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Biogas and nutrients from blackwater, lawn cuttings and grease trap residues—experiments for Hamburg's Jenfelder Au district

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Abstract

Background: The project KREIS focuses on a new combination of renewable energy provision with innovative wastewater treatment, called the "Hamburg Water Cycle®" (HWC) which will be applied in Hamburg's neighbourhood Jenfelder Au. HWC includes a separate collection of rainwater, greywater and blackwater. Vacuum toilets are used to concentrate the blackwater. Biogas will be produced from the blackwater in an anaerobic digestion process together with co-substrates. The blackwater will be transported to the anaerobic pre-treatment facility via a vacuum system. Construction of water systems started in 2013, and commercialization of houses is planned to be finished in 2018.

Methods: The article focuses on research work accompanying the demonstration project. Blackwater and the co-substrates, lawn cuttings and grease trap residues from restaurants and canteens will be considered as bioresources, not as residues. To evaluate the utilization efficiency, three investigation steps were carried out: inventory to determine substrate quantities and qualities, anaerobic digestion to determine biogas production, and evaluation of digestate utilization options.

Results: The daily amount of blackwater in Jenfelder Au is calculated to be about 12 m^3 (dry matter (DM) 0.6 %; organic dry matter (oDM) 65 % DM; nitrogen (N) 28 % DM; phosphorus (P) 2.7 %). To increase the biogas production, co-substrates will be added. Grease trap residues (averages: DM 2 %; oDM 85 % DM; N 2.5 % DM; P 0.6 % DM) and lawn cuttings (averages: DM 30 %; oDM 80 % DM; N 2.6 % DM; P 0.3 % DM) were selected. The inventory study showed a sufficient potential of lawn cuttings within a 5-km radius. The lawn cuttings must be pre-treated for wet fermentation. Two options were investigated: press juice preparation and wet shredding of the fresh and silage lawn. Batch test was used to determine the biogas potential of the substrates with the following average results: blackwater 500 nl/kg oDM, grease trap residues 1000 nl/kg oDM, lawn cuttings 400 nl/kg oDM and lawn juice 500 nl/kg oDM.

The effects of the composition of the substrate mixture and of the retention time in the reactor on biogas quantity and process stability were studied in semi-continuous operating reactors. Experiments showed that a stable process with an average biogas production of 800 nl/kg oDM is, e.g., possible with a mixture of blackwater, press juice of lawn cuttings and grease trap residues in a fresh mass ratio of 1:1:1.

Furthermore, the N and P contents in digestates were determined. These nutrients are valuable for fertilization.

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Conclusion: It has been shown that blackwater combined with local waste streams can be used for biogas generation and that it has a potential as fertilizer. The experiments have shown that co-digestion has a positive effect on biogas yields and lawn cuttings are suitable as co-substrate. Lawn cuttings can be applied as lawn juice or lawn suspension. Ways of an integral utilization and the potential of nutrient recovery are shown in this work.

Keywords: Blackwater; Grease trap residues; Lawn cuttings; Lawn juice; Anaerobic digestion; Biogas; Bioresources; Inventory; Fertilizer; Nutrient recovery; Digestate utilization; Hamburg; Jenfelder Au

Background

Overview on the Jenfelder Au project

Fossil raw materials for energy production are becoming scarcer. The natural resources for phosphorus (P) fertilizers are declining. The production of the mineral nitrogen (N) fertilizer by the Haber-Bosch process needs a lot of energy. The demands of fertilizers increase. Human toilet waste (blackwater = urine + faeces + toilet paper + flushing water) contains energy and a lot of nutrients. In Hamburg, it is actually treated together with rainwater and greywater for N elimination in a centralized way using nitrification and denitrification processes. Anaerobic treatment, centrifugation, drying and incineration are further cost-intensive follow-up steps for sewage sludge treatment. The whole actual cascade is very energy intensive and the nutrients are lost. Similarly, in urban areas, also other residues are actually often inefficiently used or disposed. Besides blackwater, organic waste from households, gardens, public areas, industry and commerce can be valuable secondary, tertiary or quaternary bioresources for energy and nutrient recovery.

The aim of this paper is it to show that it is possible to produce energy from wastewater and to recover nutrients. These works are incorporated in the KREIS project. The project focuses on the combination of systems for innovative wastewater management, renewable energy generation and waste utilization. The basic system is the “Hamburg Water Cycle®” (HWC) developed by Hamburg Wasser. HWC contains a separate collection of rainwater, greywater and blackwater. Vacuum toilets are used to concentrate blackwater; via a vacuum system, it is transported to a decentralized anaerobic treatment facility where biogas will be produced from blackwater in an anaerobic digestion process together with co-substrates [20].

In the *Jenfelder Au neighbourhood*, a new residential area for about 2000 people is under development. Vacuum toilets with only 1 l water per flush are used to concentrate the blackwater. A daily blackwater generation of 12 m^3 has been calculated. Targets given by the operating company for anaerobic digestion include 900 m^3 fermenter volume and 25 days substrate retention time. Under these conditions, blackwater will fill a third of the reactor and biogas production of blackwater alone would be low. This is the reason why regional co-substrates with a suitable biogas potential are required. For co-substrates, waste streams should be used which have no useful application so far. Blackwater and co-substrates contain N and P, which are valuable nutrients for fertilization purposes, and therefore provide a further utilization option [20].

The Jenfelder Au project is the first project in that dimension. It is realized by the municipal wastewater disposer. Earlier projects using blackwater as biogas substrate were realized in a much smaller scale and mostly carried out by the habitants themselves, e.g. in China and India, family-sized biogas plants exist, where blackwater is treated together with animal and kitchen waste to produce biogas for cooking [37]. One example for a housing estate is in Northern Germany in Lübeck called *Flintenbreite*, where blackwater from about 400 people is collected via vacuum toilets. Investigations of the biogas yield were done by Wendland [37] and found a specific methane generation rate of 14 l CH_4/cap/day. Also in *Sneek*, a Dutch city, an anaerobic blackwater treatment was realized for 32 houses [39].

In order to support and achieve the sustainable implementation of this new wastewater, waste and energy management system in Hamburg’s Jenfelder Au neighbourhood with a high bioresource utilization efficiency, an accompanied research programme was carried out and some results are presented in this paper.

Organic waste as a bioresource

“Bioresources are non-fossil biogenic resources which can be used by humans for multiple purposes: to produce food, substantial products and/or energy carriers.” That definition of bioresources is given by [17]. Körner also classifies bioresources into primary, secondary, tertiary and quaternary bioresources. The preferable utilization steps depend on the type of bioresources. Multichain and cascade utilization are important aspects for ecological sustainability.

Primary bioresources

Primary bioresources are generated for a specific application-oriented purpose in forestry, agriculture or aquaculture. The most important primary bioresources are not only harvested plants, but also slaughtered animals. The minor part is given by cultivated algae, microorganisms or fungi. Plants which are not specifically cultivated with the aim of food, material or energy production cannot be classified as primary bioresources. In the Jenfelder Au project, primary bioresources shall not be used.

Secondary bioresources

Secondary bioresources are residues that occur during processing of primary bioresources or are generated within landscaping activities. Regarding properties, they have to be available in large quantities and define qualities with low impurity contents. For the Jenfelder Au project, commercial processing residues from nearby industries as well as cuttings from large green areas such as parks, lawns or sport places may be of interest but were not considered in this publication.

Tertiary bioresources

Tertiary bioresources are residues which occur in rather small amounts and/or in undefined fractions. They have a lower value than secondary bioresources. Tertiary bioresources may be generated along the chain in primary bioresource production, harvesting, post-harvesting and storage activities, and during industrial processing, packaging and distribution up to the retail sector. Furthermore, they may occur at consumer level in small commerces (e.g. restaurants, canteens), in private kitchens at household level or in private gardens. In the Jenfelder Au project, kitchen waste was of interest but is not considered in this paper. Considered were lawn cuttings from private gardens, public areas, and green waste collection by landscaping businesses.

Quaternary bioresources

Quaternary bioresources occur after a product was used by the consumer. It can be distinguished between the time frames of their generation into short, mid and long term after start of product use. Short-term-after-use quaternary bioresources are generated in all cases of food consumption in the form of faeces and urine. Such bioresources are generated with short delay after food consumption at a time scale of hours. The blackwater used in Jenfelder Au belongs to that group. Furthermore, the greasy water belongs to that group, too. Fats are used for cooking and accumulate after cooking in grease traps in restaurants and canteens.

Aim of the work

The potential of blackwater, greasy water and lawn cuttings as substrates for energy and nutrient recovery within the integrated Jenfelder Au system shall be evaluated. The objective is the utilization of actually unused or inefficiently used tertiary and quaternary bioresources for the anaerobic digestion with blackwater as the main substrate and the others as the co-substrate. Suitable substrate mixtures should guarantee a stable biogas process and high biogas production. Also, options for digestate treatment to recover nutrients and transform them into mineral fertilizers are part of the investigations. The digestate should not be disposed into the wastewater system, since all the advantages of the previous step would be lost. The digestate would run through the very energy-intensive and nutrient-destroying wastewater treatment complex again.

Methods

Origin of substrates

Blackwater (BW). For experiments, concentrated blackwater was taken from vacuum toilets in the Flintenbreite settlement in Lübeck, Germany. The installed vacuum toilets use 0.7 to 1.0 l of water per flush with a suction pressure of 0.3 to 0.5 bar for the vacuum pumps and deliver the BW into a vacuum tank.

Greasy water (grease trap residue, GW). Grease traps are used, for example, in food processing companies, restaurants and canteens. They are installed for the pretreatment of wastewater containing high amounts of fat before the wastewater is disposed into the sewer. The grease traps should be emptied by regulation once a month (DIN 4040-100). In practice, however, the intervals are often longer. This results in the fact that a major part of the greasy waters disappears in the sewerage. GW used in this experiment was taken from the wastewater treatment plant *Köhlbrandhöft* in Hamburg, Germany. To this facility, Hamburg's GW is actually delivered and processed by anaerobic treatment.

Lawn cuttings (LC). Lawn cuttings for experiments were collected from different places. The main part originated from public areas and was cut by landscapers and delivered to the private waste company BUHCK. The specific original harvesting areas are not known as well as the harvesting type and harvesting history. The sampling was carried out at one of the BUHCK collection places. Samples were taken in May, June, July, September and October and used for substrate characterization. Samples for batch test were collected in June and September. LC for semi-continuous experiments were taken in September and October. Furthermore, lawn cuttings from private gardens in *Hamburg Niendorf* and *Bergedorf* were investigated. The samples were taken from April to July and used for substrate characteristics.

The average values of all samples are given in Table 5. For substrate characterization, the substrates were stored frozen until use. Additional samples were stored in vacuum bags before biogas potential was determined.

Methods for substrate analyses

The analysis of the substrate was carried out at the Institute of Wastewater Management and Water Protection

Table 1 Methods for substrate analysis

Parameter		Guideline/equipment
Dry matter content	DM in % FM	DIN EN 12880 [8]
Organic dry matter content	oDM in % DM	DIN EN 12879 [9]
Chemical oxygen demand	COD in mg/l	Cuvette test by Hach Lange, Germany
Total organic carbon	TOC in mg/l	TOC/TN analyser multi N/C 3000 by Analytika Jena, Germany
Total nitrogen	TN in mg/l	TOC/TN analyser multi N/C 3000 by Analytika Jena, Germany
Ammoniacal nitrogen	NH_4^+/NH_3-N in mg/l	Destillation unit K350 by Büchi, Germany
Total phosphorus	TP in mg/l	Cuvette test by Hach Lange, Germany
pH value	pH	pH meter, model 323 by WTW, Germany
Ratio volatile fatty acids to total inorganic carbonate	FOS/TAC	Automatized titrator model FOS/TAC 2000 by Pronova, Germany

FM fresh matter

of Hamburg University of Technology (TUHH). The used methods are summarized in Table 1.

Methods for substrate pre-treatment and anaerobic digestion

Table 2 shows an overview of the equipments used for pre-treatment of lawn cuttings and the experimental set-up to determine digestibility of substrates and substrate mixtures. For use of LC in wet fermentation, it has to be pumpable and mixable with the liquid substrates. For that reason, a pre-treatment is necessary. For biogas test, the substrate was frozen until use to get values of the fresh material. LC were stored in vacuum bags in the cooling chamber at 8 °C for 3 to 6 month before use in anaerobic fermentation batch tests. The lawn juice (LJ) was prepared from the same fresh or stored LC. LJ preparation for the fresh LC used for batch tests was done by a screw press, and for stored material, it was done with a hydraulic laboratory press. The LJ preparation for semi-continuous experiments was carried out for both types in the same way using a slab press.

Collected BW and GW were homogenized in 60-l barrels and distributed in 10-l canisters which were then stored in the refrigerator until the moment they were used for loading the reactors. Every time a new canister was utilized, a sample of it was analysed.

The batch tests were performed to determine the biogas potential of the pure substrates and mixtures of the substrates. The semi-continuous experiments were carried out for determination of biogas amount of different substrate mixtures according to the retention time in the reactor. In four bench-scale continuous stirred tank reactors (CSTR), various mixtures of substrates were investigated.

Calculation of digestate characterization

Scenarios for substrate mixtures in Jenfelder Au were selected, and the composition of the digestate was calculated with an excel model based on the substrate characteristics (Table 8). The biogas yield was calculated via addition of the biogas yield of the single substrates depending on the amount of input.

$$\dot{V}_{\mathrm{biogas}} = \dot{m}_{\mathrm{feed}} \sum \left(V_{\mathrm{S}i} * x_i * w_{\mathrm{DM}i} * w_{\mathrm{oDM}i} \right)$$

$$\dot{m}_{\mathrm{biogas}} = \dot{V}_{\mathrm{biogas}} * \rho_{\mathrm{biogas}}$$

where

$\dot{V}_{\mathrm{biogas}}$ biogas yield in $\mathrm{m}^3_{\mathrm{biogas}}$/day

$\dot{m}_{\mathrm{feed}}$ mass of feed in t_{FM}/day

$V_{\mathrm{S}i}$ specific biogas production of substrate in nl/kg organic dry matter (oDM)

Table 2 Methods for substrate pre-treatment and anaerobic digestion

	Guideline/equipment
Technique for substrate pre-treatment	
Maceration of lawn cuttings	Knife mill GRINDOMIX GM 300 by Retsch, Germany
Preparation of lawn juice	Screw press-type CV by Anhydro, Germany[a], slab press LA 180 by Bürkle, Germany[b]
Storage of lawn cuttings	Vacuum bags and store in a cooling chamber (8 °C) until utilization
Technique for anaerobic digestion	
Batch tests for biogas potential	VDI 4630 [35]
Semi-continuously fed biogas experiments	Continuous stirred tank reactors (CSTR) with a volume of 10 l, mesophilic conditions about 37 °C ("Semi-continuous biogas production")

[a] Used at the Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB), Germany

[b] Used at the Thünen Institute Hamburg-Bergedorf, Germany

x_i mass ratio of substrate i in the feed

$w_{\mathrm{DM}i}$ dry matter content of the substrate i in kg dry matter (DM)/kg fresh matter (FM)

$w_{\mathrm{oDM}i}$ dry organic matter content of substrate i in kg oDM/kg DM

$\dot{m}_{\mathrm{biogas}}$ mass of biogas in t/day

ρ_{biogas} biogas density depending on methane quantity in t/m^3: $\rho_{\mathrm{biogas}} = -0.013\,x_{\mathrm{CH}_4} + 1.9933$ [30]

x_{CH_4} content of CH_4 in %

For the estimation of digestate composition, it is assumed that biogas is produced from 85 % organic compounds and 15 % water [30]. The mass of nitrogen and phosphorous is not changing and remains in the digestate. The results are given in Fig. 5 and Table 12.

Based on a literature research [16], a preferred way of digestate utilization was selected and is given in Fig. 6. Separation efficiency of solid–liquid separation is estimated by literature data given by Fuchs and Drosg [12] and Hjorth et al. [15].

For stripping process, an ammoniacal nitrogen recovery of 90 % is supposed. It is assumed that the total stripped ammoniacal nitrogen can be transformed into ammonium sulphate, which contains 21 % nitrogen. The amount of limestone is calculated by an assumed ratio of limestone to ammonium sulphate solution of 0.58, which is calculated from data given by Bauermeister and Wild [5]. The lime content of the ammonium limestone is 70 %.

The expected structure material for composting is woody material with 70 % DM, and the amount is calculated for a supposed DM content of 55 % for structure material and digestate mixture. For composting process, an organic degradation of 20 % is assumed.

Results and discussion

Inventory and substrate analysis

An inventory study determined the potential of various secondary, tertiary and quaternary bioresources in Jenfelder Au and the surrounding district *Wandsbek*, which were expected to deliver suitable biogas amounts. They were partly published in [18, 19] and summarized in the following. The inventory results were completed by substrate analysis data for the substrates investigated in this publication.

Blackwater. BW is a quaternary bioresource and should be treated in Jenfelder Au. A person produces 500 l of urine and 50 kg of excrement per annum [20]. Furthermore, 1 l flush water per flush [20] and 15 kg toilet paper per person and annum are used on average [33]. The specific rate of blackwater from vacuum toilets is given with 6 l per person and day on average [14]. In Jenfelder Au, around 2000 people will generate about 12 m^3 blackwater per day.

Table 3 shows analytical results for BW from our own analysis as well as from the analysis carried out by Wendland [37] and Alp [3]. All analysed BW is from Flintenbreite and in a similar range. Our own analysis and the values of Alp compared with those of Wendland show a lower DM and oDM content due to a change in the flush settings between 2008 and 2010.

Greasy water. GW is a quaternary bioresource and actually treated in the municipal wastewater treatment complex Köhlbrandhöft by anaerobic digestion. It is very inhomogeneous and contains, in addition to fats and oils, food leftovers, detergents and cleaning agents. The amount of greasy water collected in the district Wandsbek was estimated via the amounts generated in the close-by district Bergedorf [25], considering the number of habitants of both districts. This resulted in a daily amount of 4 m^3 greasy water from the district Wandsbek.

Our own characterization of GW compared with literature data is given in Table 4. The table shows that the analysed greasy water consists mainly of water, but the organic matter based on DM is high. Additionally, the high chemical oxygen demand (COD) and total organic carbon (TOC) values probably result in high biogas potentials.

Lawn cuttings. LC from lower quality are tertiary bioresources. Approximately 1–2 kg lawn cuttings per square metre and annum accrue in private gardens and on public green space from March to October. The amount and quality depend mainly on the season and on the type and care of the lawn. Fresh lawn cuttings are humid and contain high shares of easily fermentable organic material. Lawn cuttings are actually either left on the lawn or on a heap, composted in the garden, supplied to the collection station, collected by gardeners or landscapers, or collected in the biowaste and residual waste bin. Lawn cuttings also contains high amount of N and P. The area-specific generation rates of 1.7 kg/m^2 for lawn cuttings from public areas and 1.0 kg/m^2 for lawn cuttings from private areas were given by the literature [1, 6]. An inventory study, using GIS (Geographic Information System), was done with zones of 5, 10, 15 and 20 km around Jenfelder Au. The study shows an annual potential of lawn cuttings of 21,000 t/a in 5 km surrounding Jenfelder Au [10]. Another study resulted in nearly 30,000 t/a of lawn cuttings for the district around Jenfelder Au, called Wandsbek [28].

In literature, limited data are available for fresh lawn. The mostly used substrate is grass silage from farmland. A comparison of our own investigations and literature values for lawn cuttings and grass silage is given in Table 5. The values for grass silage are in the same range of our own analyses, and only for ammoniacal nitrogen, the value is lower, possibility due to ammonia losses during the ensilage process.

Table 3 Characterization of blackwater, our own analysis in comparison with literature values

Parameter	Unit	Own analysis		Literature	
		No. of samples	AWW[a]	Wendland [37]	Alp [3]
			Average ± SD[b]	Average ± SD	Average ± SD
DM	%	10	0.57 ± 0.15	0.65 ± 0.21	0.48 ± 0.03
oDM	% DM	10	55.54 ± 6.35	62.36 ± 12.29	55.93 ± 5.04
COD	mg/l	12	7615 ± 2990	8060 ± 2950	5461 ± 1634
TOC	mg/l	12	2428 ± 878	2410 ± 720	2253 ± 780
TN	mg/l	12	1455 ± 220	1495 ± 244	1382 ± 435
NH_4^+/NH_3-N	mg/l	4	1090 ± 121	1111 ± 137	1002 ± 59
pH	–	9	7.58 ± 0.17	7.7	7.1 ± 0.3

[a] Institute of Wastewater Management and Water Protection
[b] Standard deviation

Kitchen waste. Kitchen waste is a tertiary bioresource and generated in the district. Due to the material properties of kitchen waste, it would be an ideal co-substrate for fermentation. Currently, it is collected in Wandsbek via the biowaste and residual waste bin. As a result of mixings with other waste types, the contents of these bins are not suitable for the wet fermentation in Jenfelder Au. Kitchen waste grinders installed in the sink offer a new collection possibility. These promise a nearly complete and, in addition, very user-friendly possibility of kitchen waste collection, with a homogeneous sludge as a result. In Jenfelder Au, a few kitchen waste grinders are expected to be installed for a test operation. However, an area-covering installation is not possible under the actual situation but may be a promising option for similar undertakings [18, 19]. In these investigations, they are not further considered.

Other bioresources. In gardens and public areas, large amounts of green waste such as weeds, branches and boughs from bushes and trees accumulate. These fractions are not directly suitable for fermentation, as they either contain too high soil shares or woody components. However, after separation of disturbing fractions, they may be handled in similar ways as lawn cuttings. Leaves are, on principle, fermentable. The biogas yields significantly depend on the type and age. Furthermore, residues from a fruit-processing company that accumulate in the proximity of 7 km are very well fermentable. These residues occur as fruity water composed of shredded fruit peeling residues, mixed with process water, that accrue during the industrial fruit processing [18, 19]. These fractions could also not be considered in these investigations. But especially the fruity water should be kept in mind for later inclusion.

Pre-treatment and storage of lawn cuttings

Pre-treatment by pressing and maceration

In Jenfelder Au, a wet fermentation system will be installed. To use the bulky LC together with BW, a pre-treatment is necessary. The dry matter content of the mixture shall not to be higher than approximately 10 %, since the substrate mixture has to be pumpable. Two options are tested to transform LC into a pumpable form: generation of a suspension with macerated lawn particles and of a juice pressed out of lawn cuttings.

- Lawn has long fibres and is not easy to shred. To get good grinding results, the addition of a liquid was necessary. The homogeneous suspension was prepared by maceration of lawn fresh matter with

Table 4 Characterization of greasy water, our own analysis in comparison with literature values

Parameter	Unit	Own analysis		Literature	
		No. of samples	AWW	FNR 2006 [13]	Deegener [7]
			Average ± SD	Min–max values	Average ± SD
DM	%	6	2.32 ± 0.22	2–70	4.52 ± 4.03
oDM	% DM	6	81.59 ± 11.31	75–93	88.4 ± 10.5
COD	mg/l	7	63,374 ± 33,582	–	63,900 ± 56,500
TOC	mg/l	7	9158 ± 2805	–	16,100 ± 13,600
TN	mg/l	7	567 ± 230	0.1–3.6 % DM	540 ± 520
NH_4^+/NH_3-N	mg/l	–	–	0.02–1.5 % DM	–
pH	–	4	4.54 ± 0.32	–	4.1 ± 0.7

Table 5 Characterization of lawn cuttings, our own analysis in comparison with literature values

Parameter	Unit	Own analysis		Literature		
		No. of samples	AWW	Green cuttings [13]	Lawn cuttings [38]	Grass silage [34]
			Average ± SD	Min–max values	Min–max values	Average values
DM	%	19	30.59 ± 13.46	12	18–37	30.66
oDM	% DM	19	82.53 ± 7.54	83–92	77–88	92.46
COD	g/kg	4	275.8 ± 81.1	–	–	396.88
TOC	g/kg	4	80.3 ± 17.4	–	–	–
NH_4^+/NH_3-N	g/kg	6	1.98 ± 1.18	–	–	0.44
TN	% DM	6	3.1 ± 0.6	2–3	1.7	1.6[a]
TC	% DM	4	34.78 ± 6.73	–	34–45	43.04
pH		8	5.3 ± 1.15	–	–	4.3

[a] TKN

water in a ratio of 1:4. In practice, water shall be exchanged by the liquid digestate or liquid substrates like BW and GW. Lawn cuttings may also contain contaminations like branches, stones and sand. Large particles were separated out, but especially sand lead to high wear of cutters and should be taken into account in the planning process for a fermentation plant.

- LJ was prepared by pressing the LC in a screw press or a slab press. The characterization is shown in Table 6. On average, 40 % LJ related to the lawn fresh matter can be obtained from fresh LC; the harvest varies from 20 to 60 %. The amount depends strongly on the type of lawn and decreases with a higher amount of woody, dry or mossy material. The juice is easily mixable with BW and GW.

Previous research works in the field of juice preparation from lawn or grass were done mainly for green biorefineries with the aim of protein and lactic acid extraction. Within the Austrian research project "FABRIK der Zukunft", grass silage was pressed out. Mandl et al. [24] carried out that 85–95 % of total lactic acid and about 55–65 % of crude protein can be transferred into the juice.

Table 6 Characterization of lawn juice

Parameter	Unit	No. of samples	Average ± SD	Min	Max
DM	%	12	4.24 ± 1.50	1.82	8.30
oDM	% DM	12	65.37 ± 11.19	47.30	72.80
COD	mg/l	7	41,581 ± 27,209	14,194	105,520
TOC	mg/l	10	16,135 ± 9336	6438	39,786
TN	mg/l	10	1914 ± 1052	672	4527
NH_4^+/NH_3-N	mg/l	7	386 ± 285	279	980
pH	–	9	5.6 ± 0.89	4.2	7.4

Storage of lawn cuttings

LC only accrue between March and October. To ensure substrate availability for the biogas plant in the whole year, lawn cuttings have to be stored. One possibility is preparing silage, which is a common way used in agricultural biogas plants for maize and grass cuttings. Grass is compacted as bale silo or in a driving silo. Under anaerobic conditions, lactic acid fermentation takes place; due to a production of acids, the pH value decreases and leads to inhabitation of spoilage microorganisms, and a conservation of the material is achieved. [27]

Lab-scale storage was done by using vacuum bags which also imply anaerobic conditions and can be compared with the silage process.

Biogas potential of substrates

Biogas potentials for black and greasy water as well as fresh and stored LC and LJ were determined in mesophilic anaerobic batch tests. Average results for BW and GW as well as results from specific lawn samples are shown in Table 7 and compared with literature sources. LJ and LC correspond to the same original samples. The results of our own substrate analytics was within the same range as literature values.

The specific biogas potential (based on organic dry matter) of BW (500 nl/kg oDM) and GW (1000 nl/kg oDM) has been in the expected range given by the literature. Since BW contains a low amount of organics, the absolute biogas production (based on fresh matter) is low. For lawn, the variation within one group has several reasons. The biogas potential of LC and LJ is highly dependent on the substrate quality. For example, the DM content of LC harvested in June of around 20 % was lower compared to that of LC harvested in September of 30 %, which was dry and more ligneous. Additional leaves which are poorly anaerobically degradable were contained as impurity due to the beginning of autumn. The biogas potential of the stored material was in the same range like the fresh

Table 7 Biogas potential of different substrates, our own analysis (average values + standard deviation) in comparison with literature values

Substrate	No. of samples	DM %	oDM % DM	Bulk density kg/m^3	Own investigation Specific biogas nl[a]/kg oDM	Own investigation Absolute biogas nl/kgFM	Own investigation Methane %	Literature Specific biogas nl/kg oDM	Literature Source
Blackwater	6	0.6	60	1000	489 ± 51	2	n.a.	500	[37]
Greasy water	10	3	94	1000	1066 ± 42	30	n.a.	1000	[22]
Lawn cuttings									
Fresh	2	38	52	300	393 ± 4	78	n.a.	300	[13]
								550–680	[22]
								300–600	[38]
								700	[21]
3 months stored	2	23	62	600	329 ± 12	87	71		
6 months stored	2	33	78	600	419 ± 19	60	70	600	[22][b]
Lawn juice									
From fresh cuttings	2	8	72	1000	507 ± 1	29	n.a.	617	[36]
								600[c]	[11]
From 3 months stored cuttings	2	4	65	1000	352 ± 25	4	59		
from 6 months stored cuttings	2	2	55	1000	633 ± 66	17	64		

[a] Norm litre

[b] Grass silage

[c] 350–400 l methane/kg oDM with an assumed methane rate of 60 % in the biogas

material. Also, the investigation of [32] showed that ensilage of LC had no mentionable influence on biogas potential. On one side, the lactic acid fermentation process of ensilage leads to degradation of organics which could lower the biogas potential. On the other side, a cell disruption takes place which could improve the biogas potential [31]. Similar to fresh cuttings also in the stored variants, the DM content and degree of lignification of the lawn had a main influence of the specific biogas potential. It decreases with increasing water content and lignification, but differences were low (Fig. 1).

The specific biogas potential (related to organic dry matter content) was higher for LJ than for LC with the highest value for the LJ from June cuttings with approximately 600 nl/kg oDM and 350 nl/kg oDM for September cuttings. It is assumed that the moister the LC, the more water with dissolved degradable substances is pressed out.

Also, various mixtures of BW with GW, LC and LJ were tested regarding their biogas potential [19]. They showed the expected range in comparison to the calculated values considering the biogas potential and share

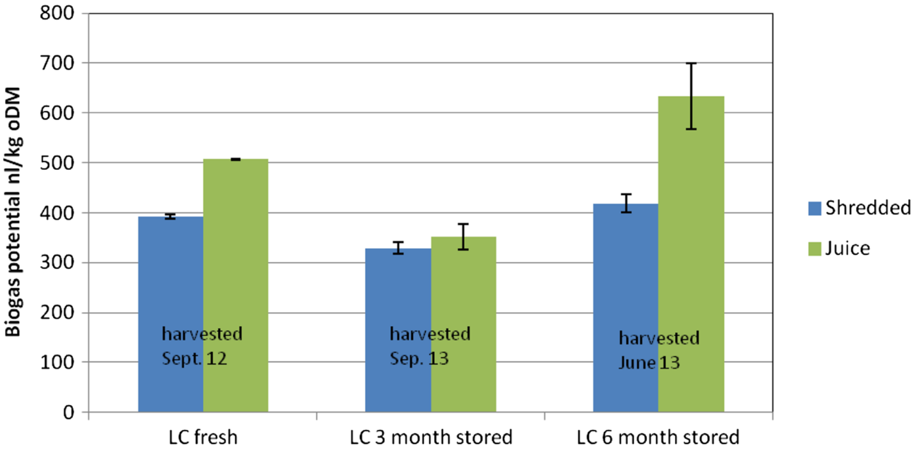

Fig. 1 Biogas production of shredded lawn cuttings and lawn juice from fresh and stored LC with min and max values

of the single substrates. That allows to model biogas potentials of mixtures based on single substrate data.

Basic modelling data

The variation in composition of the bioresources can vary in a wide range and is highly dependent on weather, season, origin and harvest type. Table 8 shows the results of inventory with average values from our own analysis of selected properties, which are used for calculation of expected biogas and nutrient amount in substrate mixtures.

Semi-continuous biogas production

The batch test gives values for biogas production in an ideal case, without adding a substrate to the original during the process. In the real scale of Jenfelder Au, a semi-continuous operating fermenter will be used. Therefore, semi-continuous experiments must be carried out in order to have values closer to the reality. The method for the experiments is given in "Methods for substrate pre-treatment and anaerobic digestion".

In the following, the influence of LJ and GW on the digestion of BW was investigated in semi-continuous experiments at different retention times. The objective was to find a mixture that enables a stable process with low retention time and high biogas production.

Characteristics of substrates used for semi-continuous fermentation

The specific characteristic of substrates used for the semi-continuous biogas experiments is given in Table 9. The specific data are shown, since the inventory and substrate analyses ("Inventory and substrate analysis") showed a certain range of variability within one substrate type and biogas potentials showed a dependency from specific substrate parameters ("Biogas potential of substrates").

BW was collected twice during the experiment. Table 9 shows that the BW composition was quite constant over the whole period of the investigation. A similar variation was observed for the GW; it was collected once before the experiment. Origin and storage are described above ("Origin of substrates" and "Methods for substrate pre-treatment and anaerobic digestion"). However, for the LJ, there was a considerable change in the composition between LJ 1 and LJ 2 (Table 6). LJ 1 was richer in all properties compared to LJ 2 and additionally more acidic. The main reason for the differences in composition presumably resulted from the different harvesting times; LC for LJ 1 were taken in summer while LC for LJ 2 in autumn. Therefore, the latter were very dry, and additionally, they contained a high proportion of branches and leaves. The higher acidity in LJ 1 is probably due to a longer storage time of the juice before use.

Substrates mixtures and feeding period in semi-continuous fermentation

The fresh mass composition of the substrate mixtures investigated in four 10-L-CSTR systems ("Methods for substrate pre-treatment and anaerobic digestion") is shown in Table 10.

The time lapse of the experiments was divided into three periods in which the substrates and retention times were changing (Table 11), but the composition was the same in each reactor over the whole experiment time.

Biogas production in semi-continuous fermentation

Figure 2 shows the absolute biogas production per kilogram of fresh matter, and Fig. 3 shows the specific biogas production per kilogram of organic dry matter (oDM) for the semi-continuously fed anaerobic digestion experiment in the four reactors over a period of 130 days.

Absolute biogas production refers to the fresh mass fed to the reactor as already-prepared substrate (e.g. kilogram of lawn juice and not kilogram of fresh lawn cuttings). The highest absolute biogas production was observed in reactor 4 during periods I and II (start). It was the variant with the highest share of LJ from the average composition. In period II, the value decreases due to, especially in the case of LJ, the composition of

Table 8 Results of inventory and biogas potential of substrates; values rounded for modelling [18, 19]

Bioresource	Bio-resource potential t FM/a	Biogas potential l/kg FM	Biogas potential l/kg oDM	Methane %	Bulk density kg/m^3	DM %	oDM % DM	Nitrogen % DM	Phosphorous %DM
Blackwater	5000[a]	2	500	75	1000	0.5	65	28.0	2.7
Greasy water	1500[b] 7830[c]	13	1000	70	1000	2	85	2.5	0.5
Lawn cuttings	21,000[d]	96	400	60	300	30	80	3.0	0.5
Lawn juice	8400[d]	18	500	70	1000	5	70	4.0	2.0

[a] Jenfelder Au
[b] Whole Wandsbek
[c] Whole Hamburg
[d] 5 km surrounding within Wandsbek

Table 9 Characterization of substrates used for semi-continuous biogas production (average ± standard deviation) [26]

Parameter	Unit	Blackwater	Greasy water	Lawn juice 1 fed in periods I and II	Lawn juice 2 fed in period III
pH	–	7.4 ± 0.2[a]	4.8 ± 0.2[a]	4.2 ± 0.2[d]	6.2 ± 0.2[e]
DM	%	0.52 ± 0.06[b]	1.95 ± 0.22[c]	4.64 ± 0.12[c]	2.07 ± 0.25[f]
oDM	% DM	59.6 ± 7.69[b]	67.69 ± 10.25[c]	77.59 ± 14.01[c]	68.12 ± 13.04[f]
COD	mg/l	8611 ± 1664[b]	41,783 ± 11,185[c]	64,061 ± 11,325[c]	23,200 ± 3726[f]
TOC	mg/l	2371 ± 477[b]	6544 ± 957[c]	27,450 ± 7,215[c]	8748 ± 2714[f]
TN	mg/l	1753 ± 248[b]	323 ± 136[c]	2,272 ± 713[c]	917 ± 312[f]

[a] 60 analysed samples
[b] 9 analysed samples
[c] 5 analysed samples
[d] 38 analysed samples
[e] 22 analysed samples
[f] 3 analysed samples
[g] 7
[h] 10

solids which varied highly and thus also the absolute biogas production.

During period III, the biogas production decreased further since the autumn LJ 2 had a low quality and contained much less degradable solids (Table 9). Regarding organic dry matter and water content, it was comparable with GW. The biogas production decrease of reactor 2 in period II was caused by accumulation of acids due to higher loading rates and will be discussed below. Reactor 3 showed a constant value in periods I and II, and only the use of low-potential LJ 2 in period III led to lower biogas production rates.

The *specific biogas productions* are compared in Fig. 3 for the four reactors. Reactor 2, which contained only BW and GW, had the highest specific biogas production presumably due to the high proportion of fat-containing molecules in the mixture. The degradation of fat provides higher yields (1390 nl/kg oDM) than the degradation of carbohydrates (750 nl/kg oDM) and proteins (800 nl/kg oDM) (VDI 4630). However, it is also visible that a change in conditions, namely the retention time, had a big influence on the biogas production of reactor 2. Shorter retention times and consequently higher loading rates in period II (Table 11) resulted in the accumulation of acidic compounds which may be harmful to the methanogens. If concentrations of those become too high, it can lead to reactor breakdown, as what happened in reactor 2 which was only able to recover after feeding only BW for several days until its recovery in period III (Fig. 4).

Table 10 Composition of the substrate mixtures fed into reactors of the semi-continuous anaerobic test system [26]

Reactor	Blackwater (BW)	Greasy water (GW)	Lawn juice (LJ)
	% FM	% FM	1/2 % FM
1	100.0	–	–
2	33.3	66.7	–
3	33.3	33.3	33.3
4	33.3	–	66.7

The *process stability* can be determined by FOS/TAC (volatile fatty acids to total inorganic carbonate) measurement. The FOS/TAC value represents the organic acids in relation to total inorganic carbonate in the substrate. For a stable process, the FOS/TAC value should be around 0.3 and the pH value should be around 7 [29]. Figure 4 shows the development of the FOS/TAC value for the substrate mixture BW with GW in reactor 2. After the increase of substrate loading rate, connected to a decrease of hydraulic retention time (HRT) from 55 to 40 days at the beginning of period II (on day 41), the FOS/TAC value increased from 0.2 to 0.4 and correspondingly the biogas production decreased by half, as shown in Fig. 4. On day 60 within period II, the FOS/TAC value increased further up to 0.7 and the pH dropped below 7. In order to avoid a reactor breakdown, the feeding of GW was stopped and substituted by BW. Until day 80, pH rose above 7 and the FOS/TAC value decreased to 0.2. The process was considered as stable again. The feeding with GW was resumed, and high loading rates with retention times of 40 days were adjusted again (period III). The biogas production improved again and remained stable this time. The specific biogas production related to organic dry matter amount was comparable between low (period I) and high (period III) loading rates. That shows that methanogenic bacteria can tolerate also a higher loading rate but need time to adapt to the new conditions [26].

All other reactors showed pH values ranging between 7 and 7.8 and FOS/TAC values around 0.20 all the time. They were considered as stable and have room for further reductions of retention times. The retention time should be reduced as far as possible to increase the overall process efficiency.

Overall evaluation. The mixture of BW, GW and LJ in reactor 3 showed not only a stable process (FOS/TAC

Table 11 Different timely periods according to changes of hydraulic retention time (HRT) and substrate characteristics performed in the experiments [26]

Period	Relevant changes in the process made in this period	Reactor 1		Reactors 2–4	
		HRT	Loading rate	HRT	Loading rate
		days	kg FM/m^3*day	days	kg FM/m^3*day
Period I	LJ1 in reactors 3 and 4	20	50	55	18.18
Period II	Change of HRT from 55 to 40 days in reactors 2–4; reactor 2 only fed with BW between day 61 and 75[a]	20	50	40	25.00
Period III	Use of LJ 2 with low VS, COD and TOC content (Table 4) in reactors 3 and 4	20	50	40	25.00

[a] In order to recover from organic overfed

around 0.2 ± 0.05), but also a constant and highly specific biogas production over the whole experimental period. It produced an average of 834 ± 87 nl/kg oDM of biogas.

In comparison to the calculated theoretical biogas potentials based on the batch experiments (Table 7), the continuous experiments showed higher biogas yields regarding GW and LJ. This may be because unadapted inoculum was used for potential determination. The mixture of GW with BW in reactor 2 produced an average of 1234 ± 152 nl/kg oDM, while the mixture of LJ with BW in reactor 4 produced 728 ± 90 nl/kg oDM (with LJ 1), in comparison to the respectively theoretically calculated 1000 and 500 nl/kg oDM.

Fertilizer from digestate

Feeding scenarios

After anaerobic digestion, a digestate remains. Three scenarios with different substrate mixtures were chosen to simulate the digestate flows which could be expected in Jenfelder Au. All scenarios are calculated with a hydraulic retention time of 25 days, which is the target time of the operators. The feed mixtures are based on the findings in the previous chapters:

- *Scenario 1* contains only BW (40 % FM) and GW (60 % FM). It illustrates the actual plannings in the Jenfelder Au demonstration project.
- *Scenario 2* contains BW (40 % FM) with GW (30 % FM) and LC (30 % FM) as co-substrate. The mass of LC addition was limited by the dry matter content in the fermenter, which should be not more than 10 % to allow pumping and stirring operations.
- *Scenario 3* contains BW (40 % FM) with GW (13 % FM) and LJ (47 % FM) as co-substrate. The amount of GW was restricted by the potential available in the district Wandsbek where Jenfelder Au is located.

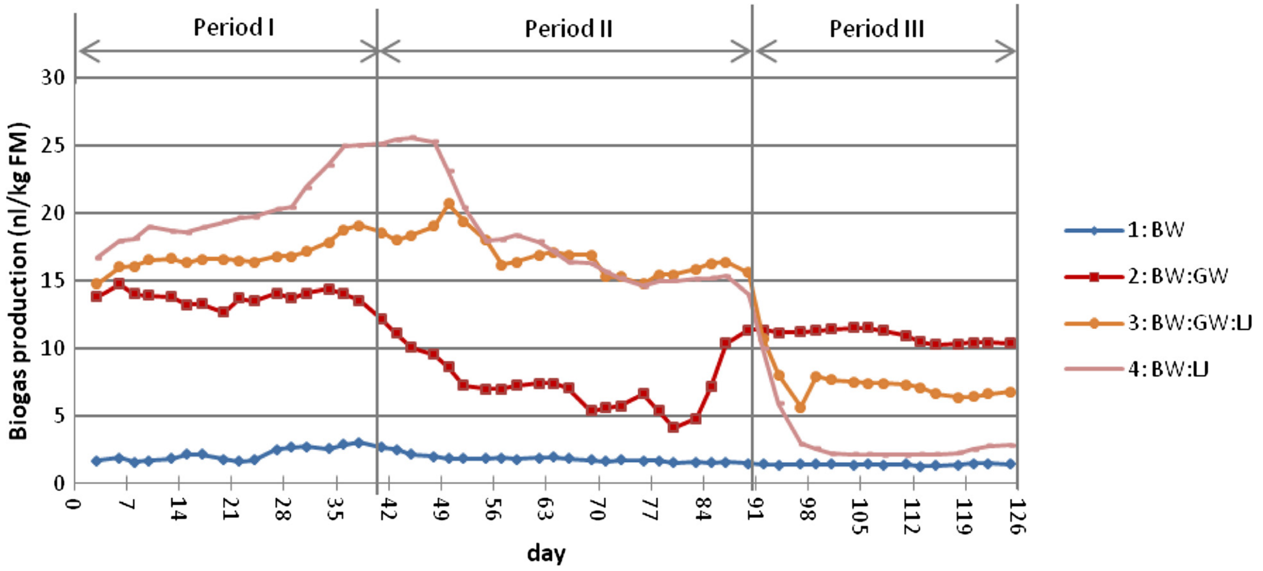

Fig. 2 Absolute biogas production in semi-continuous fermentation in 10-l reactors for four different mixtures with the substrates BW, GW and LJ during three different feeding periods

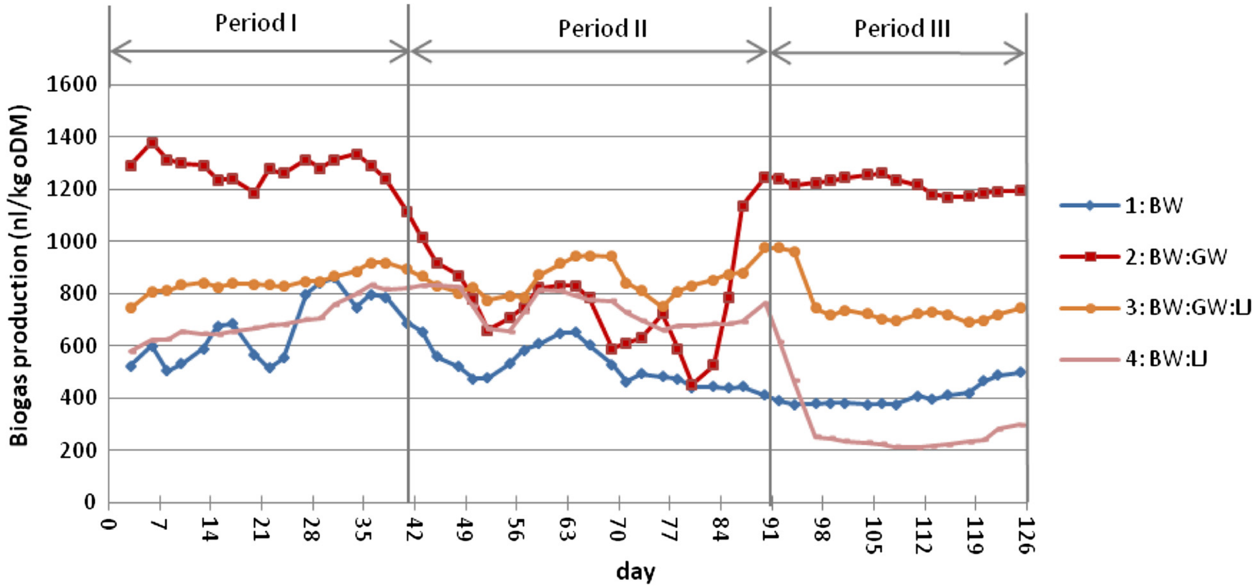

Fig. 3 Specific biogas production in semi-continuous fermentation in 10-l reactors for four different mixtures with the substrates BW, GW, LJ during three different feeding periods

Digestate characterization

The characteristic of digestates which could be expected from the three scenarios is given in Fig. 5. The methodology was described in "Calculation of digestate characterisation".

Figure 5 illustrates that the initial masses are transformed only to a small extent into biogas between 1.2 and 4.4 % of input mass and that digestates remain in amounts comparable to the input. The most important compound in the digestate is water with more than 90 %. The remaining is composed of organics and ash. Digestate contains also nutrients, which may be dissolved in the water fraction and are bound in organics and ashes. The most important nutrients regarding quantity are nitrogen (N) and phosphorous (P). Their contents in the feed are given in Table 8. The concentrations of the relevant nutrients in the digestate were calculated following the procedure in "Calculation of digestate characterisation", and the results for the three scenarios are given in Table 12.

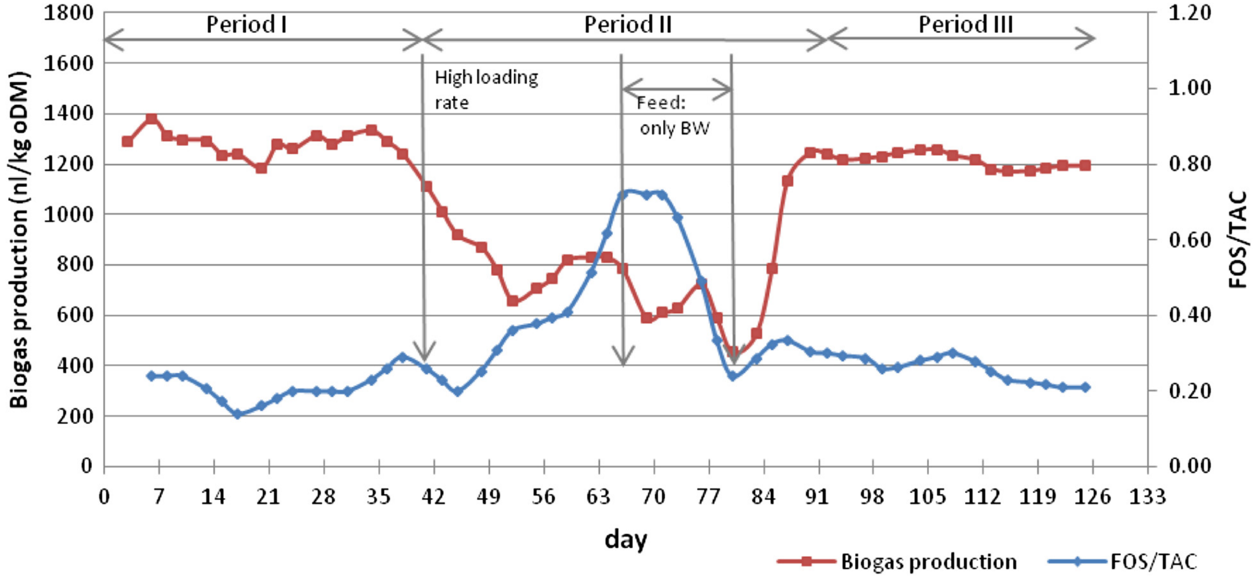

Fig. 4 Biogas production and FOS/TAC during semi-continuous fermentation in 10-l reactors with BW and GW mixture as substrate

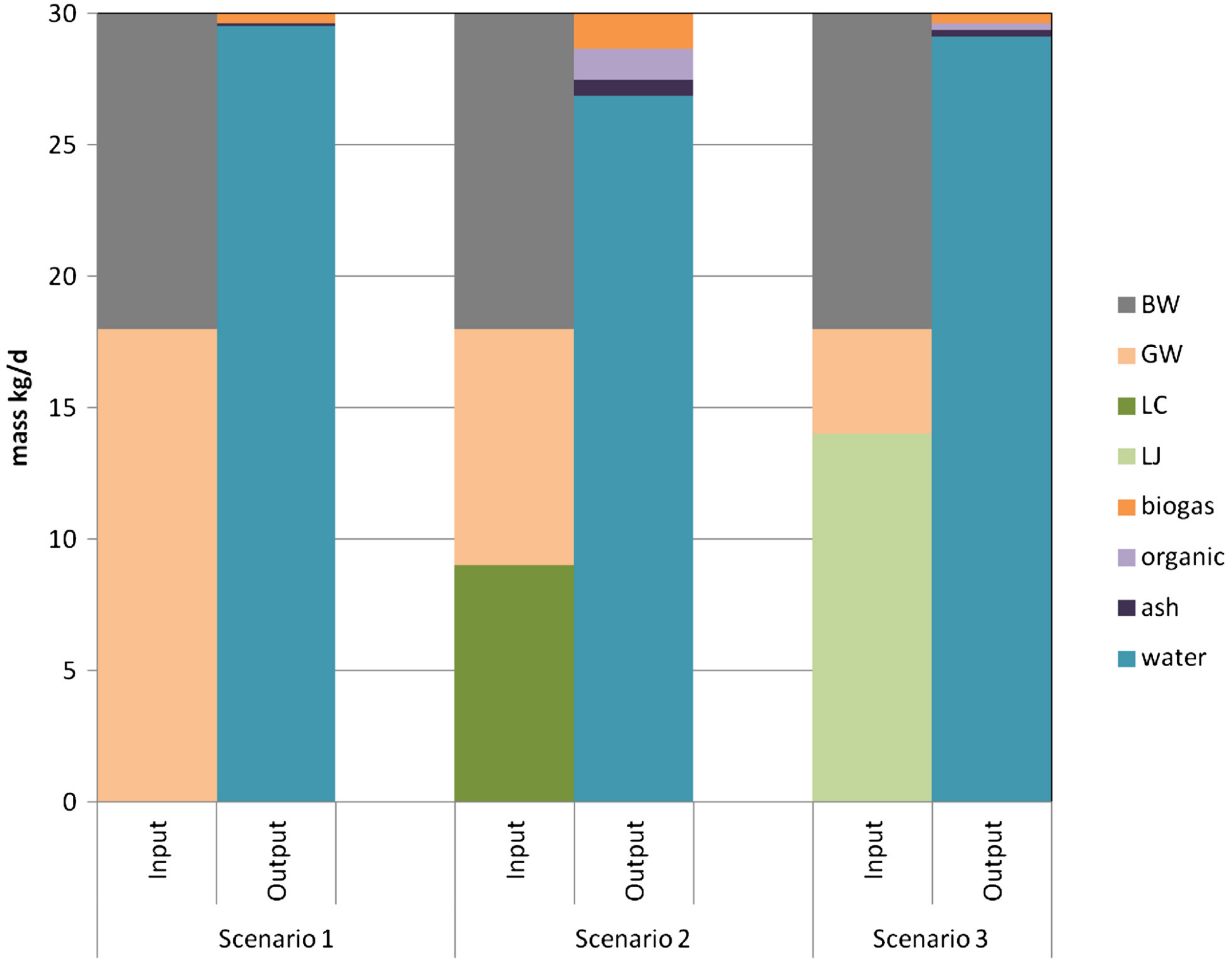

Fig. 5 Mass balances for the three scenarios with different feed mixtures and corresponding outputs for the Jenfelder Au situation. Output: digestate (composed from water, ash and organic) and biogas

The content of ammoniacal nitrogen ranges between 0.6 and 1.2 g/l. The ammoniacal nitrogen is almost completely contained in the liquid phase. It is plant available and therefore has a potential for fertilization. The organic nitrogen remains mainly in the particles, due to a high input of LC in scenario 2 with a high content of organic matter and organic N, and also the N potential of the digestate is high. The P content ranges between 0.2 and 0.5 g/l, which is mostly obtained in scenario 2 due to the high amount of LC. But also scenario 3 with LJ has notable P potential, because P is mainly solved in the liquid phase and a high amount can be recovered in the LJ after pressing.

Utilization of digestate

N and P are important fertilizing elements but have to be recovered to make them usable. A direct application of the digestate within the near surrounding of Jenfelder Au is not possible because of an urban development. Transport to rural areas is expensive and mainly water is transported. Additionally, a hygienization of digestate has to be done with high input of heat. Therefore, different methods for treatment based on literature research were investigated with the objective to generate valuable fertilizer products.

One considered process step is *solid–liquid separation*. A literature research has been carried out for solid–

Table 12 Calculated nutrient concentration in digestate for the three Jenfelder Au scenarios

Scenario		Units	Dry matter	Organic N	NH_4^+/NH_3-N	Total N	Total P
1	BW:GW	mg/l	4120	220	680	900	180
2	BW:GW:LC	mg/l	65770	1700	1160	2860	450
3	BW:GW:LJ	mg/l	18080	950	650	1600	370

liquid separation practices of agricultural digestates, and the theoretic separation efficiency of mass, DM, oDM TN, NH_4^+/NH_3-N and TP was determined [16]. A screw press is assumed with separation efficiency based on data given by [12, 15] (Table 13).

From the *liquid fraction*, ammoniacal nitrogen can be removed from the digestate by stripping with sulphuric acid or limestone and recovered from the gaseous phase via scrubbing with an ammonium sulphate solution [5]. Additionally, the recovery of phosphorus could take place in a stirred loop reactor through the addition of lime [20]. For the *solid fraction*, the prioritized utilization option is composting. In order to do so and to generate compost, mixing with structure-rich materials, for example with wood chippings, is necessary.

Figure 6 shows one possibility of digestate utilization with solid–liquid separation, ammonia stripping with the production of ASL fertilizer,[1] ammonium lime and composting [23]. Ammonium lime is also used as a fertilizer in agriculture, and compost is an important soil conditioner with fertilizing properties. The remaining water could eventually be treated together with greywater of Jenfelder Au [20]. The stripping process takes place with high temperatures and may lead to a hygienization of the digestate.

Based on the exemplarily process cascade in Fig. 6, various amounts of the product for the three different scenarios were calculated. The method and the assumptions are given in "Calculation of digestate characterisation" and table 8. Table 14 shows the expected results. An additional, even more advantageous option may be to align the solid–liquid separation after the stripping.

The comparison of the scenarios shows that the addition of LC increases the amount of nutrients and decreases water content in the digestate. For that reason, scenario 2 produces about twice as much ASL fertilizer compared to scenarios 1 and 3. The amount of compost in scenario 2 is lower since less structure material is necessary due to lower water contents in the solid phase. Additionally, phosphorus precipitation could take place with a supposed recovery rate of 90 % of the phosphorus in the liquid phase. Table 14 shows the amount of pure phosphorus, and also scenario 2 provides the highest amount.

Conclusions

It has been shown that blackwater can be used for biogas generation and that it has a potential as fertilizer. The organic material derived from excrements and toilet paper has an energetic potential. Although the fermentation of blackwater does not result in very high biogas yields, it is energetically advantageous compared to the conventional wastewater treatment which consume energy. The nutrients N and P are of special interest for material recycling. These components can be found mainly in urine and can be used for the production of fertilizers. Blackwater combined with local waste streams is beneficial in order to gain biogas amounts in a considerable range. Inventory studies showed a sufficient potential of secondary, tertiary and quaternary bioresources around Jenfelder Au which have a high biogas potential and also contain nutrients.

Table 13 Separation efficiency of a screw press, percent by mass of selected components that remains in the solid phase [16]

Separation efficiency	Mass	DM	oDM	TN	NH_4^+/NH_3-N	TP
	%	%	%	%	%	%
Screw press	12	37	40	14	4	26

The experiments have shown that co-digestion has a positive effect on biogas yields and lawn cuttings are suitable as co-substrate. Lawn cuttings can be applied as lawn juice or lawn suspension. The lawn juice showed a higher specific biogas yield than the used lawn suspension and is easily mixable with blackwater and greasy water. Greasy water showed the highest specific biogas potential related to organic matter but has also high water content; therefore, absolute biogas generation rates are rather low. The high content of greasy water combined with a low retention time of 25 days leads to instability and can easily lead to reactor breakdown due to the high content of volatile acids and is not recommended. In case of no further availability of other co-substrates, a retention time of not less than 40 days is recommended. Process optimizations, e.g. by trace element additions and microbial adaptions, could eventually lead to further reductions of retention time.

It is advised to use greasy water only together with the other lawn-based co-substrates up to a share of one third. Furthermore, the regional available amounts have to be considered which is in Jenfelder Au and even less than 20 % of the required feed mass. In practice, dry matter content of lawn suspension can be increased up to 10 %. That means the biogas production of suspension in relation to fresh matter can be improved and the quality of digestate products can be increased.

Therefore, scenario 2 should be the best scenario for Jenfelder Au with the aim of biogas production. It is combined with a high nutrient recovery and the production of high-quality fertilizer products. For decisions on co-substrates, biogas facility operation scheme and digestate treatment strategy, the whole chains have to be considered and compared with actual strategies. Since the Jenfelder Au project aims at demonstration in small scale, technical feasibility, positive energetic gains and material product possibilities should be especially considered. For instance, if the digestate from the Jenfelder Au facility would be disposed into the sewer and not utilized, it would run through the whole central wastewater treatment

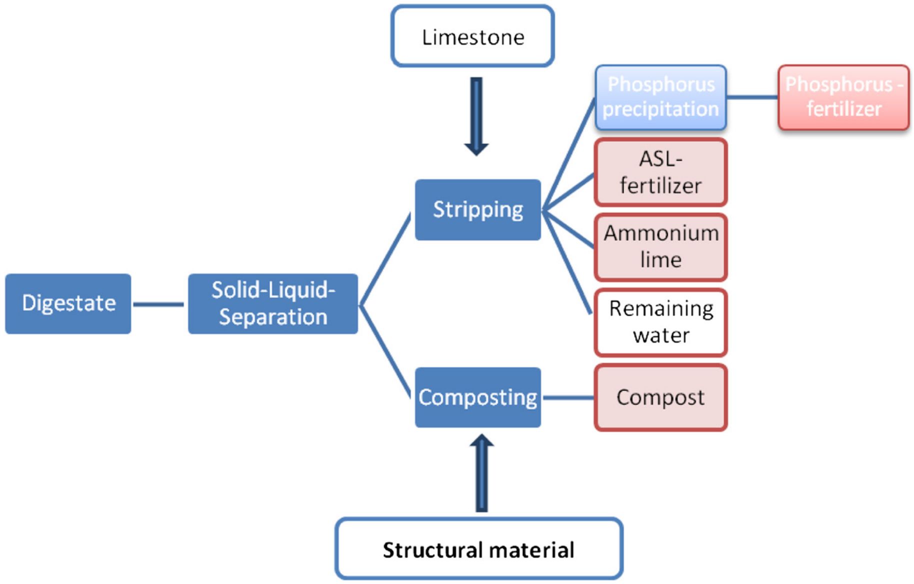

Fig 6 Suggested way of digestate utilization

complex including an anaerobic digestion step later. The new biogas facility would be an unnecessary additional step for blackwater and greasy water. Only for not yet collected lawn cuttings will the fermentation process lead to energetic gains. But in this case, a separate lawn cutting digestion would be preferable.

Several scenarios for complete or partial utilization of digestate were assessed. To calculate the amount of products, which could be generated in Jenfelder Au, a model is under development that includes cost-benefit calculation at all stages. A further step will be an energetic and economical assessment of several scenarios, including transport and pre-treatment of substrates as well as treatment of digestate in order to choose the best option for Jenfelder Au.

Also if coupled biogas and digestate facility would have no positive economical balance considering bioresource collection, pre-treatment, facility operation and investment costs, the overall system could be beneficial compared to the state of the art. The common wastewater treatment process is very energy intensive and leads to the losses of valuable plant nutrients (N and P). Compared to the actual situation of central wastewater treatment in Hamburg (for 150 million (Mio) t wastewater/a: electricity consumption 76.5 Mio MWh/a, heat consumption, 71 Mio MWh/a; [2]), the suggested procedure would be beneficial, since the most energy-intensive steps are avoided. This is on the one hand the nitrification/denitrification step for N elimination; instead, nutrients are recovered in the new process. On the other hand, wastewater can be handled decentrally and does not have to be pumed via long underground pipelines. Both the new process as well as the actual process contain an anaerobic fermentation step. The biogas potential from blackwater from the vacuum toilets from the new process (500 nl/kg oDM) is comparable with the biogas potential of sewage sludge used in the actual process (525 nl/kg oDM, ARCHEA [4]).

The new process is especially advantageous for regions where actually no wastewater treatment exists. Additionally, further actually unused residual streams can be included in the process which gives additional advantages.

Table 14 Examples for products received after digestate utilization processes with solid–liquid-separation, stripping and composting

Scenario	Digestate and its fractions			Additional input		Products			Additional product	Rest
	Digestate	Solid phase	Liquid phase	Structure material	Limestone	Compost	ASL (40 %)	Agricultural lime	Phosphorus	Remaining water
	t/a	t/a	t/a	t/a	t/a	t/a	t/a	t/a	t/a	t/a
1	10,800	1300	9500	3500	44	4800	77	37	1.3	9500
2	10,500	1300	9200	2100	76	3400	130	63	3.3	9100
3	10,800	1300	9500	3200	42	4500	73	35	2.7	9500

Further works shall focus on detailed mass and energy balances from the process and a comparison with other innovative processes for wastewater treatment. If various scenarios are suggested, the various aspects of sustainability—economical, ecological and social—should be compared for a decision [17].

Endnotes

[1] ASL fertilizer, ammonium-sulfat-lösung—ammonium sulphate solution (liquid fertilizer containing 40 % ammonium sulphate)

Abbreviations

ASL: ammonium-sulfat-lösung (ammonium sulphate solution);
BW: blackwater; COD: chemical oxygen demand; CSTR: continuous stirred tank reactors; DM: dry matter; FM: fresh matter; FOS/TAC: volatile fatty acids to total inorganic carbonate; GW: greasy water; HWC: Hamburg Water Cycle®; LC: lawn cuttings; LJ: lawn juice; N: nitrogen; nl: norm litre; oDM: organic dry matter; P: phosphorous; TN: total nitrogen; TOC: total organic carbon; TP: total phosphorous; TUHH: Hamburg University of Technology.

Competing interests

The work was founded by the German Federal Ministry of Education and Research (BMBF) in the frame of the KREIS project (Titel, FKZ 033L047C).
The academic and intellectual property rights of the authors have to be considered.

Authors' contributions

SH has made substantial contributions to the conception and design, acquisition of data, and analysis and interpretation of data and drafted the manuscript. PN has made substantial contributions in parts of the experimental work, analysis and interpretation of data and drafting of the manuscript.SD has made substantial contributions in parts of the experimental work and interpretation of data. IK has made substantial contributions to the conception and design, was involved in the drafting of the manuscript or revised it critically for important intellectual content, and have given final approval of the version to be published. All authors approved the final manuscript.

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