Research Article

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Use of local resources as co-substrates in a farm-scale biogas plant

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Abstract: Biogas production is an established technology that is suitable for small-scale decentralized solutions, for example, on dairy cattle farms where manure is formed all year round. Cattle slurry can be co-digested with other organic biomasses to boost the production of renewable energy. The aim of this study was to outline the suitability of locally available co-substrates that are characteristic to the northern rural area in Lapland, Finland. Twelve different co-substrates originating from agriculture, reindeer meat production, fisheries and food processing were studied for their chemical characteristics and biochemical methane potential (BMP) in laboratory tests. As a result, all the tested co-substrates had a higher BMP than the cattle slurry, which could be a useful boost for farm-scale energy production. The BMP was the highest for used vegetable oil (851 l/kg VS) followed by the rainbow trout by-products (728 l/kg VS). BMP was the lowest for spoiled grass silage (265 l/kg VS) and the rumen contents of reindeer (289 l/kg VS). All substrates had high concentrations of the main nutrients, and small fish especially were rich in phosphorus (7.4 g/kg) and nitrogen (24.2 g/kg). Nutrient rich co-substrates increase the fertilizer value of digestate and the nutrient self-sufficiency of the farm.

Keywords: Co-digestion; Anaerobic digestion; Cattle slurry; Methan; By-product

1 Introduction

Decentralized renewable energy production could be increased in sparsely populated areas as in Lapland, the northernmost region of Finland. The EU's target for the share of renewable energy in the European Community's gross final consumption of energy is to achieve 20% by 2020 (European Council 2009). For Finland the goal is as high as 38% and in 2016 the energy supply from renewable energy sources was 31.2% of the total primary energy supply (Pelkmans 2018). In transportation, the share of energy from renewable sources must be 10% in all EU community member countries (European Council 2009). In Finland, the possibility to produce energy from renewable sources using decentralized systems is currently underutilized. In Finnish Lapland, the renewable biomass potential in 2015 was 5.71 TWh/a where only 2.52 TWh/a was in use (Peura et al. 2017).

Biogas production through anaerobic digestion is an established technology producing nutrient-rich digestate and energy in the form of methane (CH_4) gas. Biogas technology, with its various reactor types and operational options, is highly suitable for small-scale decentralized solutions and for processing different organic materials. Livestock farms could have a biogas reactor as a natural part of their business because manure, which is formed in large quantities on animal farms, could be used as a substrate for the digestion. Secondly, the fertilizing value of organic streams could be upgraded; digestate has a uniform structure, better nitrogen usability and less odor nuisance (Hjorth et al. 2009; Holm-Nielsen et al. 2009).

The main form of agriculture in Finnish Lapland (Figure 1) is dairy cattle farming, followed by beef cattle, sheep and reindeer farming and grass production (Kuha et al. 2018). In 2018, there were around 10 000 dairy cows in Lapland (OSF 2019a). Cattle slurry is a good base substrate for the biogas formation process because the slurry is produced all year round and has fairly uniform properties. Cattle slurry also maintains a buffer capacity and mineral balance for microbes during digestion. However, it has a relatively low CH_4 yield as it is digested within the animal metabolism. The co-digestion of slurry with other biomasses rich in easily biodegradable organic matter has been shown to have many advantages, e.g., enhanced CH_4 production and improved farm income (Asam et al. 2011; Banks et al. 2011). Besides their high CH_4 production

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capacity, co-substrates with low amounts of inhibitory elements are desired to maintain successful and stable operation and gas production. Inhibitory effects can be caused by the high nitrogen content of the substrate mix, leading to ammonia inhibition and reduced CH_4 production (Chen et al. 2008; Rajagopal et al. 2013). Inhibitory effects can also be caused by the overly high loading of organic matter (Ferrer et al. 2010). Furthermore, for feasible biogas production, easily available substrates with reduced logistic costs or other expenses are often pursued. Large transportation distances for substrates reduces the advantage of the energetic balance (Gerin et al. 2008) and substrate costs, as well as income from gate fees for waste treatment, in some cases, are the most crucial parameter on the biogas supply (Hahn et al. 2014). Also the seasonality of certain co-substrates may challenge the stable operation of the microbial process. (Braun and Wellinger 2003; Mata-Alvarez et al. 2014)

When considering inclusion of co-substrates for a farm-scale biogas plant, local resources should be taken into consideration. In Lapland, by-products which are characteristic to the northern rural area are generated in reindeer meat production, in fish cultivation, in fish removals and in the food production industry. The number of reindeer in Lapland is around 200 000 (Decree 857/2014 of the Ministry of Agriculture and Forestry) of which about 80 000–90 000 are slaughtered yearly, producing 2 000 tonnes (t) of reindeer meat and slightly more slaughterhouse side streams. Inland water fish cultivation in Lapland produced 577 t of fish in 2017 (OSF 2019b). Managed fish removals are implemented to reduce the nutrient load in the water system by changing the structure of the fish population. In 2017 700 t of fish matter was caught in Finnish water systems for fish removals (OSF 2019c). The food industry covers the whole region and the volume of food waste in the manufacture of bakery products in Finland is estimated to be 21 000–25 000 t/a (Katajajuuri et al. 2014), but only 4% of Finnish bakeries are located in Lapland (Hyrylä 2017). Annually, fourteen tonnes of used vegetable oil is produced in the Finnish Lapland region (Biomass Atlas 2019). From agriculture, the total potato yields in the Finnish Lapland have varied from 1 500 to 3 400 t/a over the past years (OSF 2019d), of which approximately 16% ends up in a side stream (Hartikainen et al. 2014). Additionally, livestock farming produces organic streams that can be utilized in a biogas process, i.e., spoiled and excess silage, which consists of perennial forage grasses.

The aim of this study was to outline the suitability of local, Lappish materials to be used as co-substrates

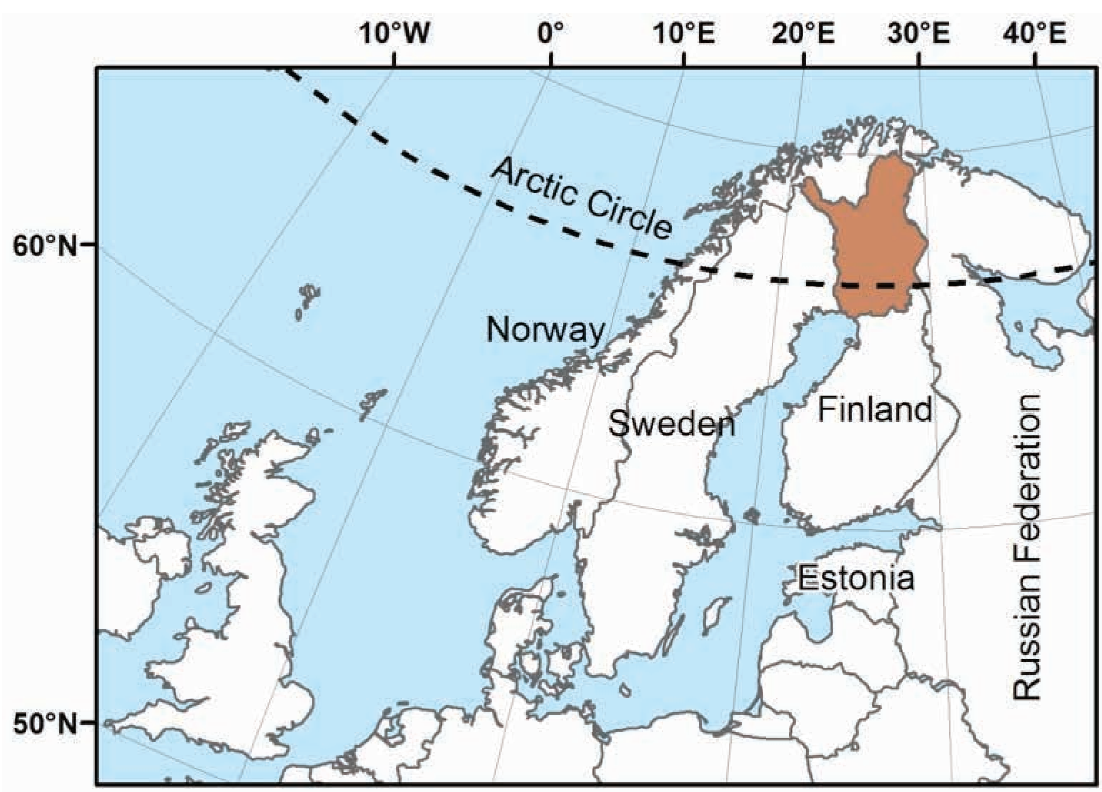

Figure 1: Location of Lapland, the northernmost region of Finland, is marked in brown

Table 1: Description of the substrates analyzed in this study and the seasonality of each material in Lapland

Biomass type	Sample name	Description/Material	Time of sample collection	Seasonality
Agricultural	Dairy cattle slurry	From an education dairy farm run by the Vocational College Lappia in Tervola, Finland. 57 lactating cows and 52 young animals	11/2018	All year round
	Grass silage	Timothy, tall fescue and red clover -mixture, 2nd harvest	10/2018	
	Spoiled grass silage	Grass silage rejected from feed use due to mold, warming etc.	10/2018	
Meat production by-products	Rumen content of reindeer calf	From slaughtering	02/2018	September-January
	Rumen content of adult reindeer	From slaughtering	02/2018	
	Intestines, reindeer calf	From slaughtering, intestines with their contents	02/2018	
	Intestines, adult reindeer	From slaughtering, intestines with their contents	02/2018	
Fish production by-products	Small fish	Catch from removal fishing (biomanipulation), inland water	05/2018	Spring-summer
	Rainbow trout by-product	Fileting side stream from cultivated rainbow trout	03/2018	All year round
Food processing side-streams	Second-class potatoes	Almond potatoes rejected for consumer use	10/2018	Autumn
	Bakery side stream	From bakery machinery cleaning, Jokioinen, Finland	11/2018	All year round
	Used vegetable oil	From the kitchen at the Vocational College Lappia, Tervola, Finland	10/2018	All year round

in farm-scale biogas plants. To evaluate the benefits of co-substrates both the CH_4 production potential and substrate characteristics were taken into account in the assessment. The CH_4 production capability was analyzed using a biochemical methane potential (BMP) test, which is an effective way to test several samples simultaneously. The substrate characterization included main nutrient and chemical composition analyses. Nutrient-rich substrates affect the overall nutrient balance on farms and affect the fertilizing value of the digestate.

2 Materials and Methods

2.1 Co-substrates and inoculum

The tested substrates consisted of 12 different biomasses, which are characteristic to the northern rural area of Finland. The substrates originated from agriculture, reindeer meat production, fisheries and food processing in Lapland, in Finland (Table 1).

All samples were frozen after collection excluding the potato sample, which was stored at +4°C due the short storage time prior to the analyses. Samples were thawed and pretreated prior to chemical analyses and BMP tests. Potatoes were manually chopped into 0.5 cm pieces and animal by-products were ground in a blender. Grass silage was manually cut to 2 cm lengths with scissors.

The inoculum came from a mesophilic, wet-type, farm-scale biogas reactor which treated manure from 120 dairy cows (Luke, Maaninka, Finland) and it was not acclimated for high lipid or N rich substrates. The inoculum was sieved to attain an even composition for the laboratory scale experiment. The inoculum total solids (TS) and volatile solids (VS) were 7.8% and 6.8%, respectively. As the studied samples were assumed to be used as co-substrates particularly in farm-scale biogas plants, it was reasonable to choose an inoculum from such a plant.

2.2 BMP test

BMP tests were performed using automated testing equipment (Bioprocess Control Ltd., Sweden) in 0.5-liter bottles and in mesophilic conditions (37°C). The volume of the inoculum was uniform (300 g) in all bottles, while the substrate volumes were calculated on the basis of the VS-ratios to the inoculum. The substrate/inoculum (S/I) VS-ratio was 0.75 with the exception of fish production by-products and used vegetable oil, where the VS-ratios were 0.5 and 0.25, respectively. BMP tests are usually recommended to conduct with VS-based S/I ratio less than 1, depending on the degradability of the sample and content of inhibitory components. For example, Holliger et al. (2016) advise using an S/I ratio of 0.25, or less, for easily degradable substrates. Distilled water was added to achieve a total liquid volume of 0.4 liters. Gas spaces of the bottles were flushed with N_2 gas to attain anaerobic conditions. Sodium bicarbonate was used as a buffer with a dosing of 3 g/l. The carbon dioxide of biogas was trapped in 3 M sodium hydroxide and the CH_4 volumes were measured by water displacement-based system. The contents of the bottles were mechanically mixed for one minute per hour (84 rpm).

Prior to the test start-up, it was ensured that the pH in the bottles was higher than 7.3 to prevent acidification during the test. The tests were done as triplicates and the average values of three bottles are presented with standard deviations. The production of CH_4 was calculated per fresh matter (FM), TS and VS of the substrate, where the CH_4 production of the inoculum was deducted from the result. Gas volumes were converted into the standard temperature and pressure conditions (pressure 101.325 kPa, temperature 0°C = 273.15 K).

2.3 Analyses

TS and VS were analyzed using the standard SFS 3008 method (Finnish Standards Association 1990). Ammonium nitrogen (NH_4-N) was determined according to McCullough (1967) and the total Kjeldahl nitrogen (TKN) was determined according to a standard method (AOAC 1990) using a Foss Kjeltec 2400 Analyzer Unit (Foss Tecator AB, Höganäs, Sweden), with Cu as a catalyst. The pH was measured using a VWR pH110 pH-analyzer (VWR International). The total sugars were determined using a phenol-sulfuric acid method where non-reducing sugars are converted to reducing sugars and sugar concentration is determined by colorimetric method (MTT 2011). For the analysis of the total phosphorus (Ptot) and total potassium (Ktot), samples were digested with HNO_3 (Luh Huang and Schulte 1985) and analyzed with an ICP-OES according to manufacturer's instructions. Crude fat was analyzed with a Soxcap-Soxtec-Analyser (AOAC 1990; Foss Tecator Appli-

Table 2: Characteristics and main nutrient concentrations of the studied substrates

Substrate	TS	VS	VS/TS	NH_4-N	TKN	Ptot	Ktot
	%	%	%	g/kg	**g/kg**	**g/kg**	**g/kg**
Dairy cattle slurry	7.8	6.8	87.8	1.1	2.8	0.4	2.0
Grass silage	31.2	29.1	93.1	0.5	6.5	0.7	5.0
Spoiled grass silage	27.7	24.4	88.0	0.6	8.4	1.0	7.5
Rumen content of reindeer calves	12.2	10.7	87.8	N/A	N/A	N/A	N/A
Rumen content of adult reindeer	10.6	9.2	86.7	N/A	N/A	N/A	N/A
Intestines, reindeer calves	20.2	18.9	93.3	0.7	16.8	1.8	2.1
Intestines, adult reindeer	32.2	31.1	96.5	0.6	12.5	1.5	1.7
Small fish	21.3	17.1	80.4	0.6	24.2	7.4	2.8
Rainbow trout by-product	71.2	70.8	99.3	0.1	8.1	1.3	1.2
Potatoes	26.6	24.5	91.9	1.4	3.5	0.5	5.5
Bakery side stream	73.7	72.6	98.5	0.0	14.4	1.1	1.5
Used vegetable oil	100.0	100.0	100.0	N/A	N/A	N/A	N/A

TS, total solids; VS, volatile solids; NH_4-N, ammonium nitrogen; TKN, total Kjeldahl nitrogen; Ptot, total phosphorus; Ktot, total Potassium; N/A, not available.

Table 3: Chemical composition of substrates (g/kg TS) and the sum of total sugars, crude fat, protein and ash (% TS basis)

Substrate	Total sugars	Crude fat	Protein	Ash	Components in total
	g/kg TS	g/kg TS	g/kg TS	g/kg TS	% TS
Dairy cattle slurry	235.7	40.6	129.8	122.0	53
Grass silage	269.7	37.3	117.6	68.6	49
Spoiled grass silage	272.2	34.9	172.1	119.9	60
Rumen content of reindeer calves	N/A	N/A	N/A	122.2	N/A
Rumen content of adult reindeer	N/A	N/A	N/A	133.4	N/A
Intestines, reindeer calves	47.6	277.9	484.9	67.5	88
Intestines, adult reindeer	46.0	514.0	226.9	35.0	82
Small fish	6.8	77.3	683.1	196.2	96
Rainbow trout by-product	3.9	456.0	70.2	6.7	54
Potatoes	690.7	1.7	51.4	81.3	83
Bakery side stream	638.7	83.5	122.9	15.1	86
Used vegetable oil	N/A	819.9	N/A	0.0	N/A

TS, total solids; N/A, not available.

Table 4: The BMP of the tested co-substrates.

	CH_4 (l/kg FM)		CH_4 (l/kg TS)		CH_4 (l/kg VS)	
	30d	50d	30d	50d	30d	50d
Dairy cattle slurry[1]	12 ± 0.1	13 ± 0.3	156 ± 2	170 ± 3	178 ± 2	193 ± 4
Grass silage	89 ± 2.5	92 ± 2.3	284 ± 8	294 ± 7	305 ± 8	316 ± 8
Spoiled grass silage	62 ± 1.7	65 ± 1.6	224 ± 6	233 ± 6	255 ± 7	265 ± 6
Rumen content of reindeer calves	30 ± 0.7	33 ± 1.3	246 ± 5	267 ± 11	280 ± 6	305 ± 13
Rumen content of adult reindeer	25 ± 1.1	26 ± 1.2	234 ± 10	250 ± 11	270 ± 11	289 ± 13
Intestines, reindeer calves	83 ± 0.8	86 ± 0.6	410 ± 4	414 ± 3	439 ± 4	454 ± 3
Intestines, adult reindeer	212 ± 2.0	214 ± 2.7	660 ± 6	664 ± 8	684 ± 6	689 ± 9
Small fish	62 ± 1.6	64 ± 2.5	292 ± 8	299 ± 12	363 ± 9	372 ± 15
Rainbow trout by-product	480 ± 59.9	515 ± 62.1	674 ± 84	723 ± 87	678 ± 85	728 ± 88
Potatoes	84 ± 1.1	86 ± 1.9	316 ± 4	324 ± 7	344 ± 5	353 ± 8
Bakery side stream	288 ± 1.8	296 ± 5.0	390 ± 2	402 ± 7	396 ± 2	408 ± 7
Used vegetable oil	660 ± 15.8	851 ± 7.4	660 ± 16	851 ± 7	660 ± 16	851 ± 7

[1]N = 2
FM, fresh matter; TS, total solids; VS, volatile solids
Values are average ± standard error of triplicate samples

cation Note AN 390). The protein content was calculated by multiplying the organic nitrogen (TKN - NH_4-N) by 6.25.

3 Results

3.1 Substrate characteristics

The proportion of solids, both total and volatile, and basic nutrients N, P and K were analyzed to evaluate the suitability of substrates for anaerobic digestion. The substrates

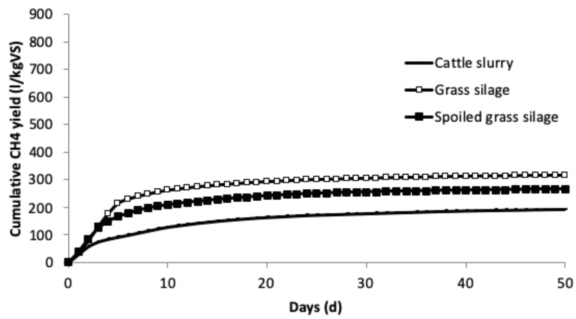

Figure 2: 50-day cumulative CH_4-production curves of agricultural materials

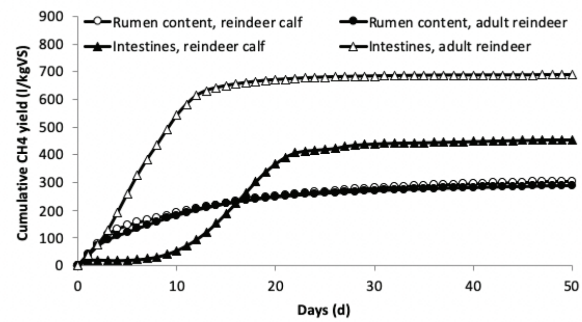

Figure 3: 50-day cumulative CH4-production curves of reindeer meat production by- fig3

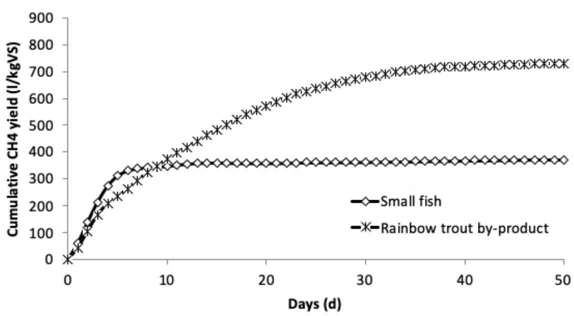

Figure 4: 50-day cumulative CH4-production curves of fish production by-products

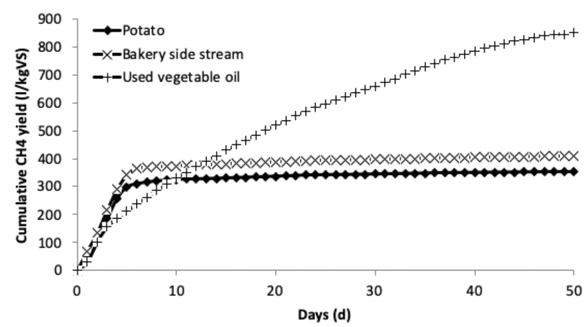

Figure 5: 50-day cumulative CH4-production curves of food processing side streams

varied highly in their chemical composition, for example VS ranged from 6.8 to 100.0% (Table 2). Some of the substrates had high concentrations of nutrients; the P of small fish was 7.4 g/kg, while the TKN of reindeer calf intestines was 16.8 g/kg and for small fish it was 24.2 g/kg.

Three main compositional groups, total sugars, proteins and crude fat, were determined, where the substrates varied depending on the sample origin (Table 3). The side streams for potatoes and bakery products had the highest total sugar proportion, with 691 and 639 g/kg TS, respectively. Small fish were rich in proteins (683 g/kg TS). Reindeer intestines were rich both in crude fat and proteins; the crude fat content was 514 and 278 g/kg TS and the protein was 227 and 485 g/kg TS in adult and calf intestines, respectively. The substrates, which had most of their TS-based weight as crude fat, were used vegetable oil (820 g/kg TS), the intestines of adult reindeer (514 g/kg TS) and rainbow trout by-products (456 g/kg TS).

3.2 Methane potential

The BMP-tests lasted 50 days until the gas production had reached a plateau, i.e., the daily CH_4 production in the samples was less than 0.5% of the cumulative production or had ceased (Figures 2–5). The CH_4 production rates varied among substrates and both 30 d and 50 d cumulative CH_4 production values are shown in Table 4. The 50-day cumulative BMP of dairy cattle slurry was 193 l/kg VS and it was the lowest for tested materials. The BMP was the highest for used vegetable oil, at 851 l/kg VS (Table 4). The CH_4 production rate for used vegetable oil was slow and cumulative gas production slowly increased until day 50 (Figure 5).

The BMP of grass silage was 316 l/kg VS and spoiled silage had a BMP of 265 l/kg VS (Figure 2). For the rumen contents of both adults and calves, the CH_4 potential values were 289 and 305 l/kg VS, respectively (Figure 3). The intestines of reindeer calves and adult reindeer produced CH_4 454 and 689 l/kg VS, respectively. There was a lag phase in the CH_4 production of reindeer calf intestines until day 10. The BMP of small fish from fish removal was 372 l/kg VS, and for rainbow trout by-products it was 728 l/

Table 5: Dairy cattle slurry and grass silage methane potential in previous studies

Material	CH_4 yield (l/kg VS)	Reference
Dairy cattle slurry	196–227	Luostarinen 2013
	100–250	Lehtomäki et al. 2007
	243	Labatut et al. 2011
	230	Miranda et al. 2016
Grass silage	207–263	McEniry and O'Kiely 2013
	253–394	Seppälä et al. 2009
	red clover 291, grass 344	Seppälä et al. 2013

VS, volatile solids

kg VS (Figure 4). Potato and bakery side streams had BMP values of 353 and 408 l/kg VS, respectively.

4 Discussion

In this study, the possibilities for local, Lappish, co-substrates for farm biogas plants were evaluated. The evaluation was accomplished by determining the chemical characteristics and CH_4 production potential of materials in laboratory tests. Both the CH_4 yield and main nutrient concentrations of the co-substrates affect the applicability, i.e., the digester stability, energy production and digestate fertilizer value for farm-scale use. In addition, seasonality and logistics affect the usability of co-substrates on farms.

4.1 Agricultural substrates

Substrates produced in a dairy cattle farm, the slurry and the grass silage as well as spoiled grass silage, were assessed in this study. Animal slurries are widely analyzed and studied biomasses, but they are known to vary from farm to farm due to differing manure management practices and animal feeding. In the present study, the slurry had low concentrations of the main nutrients (N 2.7 g/kg and P 0,4 g/kg) and also the TS (7.8%) and VS (6.8%) values were lower than the average values for Finnish dairy cattle slurry, in the Finnish Normative Manure System (TS 9.7%, VS 7.5%, Ntot 5.3 g/kg and Ptot 1.0 g/kg, Luostarinen et al. 2017). The BMP of cattle slurry in the present test (193 l/kg VS) was slightly lower compared to previously published data on the CH_4 yields of dairy cattle slurry (Table 5). A relatively low BMP can be related to the slurry composition, as sugars with low CH_4 production potential (Angelidaki and Sanders 2004) were the dominant organic compounds (235.7 g/kg TS) in the slurry. Cattle slurry was considered as the primary substrate in the farm biogas plant as the material is possible to move by pumping (TS 7.8%) and slurry is formed all year round. From the base of present analyses and literature, with moderate organic loading rates slurry has a low risk for microbial inhibition as the VS and TKN concentrations are low, which reduces the risk of NH_3 inhibition and organic overloading (Ferrer et al. 2010; Rajagopal et al. 2013).

Grass silage had N concentration of 6.5 g/kg and K of 5.0 g/kg. The BMP of grass silage (316 l/kg VS) was in the range of previous experiments (207–394 l/kg VS, Table 5), and the FM-based BMP of grass silage was 7 times higher compared to cattle slurry. In the present study, silage and spoiled silage had similar ratios of sugars, fats and proteins (per TS), but higher VS concentration than slurry, which led to a higher BMP per FM (silage 92 l/kg and spoiled silage 65 l/kg vs. 13 l/kg in slurry). Spoiled grass silage had lost some of its organic matter (16%) due to microbial activity, which led to a 16% reduced BMP (VS-based) and had more concentrated N, P and K contents than regular grass silage. Unexpectedly, also the sugar content of spoiled silage was higher than for regular silage. This could be because of differences in the fresh grass quality, different harvesting times and weather conditions, different location on the field etc. One explanation could also be a failure in the lactic acid preservation, which would affect the conversion of sugars into lactic acid. In the present study, at the beginning of the BMP test, there were no differences in the CH_4 production rates between the regular and spoiled silage, indicating that the microbes of the inoculum were not inhibited due to the use of spoiled silage. Altogether, the utilization of the farm's own spoiled grass silage in the biogas production process is a reasonable option, as its generation (t/a) is likely to be relatively low, the CH_4 potential is higher than for the slurry, the logistic costs are low, and nutrients are recovered for the digestate.

4.2 Reindeer meat production by-products

As a biomass, the characteristics of the rumen content were between grass silage and manure, which was also reflected in its BMP value. The FM-based CH_4 potential of the rumen contents was low, at 33 and 26 l/kg FM, as the most easily degradable material had already been digested by the animal and the rumen contents had relatively low TS contents (TS 12.2% and 10.5%, calf and adult respectively). However, the BMP of the rumen contents (289 and 305 l/kg VS) exceeds the BMP of cattle slurry (193 l/kg VS). The rumen contents of adults and calves had similar chemical compositions, VS/TS ratios, BMP, as well as the shapes of the gas production curves, which seems natural as the characteristics are defined by what forage the animals have eaten. Logistically this material is easily available in Lapland and thus it is a good potential co-substrate for farm-scale digestion.

Intestines had high organic N concentrations following a high share of proteins (calves 484.9 g/kg TS and adults 226.9 g/kg TS). The intestines also contained P and K, which increase the fertilizing value of the digestate (P 1.80 and 1.45 g/kg; K 2.14 and 1.69 g/kg, for calves and adults respectively). There was a clear variation in the composition of the adult and calf intestines; calf intestines were rich in protein but the prevailing component in adult intestines was fat (514.0 g/kg TS) since the older animals had gained fat reservoirs. Lipids are known to lead to high CH_4 yields (Alves et al. 2009) and the intestines of the adult reindeer had a very high BMP (689 l/kg VS). Our results from reindeer slaughtering side streams were in line with materials from other species, where animal by-products are considered to have a high BMP. Jensen et al. (2014) determined the BMP of cattle paunch processing waste to be around 300–600 l/kg VS and for cattle offal processing waste to be around 800–1 000 l/kg VS. Ware and Power (2016) reported specific CH_4 yields for soft offal (intestinal residues, fat and meat trimmings and some blood) to be around 650 l/kg VS.

In this present study, the only sample with a lag phase in CH_4 production was reindeer calves' intestines. The inhibition was most likely to be due to the high N (16.8 g/kg) and protein concentration (484.9 g/kg TS) combined with reasonably high crude fat concentration (277.9 g/kg TS), which together caused a cumulative inhibitory effect. To avoid the risk of inhibition in farm biogas plants, co-substrates with high N and protein contents should be mixed with the slurry and fed in small proportions. However, the co-substrates from reindeer slaughtering are very seasonal substrates, which are generated between September and January. This challenges the farms to monitor the digestion process during the time when these materials are fed into the reactor, to detect the signs of inhibition and to dilute the substrate mix and to prolong the retention time, if needed.

4.3 Fish production by-products

Small fish biomass could have potential also for food or feed as the material was rich in nutrients and the composition was predominated by proteins (683.1 g/kg TS). Small fish had low VS/TS ratio (80%) but the BMP was 372 l/kg VS, which makes it an interesting co-substrate for biogas production as well. Although small fish had almost double the BMP of the slurry, the abundance of nutrients may have an even more important role when especially considering the catch of removal fish as a co-substrate on a farm scale plant. Overall, the utilization of small fish for energy and nutrients is justified only if a more valuable use (e.g. as food or feed) is not feasible. In contrast to the small fish, rainbow trout by-products were rich in fat. They had modest concentrations of the main nutrients (N, P and K) and a high VS/TS ratio (99%). The CH_4 production rate of rainbow trout by-products was slow and the difference between 30d and 50d cumulative CH_4 yields came to 50 l/kg VS (50 d production 728 l/kg VS in total). The BMP of rainbow trout by-products was exceedingly high, which makes the material suitable for energy production enhancement. In previous studies, both lower (260 and 350 l/kg VS, Eiroa et al. 2012) and higher (742 and 828 l/kg VS, Nges et al. 2012) BMP values have been reported for fish by-products. The variation in the BMP of fish-based material is reasonable as the studied materials vary from whole fishes to side-streams and the fish species differ in each study. Fish by-products are recognized as promising co-substrates for co-digestion, and synergistic effects in CH_4 production yields have even been observed (Vivekanand et al. 2018).

4.4 Food production and processing industry side streams

There were two types of food processing industry side streams in our study, sugar rich materials (potatoes and bakery side stream) and lipid rich materials (used vegetable oil). Sugar rich materials, potatoes and bakery side streams, produced CH_4 quickly; 85% of the potatoes' and 83% of bakery side streams' 50 day cumulative CH_4 production was produced by day 5. The total VS-based CH_4 yields were on the same level for the potatoes and bakery side streams, but per the FM bakery side stream had distinctly higher CH_4 potential (288 l/kg FM) than the potatoes (84 l/kg FM). The potatoes were rich in K (5.51 g/kg) which may be an advantage is certain areas for digestate nutrient balancing. The bakery side stream had rather high TKN concentrations, which can upgrade the digestate N fertilization quality due to mineralization in the biogas process. Bakery side streams are formed all year round, which helps the design of the substrate mixture on farms.

The used vegetable oil lacked inorganic matter; both the TS and VS were determined to be 100.0%. The material also had a high proportion of crude fat, 819.9 g/kg TS. The 50d BMP was extremely high at 851 l/kg VS, but the CH_4 production rate was low; used vegetable oil produced CH_4 191 l/kg VS between days 30 and 50. The present CH_4 yield is high compared to CH_4 potential in previous studies, which were 648 l/kg VS (Labatut et al. 2011) and 811 l/kg VS (30d, Li et al. 2013). The VS-based CH_4 potential of used vegetable oil was still below the theoretical CH_4 yield derived from lipids, which is 1014 l/kg VS (Angelidaki and Sanders 2004). Yoon et al. (2014) tested different S/I ratios (0.1; 0.5; 1.0 and 1.5) for slaughterhouse waste and observed that accomplishing a BMP with a low S/I VS-ratio may exceed the theoretical CH_4 yields. The reason for this may be the increased degradation of the inoculum's organic material. In the present study, the VS-based S/I-ratio was 0.25, which could explain the unusually high BMP. Even so, used vegetable oil proved to be well suited for CH_4 production enhancement when accepting the low production rate.

5 Conclusion

In this study, possible co-substrates which are characteristically found in Finnish Lapland were scanned and substrate-specific BMP-trials were planned for them. Co-substrates had higher BMP when calculated per mass of VS added and especially per mass of FM added, when compared to the cattle slurry, which is usually the primary feed for farm-scale biogas plants. Compared to cattle slurry, the co-substrates also had higher concentrations of nitrogen, phosphorus and potassium. Especially reindeer intestines, fish materials and used vegetable oil were considered high potential co-substrates for farm-scale use. With the increased CH_4 production potential, co-substrates increase the total energy production and energy balance of the biogas plant. Nutrient rich co-substrates also increase the fertilizer value of digestate and the nutrient self-sufficiency within the farm. However, the selection of co-substrates for farm-scale use still needs research on the generation and volumes of the co-substrates. Knowledge on more precise schedules and transportation distances for each material is needed to assess the potential and adequacy of these materials in Finnish Lapland. The usability of the materials is also dependent on the legislation, as regulations regarding the treatment of animal-by products and the marketing of fertilizing products may constrain the use of some substrates. Furthermore, continuously fed co-digestion experiments are needed to study and simulate the performance of a farm-scale biogas process with selected co-substrates.

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Abbreviations:

BMP	biochemical methane potential
CH_4	methane
FM	fresh matter
K, Ktot	potassium, total potassium
NH_4-N	ammonium nitrogen
P, Ptot	phosphorus, total phosphorus
S/I ratio	substrate/inoculum ratio
TKN	total Kjeldahl nitrogen
TS	total solids
VS	volatile solids

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