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**'THESIS OF DOCTORAL DISSERTATION'**

**LOGISTICS AND EFFICIENCY ISSUES OF  
BIOGAS PRODUCTION BASED ON SECONDARY BIOMASS**

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## **1. AIMS OF THE RESEARCH**

Aims of the research were to elaborate a methodology to estimate biomass potential, specifically biogas potential with higher resolution than that of the national data, providing reliable estimations on the level of counties or specific areas. In addition, the aspect emerged that not only regional planning and decision making should be able to use the results of the method, but also the planners and investors of the specific plants. For this reason, it was also aim of the research to determine which capacities of biogas plants can be established based on a given area's biogas potential. This made necessary to achieve the following subordinate aims in the course of the research:

- to determine the size of the livestock on a given area;
- to determine the manure- and biogas production of the livestock;
- to determine the capacities of biogas plants that can be established on the given biogas potential;
- to investigate the possibilities of increasing biogas plants' capacity by means of transport;
- to investigate the possibilities to increase biogas plants' capacity by means of developments.

## **2. BACKGROUND OF THE RESEARCH**

In Hungary, after the political-economic change of the 1990's, the relations of plant production and animal breeding became unbalanced, which harms both sector. The decrease in livestock narrowed also the possibilities of plant production in marketizing its production with added value. At the same time, soil needs organic matter amendment, which can be supplied most cost-effectively with the residues of the already utilized biomass. By enhancing the conditions of animal breeding, anaerobe digestion can serve plant production, too.

Currently, anaerobe digestion is not as widely spread in Hungary as it would be ideal. Widespread use of biogas production would be especially reasonable on the traditionally agricultural area of the Great Hungarian Plain, which has a well-known high biomass production capacity. The question arises: what are the factual possibilities and barriers that really describe the situation and the solutions? In accordance to the role of the University of Debrecen as a regional knowledge center, my research, carried out in the Kálmán Kerpely Doctoral School, in the frames of Agricultural Engineering and Environment Management doctoral program, investigated the regional conditions and possibilities of biogas production.

### 3. MATERIALS AND METHODS

#### *A) Methods to determine regional agricultural biogas potential fit for biogas production*

In terms of biogas production, farm animals to be considered are those having largest livestock and most suited manure. These species include dairy cattle, pig, sheep, chicken and turkey, since they are kept enclosed, in a concentrated, industrialized manner. Thus manure management needs arise also concentrated, requiring appropriate manure treatment and placement. Waterfowl and horse are producing manure scattered on a large area, therefore they are not considered in the calculations. In my model, manure production figures of each considered species and some calculations based on them were used, as well as specific gas production data of manure from the different species, creating new coefficients.

With these coefficients, quantity of manure and biogas that can be produced thereof can be calculated, based on the livestock data. However, some species were not involved into the calculations. The manure handling of sheep has been solved with the more than hundred years old deep litter technology. Utilization of poultry manure is constrained because it contains sinking (sand) and up-flowing, hardly decomposing material (feather, straw) in large quantities, which involve problems in the present facilities with wet technology. Besides this, livestock data have huge variations, which hamper projection. For example, poultry livestock varied between 2 and 4 million in five years. Therefore, in the study on Hajdú-Bihar county, examined species were narrowed to dairy cattle and pig.

Based on the 1995-2005 livestock data, characteristic statistic indicators for cattle and pig livestock were examined, as well as their difference and sum, in thousand animals and Livestock Unit (LU). Using the county livestock data and data from the settlement-level census from 2000, cattle and pig manure produced in Hajdú-Bihar County were determined by species and by settlements, the amount of biogas that can be produced thereof, and its distribution among settlements.

### ***B) Logistic calculations of the utilization of the regional biomass potential suitable for biogas production***

In the calculation of the biogas potential, the biogas quantity results of the settlements were converted to energy value, then to plant capacities, with the coefficients of the gas-engine power generation (35% electric efficiency). Then the settlements were determined, which exceeded the 500, 300 and 100 kW<sub>el</sub> capacity limits. Results were analyzed in details.

After analyzing the plant capacities reachable without transport, also the possibility of creating circles around centers consisting of the settlements surpassing the 500, 300 and 100 kW<sub>el</sub> minimum capacity limits was examined, transporting input materials to the centers. The results were analyzed as to the effect of these arrangements on the exploit of the available manure's energy content and on the transport demand involved.

Biogas potential and regional distribution were examined also on a smaller area, in order to evaluate the effectivity of transport, i.e. the amount of transport required to utilize the biogas potential. Starting point of the study was that, in the future, local and decentralized energy supply would locate itself near to local consumers. The calculations examined the biogas potential and its concentration in the circle around Debrecen.

Energy-balanced transport distance of the various animals' manure were determined based on the energy demand of transport [MJ/tkm] and energy content of biogas producible from the manure [MJ/t] under the present conditions of biogas production. Energy demand of transport was derived from the fuel consumption data of heavy trucks, energy production of the manure was calculated from the manure's material composition and biogas production values.

### ***C) Examination of efficiency development***

Various biogas-substrates and the effects of chopping were examined in batch and continuous experiments, as well as in theoretical calculations. Detailed description of the diversified experiments is contained in my dissertation. The possibilities of the system-level developments were examined on cattle and pig livestock, based on literature data and own studies.

#### 4. RESULTS

##### *A) Results in the estimation of regional agricultural biomass potential suitable for biogas production*

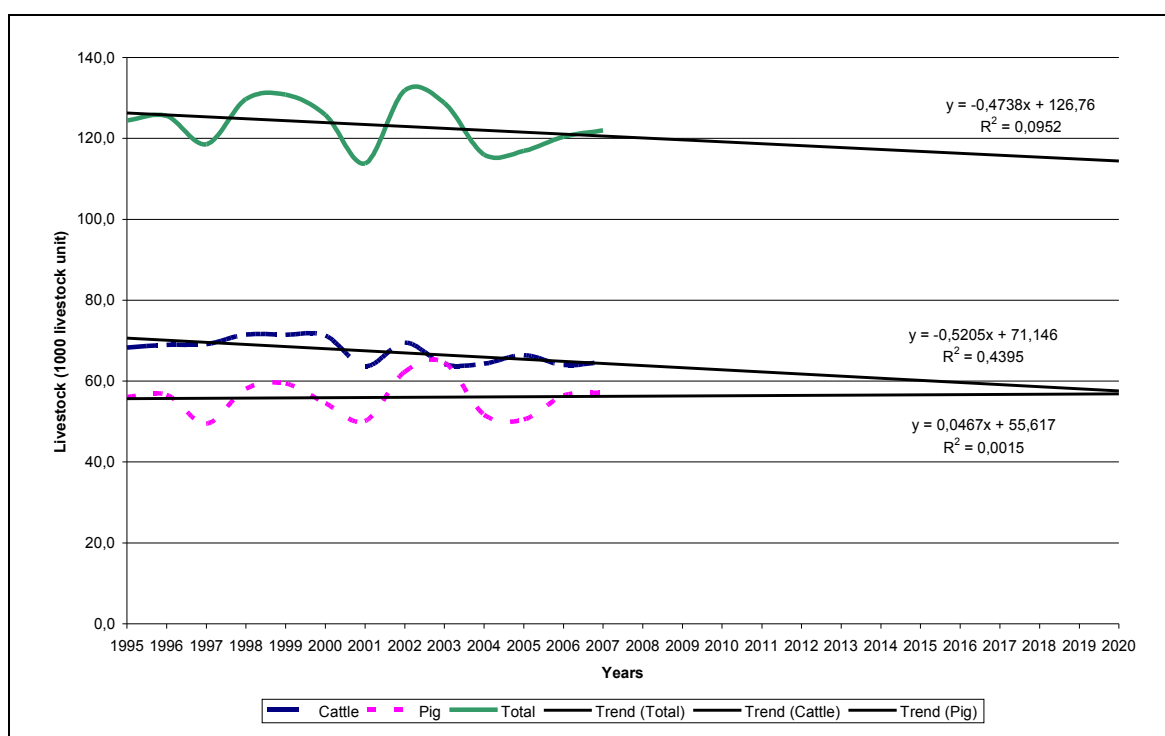
1. As the first step, **coefficients** were created on the manure and biogas production of cattle, pig, sheep, chicken and turkey. Main figures are included in *Table 1*. In case of cattle and sheep, yearly manure production of a livestock unit is 11.9 t, out of which 156.2 Nm<sup>3</sup> biogas can be produced, so the yearly energy production sums up to 8.5 GJ. In case of pig, yearly manure production of a livestock unit is 8.04 t, out of which 4.86 Nm<sup>3</sup> biogas can be produced, so the yearly energy production sums up to 1.7 GJ. In case of chicken, yearly manure production of a livestock unit is 5.66 t, out of which 309 Nm<sup>3</sup> biogas can be produced, so the yearly energy production sums up to 23 GJ. In case of turkey, yearly manure production of a livestock unit is 6.5 t, out of which 328.8 Nm<sup>3</sup> biogas can be produced, so the yearly energy production sums up to 28 GJ.

**Table 1: Specific biogas potential of some species**

<b>Basis</b>	<b>Characteristics</b>	<b>Unit</b>	<b>Cattle</b>	<b>Pig</b>	<b>Sheep</b>	<b>Chicken</b>	<b>Turkey</b>
<b>1 average animal</b>	<b>yearly manure production</b>	<b>t, kg*</b>	9.5	0.9	0.8	22.6*	129.6*
<b>1 livestock unit</b>	<b>yearly manure production</b>	<b>t</b>	11.9	8.0	11.9	5.7	6.5
<b>Specific</b>	<b>dry matter content</b>	<b>%</b>	28.8	4.5	28.8	71.2	73.1
	<b>organic matter content</b>		24.2	3.7	24.2	66.5	68.5
	<b>manure's yearly average biogas production</b>	<b>m<sup>3</sup>/t</b>	54.3	16.4	54.3	309.0	328.8
<b>1 livestock unit</b>	<b>yearly biogas production</b>	<b>m<sup>3</sup></b>	156.2	131.2	156.2	1162.0	1458.9
	<b>yearly energy production</b>	<b>GJ</b>	8.5	2.8	8.5	23.1	28.1

Source: own calculations

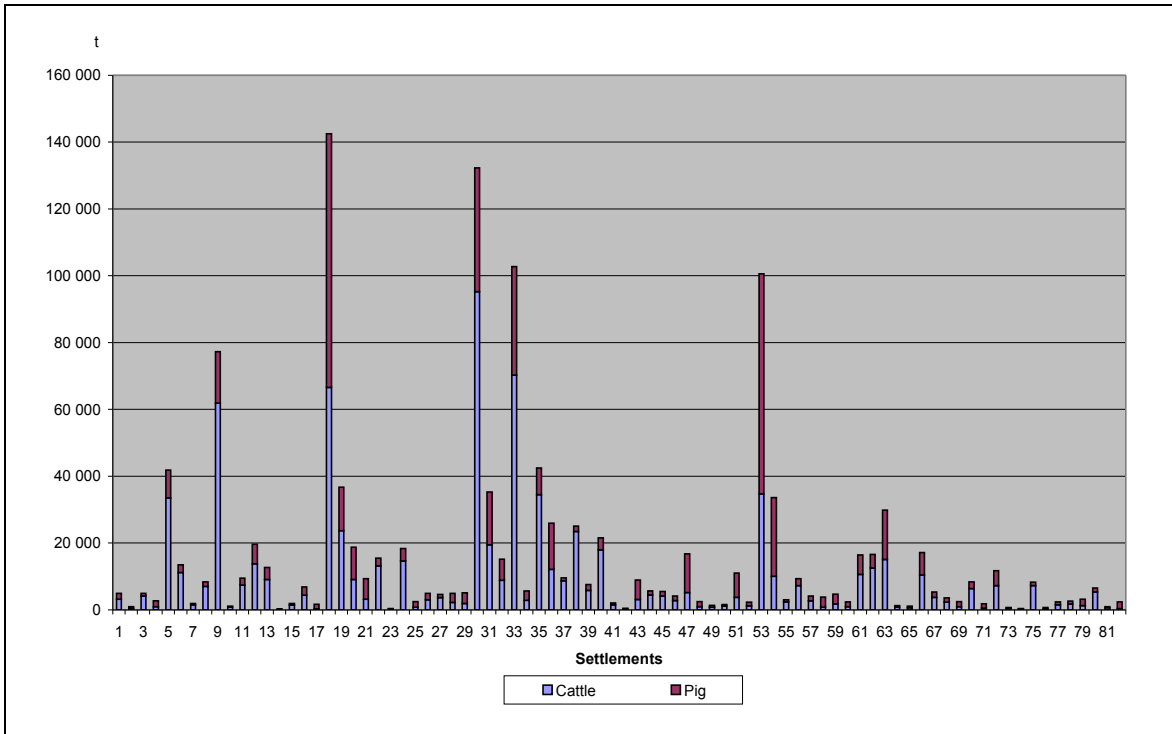
2. For Hajdú-Bihar County, the **trend** of cattle and pig livestock changes were calculated (*Figure 1*). In total, the two species make up 126 thousand livestock unit, from which the cattle has a 66, the pig a 60 thousand livestock unit share. This means an average 800 and 730 livestock unit from the species, with a high deviation: minimum values are 5 and 15 livestock units, maximum values are 8000 and 9400 livestock units, respectively. In the county, the trend of cattle livestock is decreasing in the time frame between 1995 and 2007 with a yearly 651 head, which is 0.7% of the livestock in 2000. In the same time, pig has an almost constant trend, increasing yearly with 410 heads, which is 0.1% of the livestock in 2000.



**Figure 1: Trends of the cattle and pig livestock in Hajdú-Bihar County (1995-2020)**

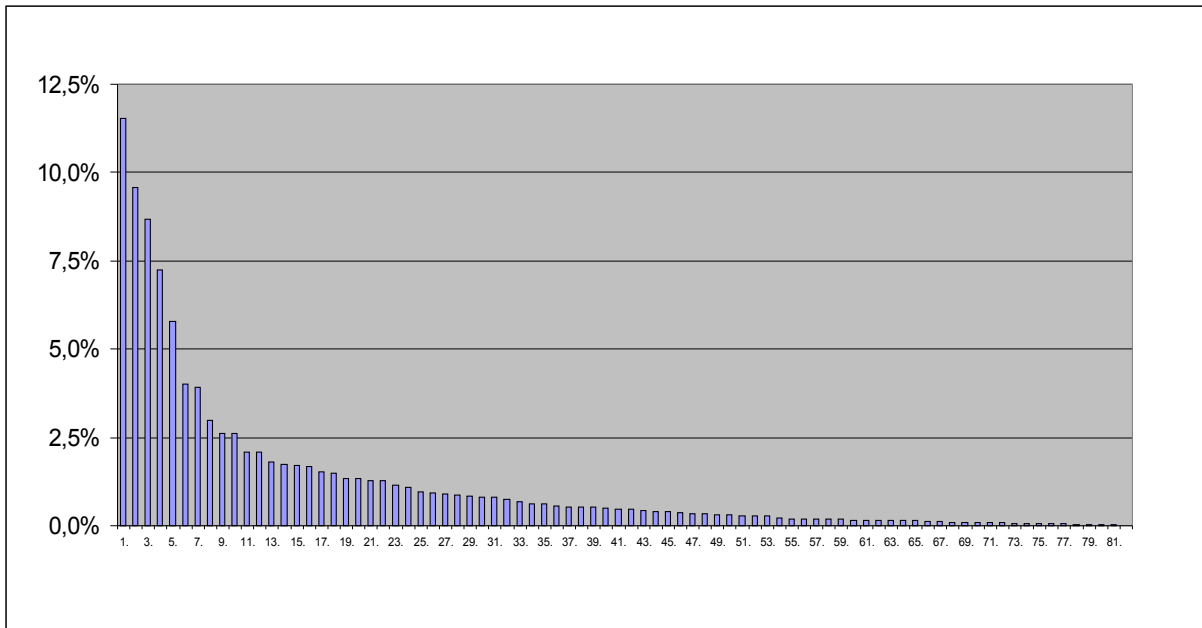
3. The **amount** of cattle and pig manure was estimated on the **settlements** of Hajdú-Bihar County, and the amount and **distribution** of biogas that can be produced thereof.

- Cattle and pig manure in Hajdú-Bihar County in total **amounts** to 1 263 thousand tons, whereas the minimum value is 300 tons and the maximum is 142 thousand tons. Manure produced on main part of the settlements (71 out of 82) is less than 50 000 tons/year (*Figure 2*).



**Figure 2: Manure production in Hajdú-Bihar county in the average of 2000-2005**

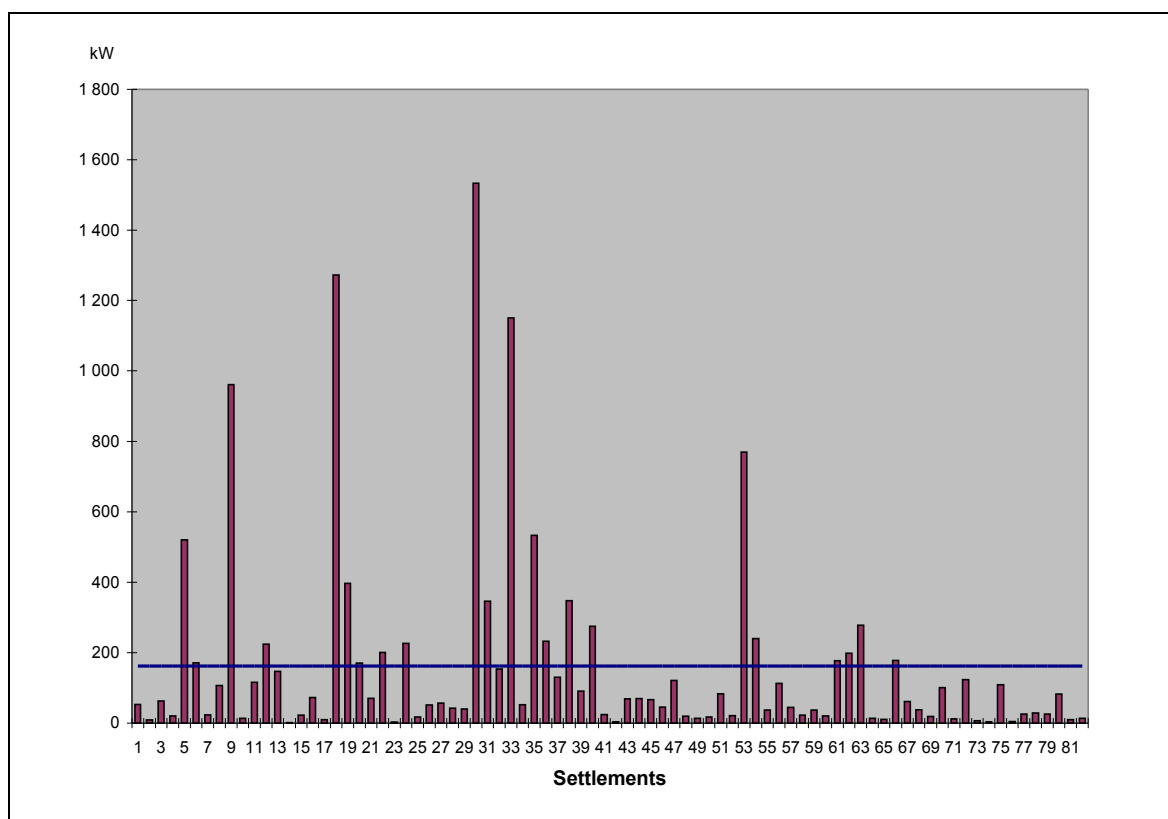
- Biogas that can be produced from the manure makes up 50 million m<sup>3</sup>, with a more or less even **distribution**, except for some larger centers: 72 settlements have the share of 0-2.5%, 5 settlements have 2.6-5% share, 2 settlements have 5.1-7.5% share, 2 settlements have 7.6-10% share, and on 1 settlement the share is higher than 10% (Figure 3).



**Figure 3: Distribution of biogas potential among the settlements**

**B) Results of the logistic calculations of regional biomass potential suitable for biogas production**

4. With the help of the 500, 300 and 100 kW<sub>el</sub> minimum plant capacity limits, **plant sizes** accessible using the biogas potential on the settlements of Hajdú-Bihar county were examined, as well as the **level of biogas potential utilization** at the given capacity limit and settlement structure, and the **transport needs** thereof.
- The calculations revealed that biogas potential in the county allows a 1500 kW<sub>el</sub> plant size on one of the settlements and 160 kW<sub>el</sub> on average (*Figure 4*). Total capacity, maximum and average plant capacity, number of settlements involved and their share in biogas production, and the utilization level of biogas potential accessible with the 500, 300 and 100 kW<sub>el</sub> minimum plant capacity limits are included in *Table 2*. Without minimum capacity limit, a theoretical 13.3 MW total capacity can be achieved in the county. *Table 2* also contains the investigated indices by plant size categories.



**Figure 4: Plant capacities on the settlements of Hajdú-Bihar County without transport**

**Table 2: Plant capacities, number of settlements involved in biogas production and biogas potential utilization in Hajdú-Bihar County without transport**

Characteristics	Unit	Characteristics by plant size limits (kW <sub>el</sub> )			Characteristics by plant size categories (kW <sub>el</sub> )				Total - average
		min. 500	min. 300	min. 100	over 500	300-500	100-300	below 100	Without limit
Settlements involved	pcs	7	10	32	7	3	22	50	82
	%	8.5	12.2	39.0	8.5	3.7	26.8	61.0	100
Total capacity	MW <sub>el</sub>	6.7	7.8	11.6	6.7	1.1	3.8	1.7	13.3
Average plant size	kW <sub>el</sub>	<b>963</b>	<b>783</b>	<b>363</b>	<b>963</b>	<b>363</b>	<b>172</b>	<b>33</b>	<b>162</b>
Maximum plant size		<b>1 533</b>	<b>1 533</b>	<b>1 533</b>	<b>1 533</b>	<b>396</b>	<b>278</b>	<b>91</b>	<b>1 533</b>
Biogas potential utilization	%	50.8	59.0	87.5	50.8	8.2	28.5	12.5	100

Source: own calculations

- Plant sizes and their total capacity can be further increased with the transport of input materials. The case of input transport to centers was examined, i.e. transport to the settlements that surpass the 500, 300 and 100 kW<sub>el</sub> minimum plant capacity limits, respectively. The question was the effect of input material transport on the utilization of the available manure's energy content and on the transport needs. *Table 3* shows the transport required to reach the 60, 70, 80, 90 and 100% biogas potential utilization. Under the given conditions of the examined area, installment of the biogas plants with 100 kW<sub>el</sub> minimum capacity can provide a more than 85% resource utilization without transport, which means a 10.7 MW<sub>el</sub> total capacity, without additional substrates.
- *Table 4* also demonstrates that further increase of total capacity with additional 0.5, 1 and 1.5 MW<sub>el</sub> involves the highest demand on transport in the min. 500 kW<sub>el</sub> and min. 100 kW<sub>el</sub> categories, whereas it involves the least transport in the min. 300 kW<sub>el</sub> size category. The specific transport demand is the least also by the min. 300 kW<sub>el</sub> category, with a 3.1; 5.2 and 5.4 tkm/kW<sub>el</sub> additional transport requirement, respectively.

**Table 3: Utilization grade of biogas potential in the different plant size categories**

Characteristics	Unit	Size limit (kW <sub>el</sub> )	Potential utilization levels				
			60%	70%	80%	90%	100%
Total capacity	MW <sub>el</sub>	-	8.1	9.3	10.7	11.9	13.3
Number of settlements	pcs	500	16	25	35	53	82
		300	12	25	35	54	82
		100	11	16	24	44	82
		100*	11	16	24	32	32
Average transport distance	km	500	9.7	11.2	13.5	15.8	19.2
		300	5.8	9.9	12.5	15.5	19.1
		100	0.0	0.0	0.0	5.0	11.4
Mass of transported manure	1000 t	500	131.9	253.6	374.1	483.8	623.2
		300	13.7	149.1	277.1	388.8	526.2
		100	0.0	0.0	0.0	29.5	170.2
Specific transport requirement	$\frac{\text{tkm}}{\text{kW}_{el}}$	500	157.3	304.6	471.6	639.6	900.2
		300	10	158	323.5	504.4	755
		100	0.0	0.0	0.0	12.2	157.3
Average plant size	kW <sub>el</sub>	500	<b>1 160</b>	<b>1 330</b>	<b>1 530</b>	<b>1 710</b>	<b>1 900</b>
		300	<b>800</b>	<b>930</b>	<b>1 070</b>	<b>1 200</b>	<b>1 330</b>
		100	<b>740</b>	<b>580</b>	<b>450</b>	<b>370</b>	<b>410</b>

Source: own calculations

\* Comment: centers are 7 settlements at the 500 kW<sub>el</sub> size limit and 10 settlements at the 300 kW<sub>el</sub> size limit. At the 100 kW<sub>el</sub> size limit, needed number of centers is shown in the table.

**Table 4: Transport requirement of total plant capacity increase in the case of plants with 500, 300 and 100 kW<sub>el</sub> minimum size limits**

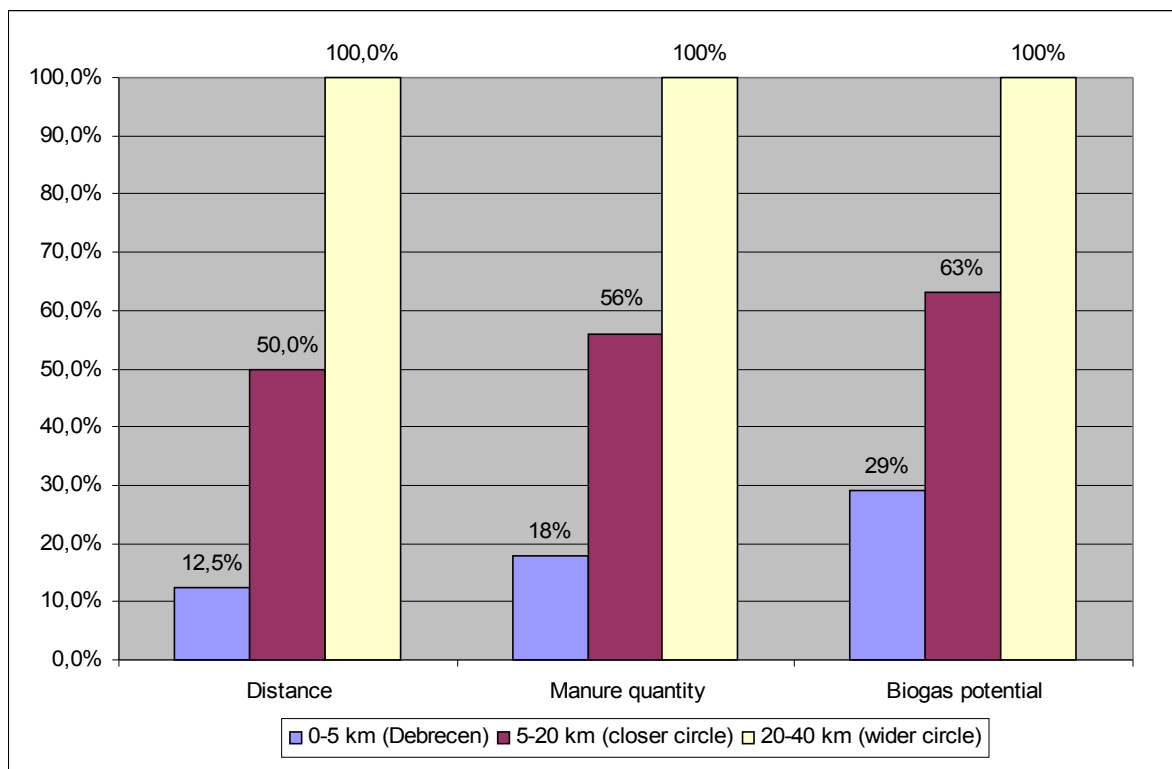
Characteristics	Unit	Size limit (kW <sub>el</sub> )	Increase in total capacity (MW <sub>el</sub> )			
			-	+0.5	+1	+1.5
Total capacity	MW <sub>el</sub>	500	7.8	8.3	9.9	10.8
		300	6.7	7.2	7.7	8.2
		100	11.6	12.1	12.6	13.1
Total transport requirements	1000 tkm	500	0.0	509.1	837.9	1 423.2
		300	0.0	<b>25.8</b>	<b>51.3</b>	<b>59.0</b>
		100	0.0	44.9	89.5	154.4
Specific transport requirements	$\frac{\text{tkm}}{\text{kW}_{el}}$	500	0	70.3	108.2	172.7
		300	0	<b>3.1</b>	<b>5.2</b>	<b>5.4</b>
		100	0	3.7	7.1	11.8

Source: own calculations

In my examinations, the conditions in the county argue for the installment of the plants of the 100 kW<sub>el</sub> category, since these provide a more than 85% resource utilization.

However, transport of input materials is advised in centers determined in the min. 300 kW<sub>el</sub> size category, based on the specific transport needs. When increasing the total capacity with 0.5, 1 and 1.5 MW<sub>el</sub>, the average plant capacity for these 10 settlements will be 830, 990, and 1 080 kW<sub>el</sub>, respectively.

- In my results, **concentration of biogas potential**, available from the manure of cattle, pig, sheep, chicken and turkey in the area around Debrecen as center, has a high grade. The examination of the circles with 20 and 40 km radius has shown that more than 60% of the biogas potential is available in the tighter circle compared to the broader circle. In the 5 km area of Debrecen, almost one third of the biogas potential is available (*Figure 5*).



**Figure 5: Concentration of biogas potential in the area around Debrecen**

- By my calculations, **energy-balanced transport distances** of the various animals' manure were determined (*Table 5*): this is the transport distance at which the transport energy demand reaches the energy content of the biogas that can be produced from the input materials. The transport energy demand of heavy trucks reaches 1.05 MJ/tkm on country lanes and 0.93 MJ/tkm on roads.

**Table 5: Energy-balanced transport distances for the manure of different species**

Animal species	Biogas energy equivalent	Transport distance on country lanes	Transport distance on road
	MJ/t	km	km
<b>Cattle</b>	1.20	1.14	1.29
<b>Pig</b>	0.36	0.35	0.39
<b>Sheep</b>	1.20	1.14	1.29
<b>Chicken</b>	6.80	6.49	7.31
<b>Turkey</b>	7.23	6.91	7.78

Source: own calculations

Transport beyond these distances can be reasoned or enabled by aspects beyond energy balance of biogas production (e.g. environment protection aspects, decreasing availability of fossil resources, job creation or preservation). As to the results, pig slurry with 4.5% dry matter content from animal keeping technologies without litter is practically ineffective to transport on wheels without phase separation. In case of ruminants, transport is reasonable only between farms, whereas poultry manure can be effective to transport also between settlements.

### ***C) Results of the utilization efficacy development of agricultural biomass potential suitable for biogas production***

#### **Results of experimental research**

7. In the course of experiments, temperature and pH-value of the samples were measured at the beginning and at the end of transport to assume **digestive losses associated with transport**. The measurements (*Table 6*) revealed that the temperature of the samples has decreased and the pH has slightly increased instead of the anticipated acidification (with one exception). Thus, no such changes have occurred during the approx. 3 hours travel from the sampling site to the laboratories which could essentially influence the evaluation of the content and gas production of the samples.
8. **Theoretical gas production** of the samples were calculated out of their content with a model that has not been used or published yet in Hungary. Results are shown in *Table 7*.

**Table 6: Change in temperature and pH during the transport of experiment samples**

No.	Sample	Temperature (°C)		pH	
		Sampling	Laboratory	Sampling	Laboratory
T03	digestion output (liquid phase)	41.0	22.0	8.0	8.5
T04	maize+sorghum silage	27.0	22.2	4.0	4.1
T05	cattle manure	36.0	22.5	7.4	7.2
T06	digestion output (solid phase)	41.0	22.0	8.1	8.7

Source: FVM MGI measurements

**Table 7: Theoretical gas production of the samples**

No.	Sample	Gas yield	CH <sub>4</sub> -ratio	CH <sub>4</sub> -yield	Gas yield	CH <sub>4</sub> -yield
		NI/kg o. m.	V%	NI/kg o. m.	NI/kg f. m.	NI/kg f. m.
T01	slaughterhouse effluents	4404.2	68.6	3021.6	2.0	1.4
T02	sewage sludge	287.8	55.8	160.7	8.7	4.8
T03	digestion output (liquid phase)	1565.4	70.5	1103.6	21.1	14.8
T04	maize+sorghum silage	498.2	53.4	265.8	111.0	59.2
T05	cattle manure	381.2	54.5	207.8	57.9	31.6
T06	digestion output (solid phase)	437.6	52.9	231.5	92.0	48.7
T07	maize+sorghum silage	499.5	52.6	263.0	112.5	59.2
T08	cattle manure	474.1	54.2	257.0	56.8	30.8
T09	inoculum cattle m	375.4	51.3	192.7	24.3	12.5
T10	digestion output (liquid phase)	1244.8	70.8	881.7	17.2	12.2
T11	digestion output (solid phase)	435.5	53.1	231.1	75.7	40.2

Source: own calculations

Comment: f.m.: fresh matter, o. m.: organic matter

- With the help of gas production measurements, the effects of sewage sludge (samples T01-06) and cattle liquid manure (samples T07-T11) as **inoculum** was examined on the gas production of various substrates. Results were compared with the calculated **theoretical values** (Table 8). Difference between gas production values in the two series of experiments is due partly to the different inoculums, partly to the different content of the samples in the different series.

10. Different **chopping** levels were examined by adding equal quantities of maize silage to the inoculum. Differences between the samples were observed, although the experiments were not easy to interpret, since, in the first measurement, maximum gas production came from the silage in original condition, whereas in the second measurement maximum gas production came from the silage at the 1<sup>st</sup> chopping level (*Table 8*, samples T04 and T07). It can also be observed in the data, that, in the second measurement series, even theoretical gas production values were exceeded by gas production data of the 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> chopping levels after correction to 30-day fermentation time. This was possibly caused by the fact that measurements were stopped at the steep part of the gas production curve, so time-proportional gas production values were higher than values that could be obtained if the gas production would have continued to the end.

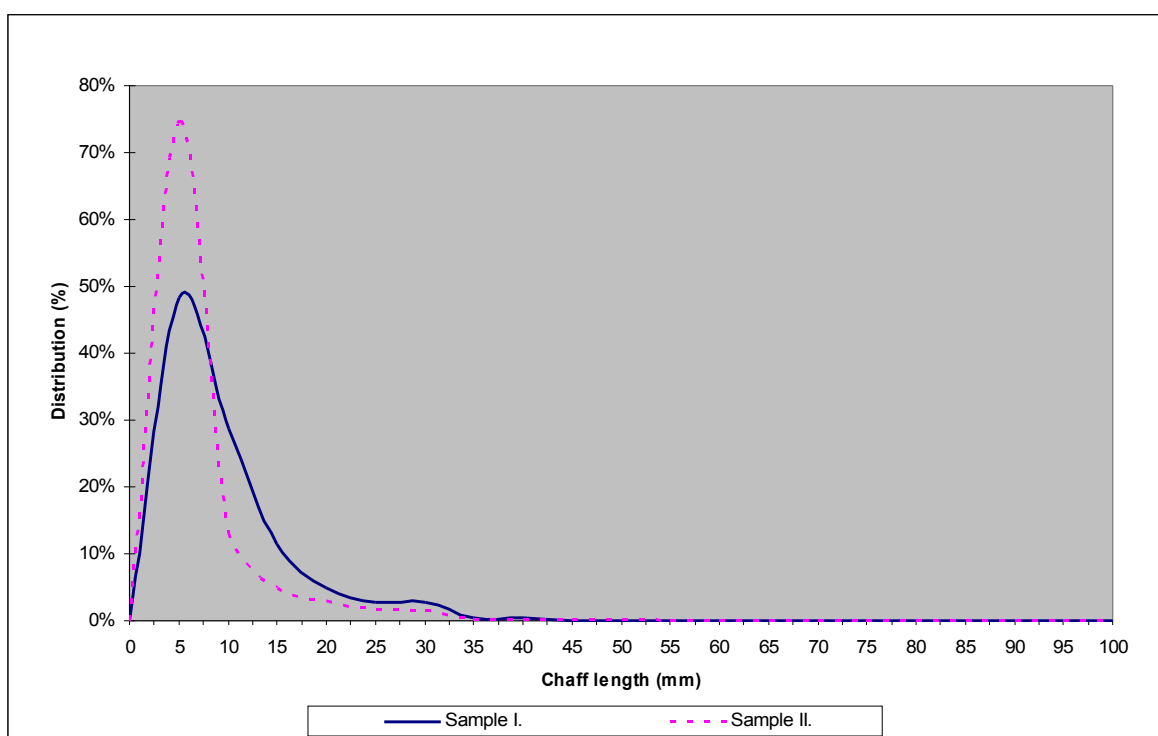
**Table 8: Theoretical and measured gas production of the samples**

No.	i.	Sample	Measured gas yield	Gas yield (30 days)	Calculated gas yield	Difference	Gas yield
			NI/kg o. m.	NI/kg o. m.	NI/kg o. m.	NI/kg o. m.	NI/kg f. m.
T01	a	slth. effluents	0	0	4 404.20	-4 404.20	2
T02	a	sewage sludge	–	–	287.8	-287.8	8.7
T03	a	digestion output (liquid)	0	0	1 565.4	-1 565.4	21.1
T04	a	silage original	137.5	412.5	498.2	-85.7	111
	a	silage 1. chopped	91	273	498.2	-225.2	111
	a	silage 2. chopped	135.3	405.9	498.2	-92.3	111
	a	silage 3. chopped	123.8	371.4	498.2	-126.8	111
T05	a	cattle manure	80.9	242.7	381.2	-138.5	57.9
T06	a	digestion output (solid)	0	0	437.6	-437.6	92
T07	b	silage original	4.9	147	499.5	-352.5	112.5
	b	silage 1. chopped	29.2	876	499.5	376.5	112.5
	b	silage 2. chopped	26.5	795	499.5	295.5	112.5
	b	silage 3. chopped	24.4	732	499.5	232.5	112.5
T08	b	cattle manure	12.5	375	474.1	-99.1	56.8
T09	b	i. cattle slurry	–	–	375.4	-375.4	24.3
T10	b	digestion output (liquid) + silage (1%)	31.1	933	1 244.8	-311.8	17.2
T11	b	digestion output (solid)	8.5	255	435.5	-180.5	75.7

Source: FVM MGI experimental measurements and own calculations

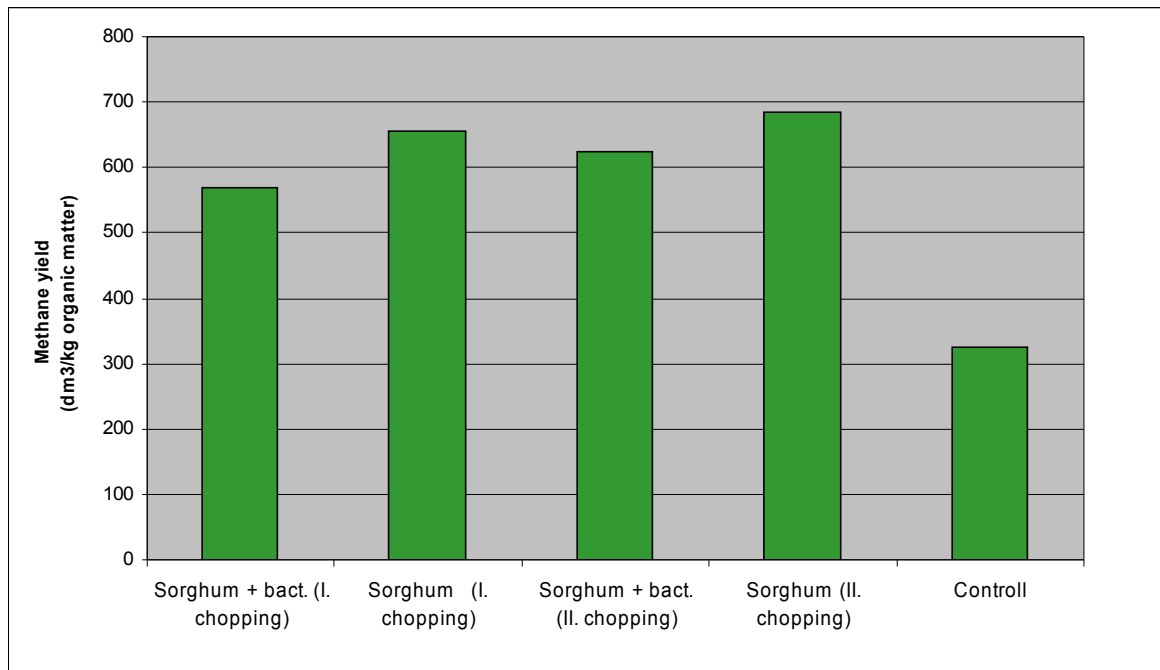
Comment: f. m.: fresh matter, i.: inoculum, o.m.: organic matter, a: sewage sludge, b: cattle slurry

11. Investigations of the **phase separated liquid and solid** phase fractions of anaerobe **digestion's output** material revealed that the separates were able to produce biogas in part of the experiments (*Table 8*, samples T10 and T11). In case of samples T03 and T06, lack of gas production may derive from the bacterial incompatibility of cattle manure based digested material and sewage sludge. It was also understood that liquid phase of digested output material is more suitable to provide technological water for the biogas process than the examined food-industry effluents.
12. Investigation of the effect of sweet sorghum on biogas production has revealed, that different **particle size distribution of chopped input** material samples has no significant effect on biogas production provided there is no significant difference in average particle size (*Figure 6*).



**Figure 6: Length distribution of sweet sorghum chaff**

13. In the experiments with chopped sweet sorghum as additive to pig slurry, difference between gas production of sweet sorghum with and without inoculum bacteria amendment showed no statistical significance. The mean specific **methane production of sweet sorghum** was 619 dm<sup>3</sup>/kg in the average of the four treatment, whereas specific methane production of pig slurry was 326 dm<sup>3</sup>/kg, in the 21 day long continuous experiments (*Figure 7*).



**Figure 7: Gas production of sweet sorghum additive**

### Results of the experiments of system-level theoretical calculations

14. In my calculations, **system-level** and system-minded **developments** showed noteworthy advantages, both on regional and on plant level.

- Total and specific energy production could be increased with 7.5–53%, provided that biogas production on a given place occurs with the combination of more than one branches (*Table 9*). Some coefficients of the literature tell that **co-digestion** of cattle and pig manure produce yearly +647.9 m<sup>3</sup> (+7.5%) biogas compared to the case when cattle and pig manure are digested separately. Mixing cattle manure to pig slurry increases the dry matter content of the latter more than 1.5 times, although in the given 1:1 mixing ratio the total dry matter does not reach the desired 8%. Gas production of unit organic matter is higher in the pig slurry, the mixing shows an increase compared to cattle manure. On the other side, gas production per unit digester space (which equals the volume of manure input), as well as per livestock unit, is higher in the cattle manure, because of higher dry matter content, so in the end mixing enhances gas production compared to the pig slurry (*Table 9*). Although the **enhancement** is below 10% at the given mixing ratio, co-digestion involves also the benefit that cattle manure's consistency becomes suitable for pumping, while pig slurry treatment becomes considerably economic.

**Table 9: Separate digestion and co-digestion of cattle and pig manure**

Quantity	Unit	Pig slurry	Cattle manure	Sep. dig.	Co-dig.	Difference to sep. dig.	Difference to lower data
livestock unit	L.U.	11.39	2.52	13.91	13.91	-	-
manure (year)	t	278.63	47.57	326.19	326.19	-	-
d. m.	%	4.00	22.41	-	<b>6.68</b>	-	167.11%*
d. m. (yearly)	t	11.15	10.66	21.80	21.80	-	-
o. m. (yearly)	t	9.13	9.13	18.25	18.25	-	-
o. m. (40 days)	t	<b>1.00</b>	<b>1.00</b>	2.00	2.00	-	-
biogas/ o. m. (40 days)	m <sup>3</sup> /t	569	380	949	1020	<b>107.48%</b>	179.26%**
biogas (year)	m <sup>3</sup>	5192.13	3467.50	8659.63	9307.50	<b>107.48%</b>	179.26%**
yearly biogas/ digester space***	m <sup>3</sup> /m <sup>3</sup>	18.63	72.90	26.55	28.53	<b>107.48%</b>	<b>153.12%*</b>
yearly biogas/ L.U.	m <sup>3</sup> /L.U.	455.85	1375.99	622.55	669.12	<b>107.48%</b>	<b>146.79%*</b>

Source: own calculations; d.m.: dry matter, o.m.: organic matter

\* Compared to pig slurry

\*\* Compared to cattle manure

\*\*\* Digester space comes from input material quantity: 1 t manure equals 1 m<sup>3</sup>

- The investigations also revealed that the best **economy of scale**'s plant capacity can be attained at a given place also using pig and cattle manure (*Table 10*).

**Table 10: Possibilities of biogas production in the 500 kW<sub>e</sub> plant size category**

Unit: 1000 m<sup>3</sup>

Settlements	Biogas potential		
	Cattle	Pig	Total
1	<b>1 822</b>	<b>125</b>	1 947
2	3 365	<b>231</b>	3 595
3	3 619	<b>1 141</b>	4 760
4	5 176	<b>556</b>	5 732
5	3 816	<b>489</b>	4 305
6	1 875	<b>119</b>	1 994
7	1 886	<b>991</b>	2 877
Total:	<b>21 559</b>	<b>3 652</b>	<b>25 211</b>

Source: own calculations

As *Table 10* shows, the biogas amount that is required to 500 kW electricity output cannot be achieved from pig slurry on any of the settlements. In case of the first settlement, this amount of biogas cannot be obtained even from either species' manure. Co-digesting cattle and pig manure, the desired plant capacity can be installed on each of these settlements. The plant that can be installed in this manner makes out 7.7% from the total biogas potential of these settlements. On the other places, involving pig farms increases the total gas production with 18%. Pig farms respond to 14.5% of the total gas production.

## 5. NEW SCIENTIFIC RESULTS

The regional biogas potential and its estimation method, as well as the enhancement of its utilization through logistics and technological development, were the subject of my research. The new scientific findings from the research are as follows.

1. As the first step, **coefficients** were **created** for cattle, pig, sheep, chicken and turkey species' specific production from manure and biogas, to estimate regional **biogas potential** for an area. Based on the settlements' livestock data, total biogas potential based on animal manure and its distribution among settlements were calculated in Hajdú-Bihar County.
2. A **method** was developed to calculate **plant capacities** and **to evaluate the logistics** of input material transport to biogas production centers, based on the **specific transport requirement** per installed plant capacity (tkm/kW<sub>el</sub>). In terms of input material transport to centers, the min. 300 kW<sub>el</sub> plant size category is to be considered out of the examined min. 100, 300 and 500 kW<sub>el</sub> categories at the given settlement structure and the input material quantities of the settlements in Hajdú-Bihar County.
3. **Energy-balanced transport distances** of biogas production input materials were calculated. The calculations has shown that while pig slurry with 4.5% dry matter content is not reasonable for road transport, ruminants' manure between neighboring farms and poultry manure between settlements may be reasonable transported.
4. Experiments of biogas production's enhancement have shown that different particle distributions of chopped input material do not influence biogas production significantly, if average **chaff lengths** do not differ significantly. Experiments have also disclosed the **gas production increase** caused by **digestion output**'s partial reuse, by **sweet sorghum** and by **maize silage**.
5. **Calculations** revealed that **co-digestion of** different farm divisions' **manure** increases the gas production by the same total amount of input materials. Calculations have also shown that the plant capacity required for the proper **economy of scale** can be provided also by co-utilization of different species' manure.

## 6. PRACTICAL UTILIZATION OF THE RESULTS

1. Coefficients and their calculation methods elaborated for the animal species considered in biogas production can be utilized in biogas plant's planning and in feasibility decisions.
2. Biogas potential estimated in Hajdú-Bihar county can help regional planning and shaping the grant programs aimed at biogas plant establishment. In terms of environment management and resource utilization, the 85% input and biogas potential utilization in the minimum size limit category represents a very good share. These plants with 100 kW<sub>el</sub> minimum capacity can provide some degree of profitability from energy production alone (Bai et al., 2007), although economic attractiveness could be achieved only with help of subsidization.
3. The 50% potential utilization and 6.7 MW<sub>el</sub> total output in case of the 500 kW<sub>el</sub> minimum capacity have a considerable importance in the energy supply of the area and in establishing a decentralized energy system.
4. With transport of input materials, plants defined at the 300 kW<sub>el</sub> minimum capacity level could approximate or surpass the 500 kW<sub>el</sub> size level. The transport is justified with the fact that input material transport is optimal in case of 300 kW<sub>el</sub> minimum capacity, based on specific transport requirement and the disclosed conditions of pig and cattle manure based biogas production in Hajdú-Bihar County.
5. Investigations of the circles with 5, 20 and 40 km radius has shown that almost one third of the biogas potential is available locally, compared to the wider circle, although the radius is 1/4 and the area is 1/16 of that of the wider circle. In the 5 km wide circle around Debrecen, 29% of the biogas potential is available, which equals to the replacement of 10.5 million tons of oil.
6. In the investigations of digestion output, organic material content of solid phase was 83.4% and dry matter content 25.5%, organic material content of liquid phase was 66.7% and dry matter content 2.15%. The reutilization of digestion output, which has a high share of digestible material, increases energy production and stabilizes the process.
7. Experiments has shown that gas production from the poultry slaughterhouse's effluents has not started because of low organic content. In my recommendation, materials that

are potentially suitable for biogas production but have practically no considerable organic matter content should be treated in an aerobic way after grease separation.

8. In the measurements of material composition, the Kjeldahl-method of total-N determination showed a tendency to exceed the same measurement values in the Dumas pyrolyzation method used in the automatic element analyzer. In order to increase comparability and convertibility, further research is advised, to define the strength of correlation between the results of the two methods and to enlighten the role of the factors influencing the correlation. This would allow C/N ratio calculation without costly equipment investments, which is beneficial in the occasional analysis of a small number of samples.
9. The comparison of the batch and continuous experiment methodology concluded that in some cases the latter could be more beneficial than the former. It has an importance that the number of containers required for the same amount of data differs in these methods. For 21 data, batch experiments require 21 container for the duration of the digestion (21 or 30 days), whereas continuous experiments require only one container to gain these data until the 21<sup>st</sup> day (in total until the 42<sup>nd</sup> day). Precondition for the use of the latter method is to ensure same input material quality during the experiments.

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