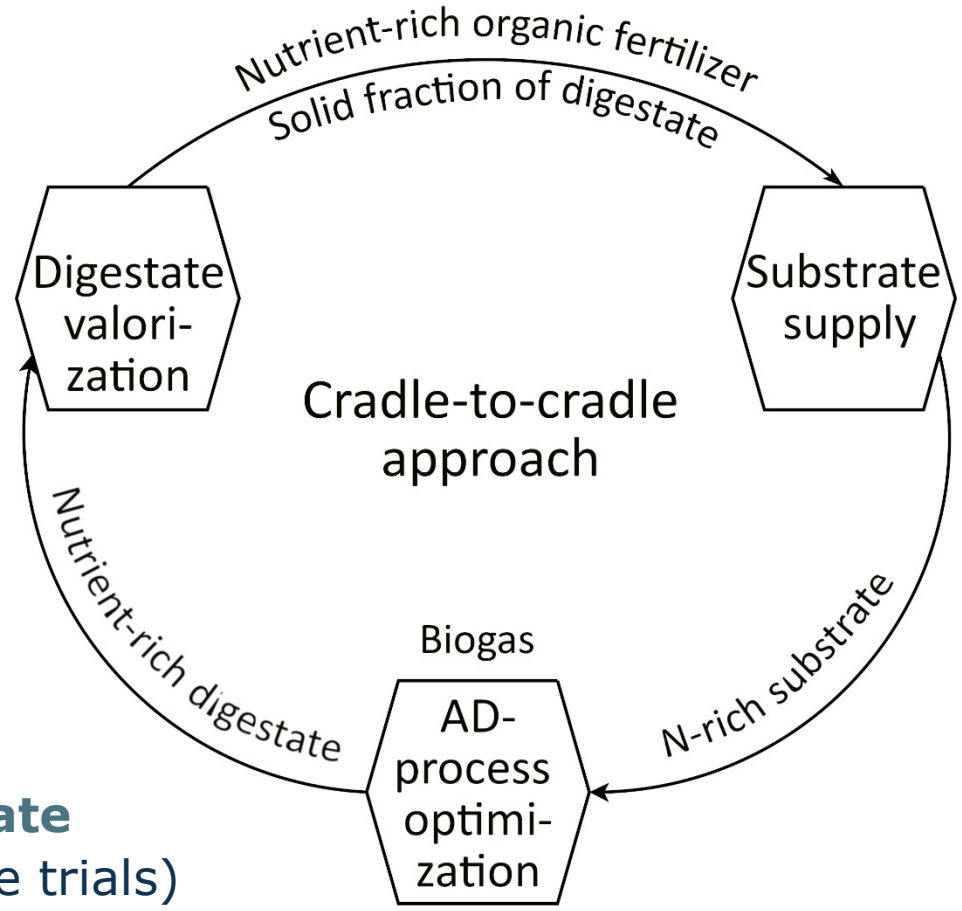


Figure.
Conceptual framework developed and investigated in this study

APPROACH ELEMENT 1

Substrate Supply:[1, 2]

- 8 plants (4 annual crops, 3 perennial crops and sugar beet)
- 26 high-yield Ukrainian varieties
- 2017*, extremely unfavorourable weather ** & 2018 for sugar beet
- 3 harvest. times; defined stages of phenological development (BBCH)
- Dry matter yields (DMY) and N content were determined
- 55 °C dried material delivered to Germany
- Specific methane yield (SMY) determined in Hohenheim Biogas Yield Test (HBT)
- Areal methane yields (AMY) in m^3_{CH4}/ha were calculated

a)

b)

Figure.
a) Field trials (UA)
b) HBT (DE)

[1] Morozova, I.; Oechsner, H.; Roik, M.; Hülsemann, B.; Lemmer, A. Assessment of Areal Methane Yields from Energy Crops in Ukraine, Best Practices. Appl. Sci. 2020, 10, 4431. https://doi.org/10.3390/app10134431
[2] Morozova, I.; Oechsner, H.; Lemmer, A. Assessment of areal methane yields from sugar beet in Ukraine. Progress in Biogas 2021.
* Miscanthus and switchgrass (perennial crops) are an exception, their rhizomes (creeping rootstalks) stayed in the soil longer.
** Higher average monthly temperature and a lower average monthly precipitation in comparison to 1985–2016. No artificial irrigation. Low-medium N contents in soils. Fertilizers, herbicides, fungicides as prescribed by the Institute of Bioenergy Crops & Sugar Beet

APPROACH ELEMENT 1

Case study best practices - Top 3: [1*]

TRL 4: Experimental testing with field trials or validation experiments

Plant	UA Variety	Harvest. time	DMY, $t_{DM} ha^{-1}$ **	SMY, $m^3_{CH4} \cdot kg^{-1} VS$ ***	AMY, $m^3_{CH4} \cdot ha^{-1}$	N contents, $mg_N \cdot kg^{-1}$
Miscanthus, "Giganteus" species	Osinnii zoretsvit	Stem elongation stage, 8th veget. year ****	30.43 (0.85)	0.26 (0.04)	7404.55 (199.00)	40.00 (2.00)
Maize	Svitanok MV (FAO 250)	Stage of wax maturity	17.70 (0.49)	0.41 (0.00)	6365.67 (55.49)	120.00 (6.00)
Sweet sorghum	Favoryt	Beginning of flowering	17.40 (0.49)	0.36 (0.01)	5968.90 (82.70)	96.00 (4.80)

[1] Morozova, I.; Oechsner, H.; Roik, M.; Hülsemann, B.; Lemmer, A. Assessment of Areal Methane Yields from Energy Crops in Ukraine, Best Practices. Appl. Sci. 2020, 10, 4431. https://doi.org/10.3390/app10134431

* Values are given as mean; standard deviation is given in round brackets.

** "DM" stays for "dry matter".

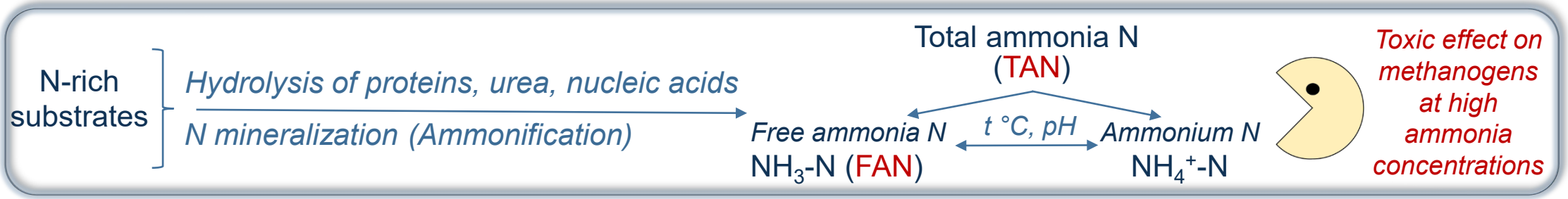
*** Volatile solids.

**** Age of miscanthus rhizomes in the soil.

APPROACH ELEMENT 2

Biogas production process optimization:[1]

- AD-inhibition due to high ammonia content in substrate and digestate
- High ammonia levels in the digestate when applying N-rich substrates
- Ammonia formation during N degradation (hydrolysis, ammonification)
- Protein-rich substrates belong to N-rich substrates (s.a. kitchen waste, legumes, etc.)
- Specific C/N ratio in the feedstock to be preserved
- Microorganisms' adaptive characteristics to certain ammonia level



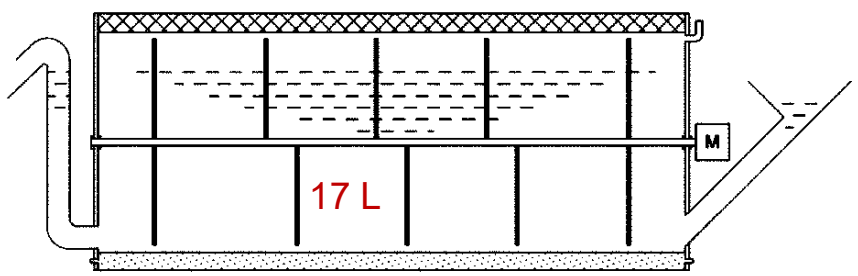
[1] Morozova, I.; Nikulina, N.; Oechsner, H.; Krümpel, J.; Lemmer, A. Effects of Increasing Nitrogen Content on Process Stability and Reactor Performance in Anaerobic Digestion. Energies 2020, 13, 1139. https://doi.org/10.3390/en13051139

APPROACH ELEMENT 2

Experimental design:[1]

- 33-week continuous study in 14 CSTR (CSTR - continuously stirred tank reactors)
- 2 different inocula with different TKN* were separately investigated
- Feeding substrates: Fresh inoculum, maize silage and soybean meal
- Changing and increasing N levels in the feeding substrates and the digestate
- Determination of C/N ratio in the feedstock
- OLR** = 3 $kg_{VS} \cdot m^{-3} \cdot d^{-1}$, HRT = 40 d, t = 37 °C, 2 repetitions

a)



b)

Figure.
a) CSTR cross-section;
b) CSTR-installation

[1] Morozova, I.; Nikulina, N.; Oechsner, H.; Krümpel, J.; Lemmer, A. Effects of Increasing Nitrogen Content on Process Stability and Reactor Performance in Anaerobic Digestion. Energies 2020, 13, 1139. https://doi.org/10.3390/en13051139

* Total Kjeldahl nitrogen. Inoculum 1 and Inoculum 2 were taken from two different biogas plants.

** "VS" stays for "volatile solids".

APPROACH ELEMENT 2

TRL 7: System prototype demonstration in operational environment

Recommendations:[1]

- Trace elements regularly supplementation (Fe, Ni, Mo, Co, Se, inter alia)
- Microorganisms' adaptivity to the N-increase
- Max. N-increase rate of 0.25 $g_N \cdot kg^{-1} \cdot d^{-1}$ to enable adaptation
- Max. N in the digestate of 5.92 $g \cdot kg^{-1}$FM* to enable adaptation
- Max. TAN in the digestate of 4.56 $g \cdot kg^{-1}$FM to enable adaptation
- Max. FAN in the digestate of 0.38 $g \cdot kg^{-1}$FM to enable adaptation
- 19.00 < the recommended C/N ratio < 28.48**
- Statistically significant inhibition in SMY under higher N, TAN, and FAN values

Inoculum adaptation to the high and increasing N and ammonia concentrations is possible!

[1] Morozova, I.; Nikulina, N.; Oechsner, H.; Krümpel, J.; Lemmer, A. Effects of Increasing Nitrogen Content on Process Stability and Reactor Performance in Anaerobic Digestion. Energies 2020, 13, 1139. https://doi.org/10.3390/en13051139

* Fresh matter

** C/N ratio higher than 28.47 was not tested. In the literature, a C/N ratio of up to 30 or 32 is also considered to be optimal.

APPROACH ELEMENT 3

Valorization of the solid fraction of digestate:[1]

- For sustainable crop production:[2, 3]
  - Nutrients applied to the field at times of crop demand
- Digestate pretreatment for a nutrient-rich solid fraction
  - Pretreatment before separation with screw press:
    - ➢ Additives based on biocoal (biochar):
      - ✓ Untreated beech wood
      - ✓ Beech wood impregnated* with $CaCl_2$ or $MgCl_2$
      - ✓ Beech wood (untreated or impregnated) pyrolysed at 350 °C or 600 °C

Figure. Production of biocoal

[1] Morozova, I.; Lemmer, A. Nutrient Recovery from Digestate of Agricultural Biogas Plants: A Comparative Study of Innovative Biocoal-Based Additives in Laboratory and Full-Scale Experiments. Molecules 2022, 27, 5289. https://doi.org/10.3390/molecules27165289

[2] Deublein, D., Steinhauser, A. (Eds.), 2008. Biogas from Waste and Renewable Resources: An Introduction.

[3] Ruppert, H., Kappas, M., Ibendorf, J. (Eds.), 2013. Sustainable bioenergy production: An integrated approach. Springer.

* For the biocoals impregnated with Ca- or Mg-salts, 1 mol of P in the digestate corresponded to 1 mol of Ca or Mg in biocoal.

APPROACH ELEMENT 3

Solid fraction valorization:[1]

TRL 4: Technology validated in laboratory

- Best performance additive:
  - ➢ $MgCl_2$-impregnated biocoal pyrolysed at 600 °C
  - – 1 mol of P in the digestate corresponded to 1 mol of Mg in biocoal
- Best performance pretreatment:
  - ➢ 20-hour reaction time (continuous mixing tested at 20 ± 2 °C)
- Removal efficiency achieved:
  - ✓ NH_4^+-removal efficiency = 56%
  - ✓ P-removal efficiency = 67%
  - ✓ K-removal efficiency = 52%

$$\text{Removal efficiency} = \frac{\text{Quantity in solid fraction}}{\text{Quantity in digestate}} \times 100\%$$

Figure. Hydraulic tincture press for the laboratory trials

[1] Morozova, I.; Lemmer, A. Nutrient Recovery from Digestate of Agricultural Biogas Plants: A Comparative Study of Innovative Biocoal-Based Additives in Laboratory and Full-Scale Experiments. Molecules 2022, 27, 5289. https://doi.org/10.3390/molecules271652

TAKE HOME MESSAGE & OUTLOOK

Key takeaways:

- Sustainable cradle-to-cradle approach was developed and investigated
- Limitations for the application of this proposed approach in the practice:
  - Scientific knowledge
  - Resources
  - Legal basis

Next steps:

- To validate the results in a full-scale application at the farm level
- To determine the emission reductions
- To calculate the economic feasibility
- Other options (biomethane, hydrogen, CO_2 liquefaction, etc.) to be considered

THANK YOU FOR YOUR ATTENTION

Dr. Ievgeniia Morozova