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Codigestion of Proteinaceous Industrial Waste

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Abstract

Organic wastes are increasingly collected source separated, thus requiring additional treatment or recovery capacities for municipal biowastes, organic industrial wastes, as well as agroindustrial byproducts. In this study, we demonstrate that anaerobic digestion is preferentially suited for high-water-containing liquid or pasty waste materials. We also evaluate the suitability of various organic wastes and byproducts as substrates for anaerobic digestion and provide a current status survey of codigestion. Biodegradation tests and estimations of the biogas yield were carried out with semisolid and pasty proteins and lipids containing byproducts from slaughterhouses; pharmaceutical, food, and beverage industries; distilleries; and municipal biowastes. Biogas yields in batch tests ranged from 0.3 to 1.36 L/g of volatile $solids_{added}$. In continuous fermentation tests, hydraulic retention times (HRTs) between 12 and 60 d, at a fermentation temperature of 35°C, were required for stable operation and maximum gas yield. Laboratory experiments were scaled up to full-scale codigestion trials in municipal and agricultural digestion plants. Up to 30% cosubstrate addition was investigated, using municipal sewage sludge as well as cattle manure as basic substrate. Depending on addition rate and cosubstrate composition, the digester biogas productivity could be increased by 80–400%. About 5–15% cosubstrate addition proved to be best suited, without causing any detrimental effects on the digestion process or on the further use of the digestate.

Index Entries: Anaerobic digestion; codigestion; biowastes; industrial wastes; proteinaceous wastes; biogas.

Introduction

For decades direct land application of biogenic wastes—i.e., use as fertilizer or soil conditioner—was applied extensively and is still in broad use (e.g., sewage sludge, animal manure). Waste recovery as a feed or as a raw material currently has decreasing significance. The recovery as

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compost depends on the quality of the waste collection and the pretreatment system as well as on the possibility of using the end product compost as soil conditioner. Since increasing amounts of organic wastes cannot be used properly in these processes, the final combustion of wastes plays an important role. Recently, controlled landfills have been required to receive inert wastes; residues from combustion; and, depending on legislation, stabilized organic wastes from mechanical-biologic pretreatment.

Anaerobic digestion, on the other hand, is an excellent supplement and alternative to composting and has proved to be preferentially suited for high-water-containing liquid or pasty waste materials. An evaluation of organic wastes and byproducts as substrates for anaerobic digestion is provided in Table 1. It is obvious that most organic wastes and byproducts can be classified excellently or well suited and only a few materials have to be considered carefully (e.g., straw, slaughterhouse wastes, garden and yard wastes). Some waste materials (e.g., source separated municipal biowaste, market waste) principally classified as well suited for anaerobic digestion require a comprehensive and costly pretreatment for the removal of physical pollutants (such as plastic, sand, metals). Some biowastes can give rise to potential hygienic or contamination risks in agricultural land application and must be subject to thermal hygienization.

Nevertheless, for several reasons organic wastes are currently applied increasingly as cosubstrates in existing and novel anaerobic digesters. As a main advantage, until recently, reasonable gate fees were paid by polluters for the digestion (treatment) of wastes. In addition, considerable amounts of additional biogas energy can be gained by applying codigestion. Both factors have considerably improved the overall economics of the digestion process. A more stringent environmental legislation, such as the forthcoming landfill ban on organic wastes, the possible European Union (EU) ban on food leftovers for animal feeding, composting problems with high-water-containing organic wastes, as well as the obviously broader dissemination and introduction of source-separated waste collection systems, can further increase the amount of organic wastes available for codigestion.

Dissemination of Codigestion

It has been estimated that conventional sewage sludge digesters are regularly oversized, thus easily providing a free digestion capacity of 15–30% *(1)*. In fact, an increasing number of existing municipal sewage sludge digesters are already using cosubstrates *(2–7)*. On the other hand, new sewage treatment plant designs, or plant extensions, increasingly implement cosubstrates such as source-separated biowaste, food leftovers, fat wastes, flotation sludges, and various other materials *(1,8–11)*. By these means, the energy balance usually can be considerably improved, thus decreasing waste treatment costs essentially. In many cases, codigestion even results in an energy surplus, providing additional income for the sewage treatment plants by selling electricity or even waste heat to the grid. As a further advantage, a controlled organic waste disposal (e.g., fat trap contents, food leftovers) can be achieved in the respective communities.

In addition, at present in agriculture codigestion is developing rapidly. Many small and medium farm digesters use considerably high amounts of single or mixed cosubstrates together with manure, generally aiming at an improved biogas energy output and reduced operating costs for the digester. Some agricultural digesters apply energy crops as a cosubstrate, aiming at additional energy output as well. The digestate of small and medium agricultural biogas plants is usually directly applied as a fertilizer on farmland. More than 1500 agricultural plants are currently in operation in Germany; much fewer are probably in function in Austria (about 115), Switzerland (about 64), Denmark, Italy, Sweden, Finland, England, and other European countries. Even less dissemination can be registered in Southern and Eastern European countries. An increasing number of the plants in operation are using cosubstrates. Surveys on existing plants are available in Germany *(12)*, Switzerland *(13)*, Austria *(14)*, Denmark *(15,16)*, and Sweden *(17)*.

By contrast, an increasing number of novel, large-scale agriculture-related or municipal digesters use source-separated municipal biowaste as the main substrate, together with cosubstrates such as food leftovers; spoiled food; crop residues from food, pharmaceutical, or biochemical industries; and various other waste materials *(18–20)*. Similar to sewage sludge codigestion, the liquid digestate must be purified aerobically, while the digested solids are used as compost in most of the large-scale agricultural biogas plants.

In Denmark, and to a smaller extent also in Sweden, several farmer cooperatives successfully operate large-scale farm digesters, usually using manure together with various cosubstrates from municipalities and industries *(15–17)*. The digester residues are recycled to farmland, while biogas is used for electricity reclamation or is upgraded as a liquid fuel *(21,22)*.

Waste Collection

Throughout Europe, wastes are increasingly collected source separated, thus requiring additional treatment or recovery capacities for municipal biowastes, organic industrial wastes, as well as agroindustrial byproducts. A recent estimation *(23)* describes a total of 1228 million t of organic wastes collected throughout Europe (Fig. 1). The majority of the overall mass (91%) originates from agriculture. Industrial wastes, municipal biowastes, and sewage sludge represent only one-tenth of the overall waste mass.

Table 1
Evaluation of Organic Wastes and Byproducts for Use in Anaerobic Digestion

Material	Excellent	Good	Poor	Remarks[a]
Biogenic materials from agriculture				
Straw and other fibrous plant residues			+	Chopping or grinding required
Green plant material, crops, grain, silages		+		Chopping required, disturbing sand, stones; possible scum layer formation
Silage leachate	+			Possible high COD loading
Harvest residues		+		Chopping required; disturbing sand, stones
Animal manure				
Chicken manure		+		Possible inhibiting NH_3 contents
Liquid piggery manure	+			NPR
Cow manure		+		Chopping of bedding straw
Manure from other animals		+		Chopping of bedding straw
Industrial and trade waste				
Food industry waste				
Expired food		+		Expensive unpacking required
Dough, confectionary		+		Liquefaction (dilution) required
Whey	+			NPR
Residues from canning and frozen foods		+		Expensive unpacking required
Residues from fruit juice production		+		Chopping advisable
Yeast and yeastlike products	+			
Yeast sludge and cooler sludge from breweries	+			NPR; possible increased H_2S formation
Sludge from wine production	+			NPR; possible increased H_2S formation
Sludge from distilleries	+			NPR; possible increased H_2S formation
Fruit, corn, and potato slops	+			NPR
Other fermentation wastes	+			NPR
Residues from animal feed production				
Expired feed		+		Case-dependent pretreatment
Animal and slaughterhouse wastes				
Slaughterhouse waste				
Animal fat	+			Possible scum layers
Flotation sludge	+			Possible scum layers
Stomach and gut contents		+		Possible need for hygienization
Blood	+			Obligatorily delivered to rendering plants
Fish waste		+		Grinding advisable
Chicken waste		+		Possible scum layers (fat, feathers)

Animal wastes				
Animal parts			+	Obligatorily delivered to rendering plants
Animals from confiscation			+	Obligatorily delivered to rendering plants
Carcasses			+	Obligatorily delivered to rendering plants
Animal homogenisate from rendering		+		Obligatorily delivered to combustion
Wastes from plant and animal fat products				
Spoiled plant oils	+			Possible scum layers
Oil seed residues		+		Possible scum layers
Fat trap contents		+		Possible scum layers and hardening
Fats		+		Possible scum layers and hardening
Oil containing bleaching earth		+		High inert materials content
Edible oil sludge	+			Possible scum layers
Edible fat sludge	+			Possible scum layers
Pharmaceutical wastes				
Proteineous wastes		+		Possible inhibiting NH_3 concentration and foaming
Bacterial cells and fungal mycelium	+			Possible need for hygienization
Leather fleshings, gelatin residues		+		Poor degradable contents; high salt and heavy metal (chromium) content
Pulp and paper industry wastes		+		High fiber (cellulose) content; bactericidal agents from pulp additives
Municipal wastes				
Wastes from source separate collection				
Biogenic wastes		+		Extended impurities separation required
Garden and yard wastes			+	Chopping and impurities separation
Market wastes		+		Chopping and impurities separation
Wastes from wastewater treatment				
Primary sludge	+			NPR
Surplus sludge	+			NPR
Decentralized sewer wastes	+			NPR
Oil and fat trap wastes		+		Possible scum layers and fat hardening
Other wastes				
Sludge from gelatin production	+			NPR
Sludge from starch production	+			NPR
Residues from potato starch production	+			NPR
Residues from maize starch production	+			NPR
Residues from rice starch production	+			NPR

[a]NPR, no pretreatment required.

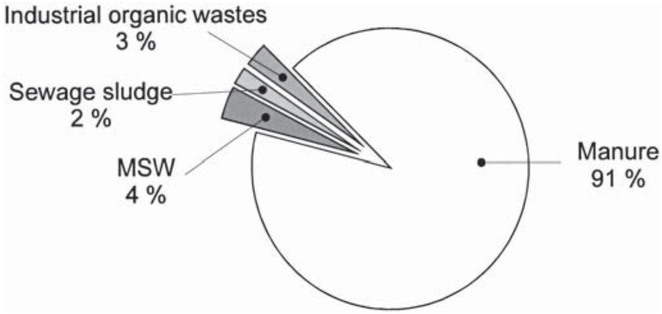

Fig. 1. Source and distribution of the 1228 million t of total organic wastes collected in Europe. MSW = organic fraction of municipal solid waste. (Adapted from ref. *23*.)

Materials and Methods

Comprehensive codigestion studies with biogenic wastes from the pharmaceutical industry (plasma protein residues), from slaughterhouses (protein- and fat-containing flotation sludge), with municipal biowastes from source-separated collection and with food leftovers from restaurants were conducted. All investigations were carried out in continuous cultivation, using prolonged investigation periods of at least 2–10 HRTs (i.e., about 2- to 6-mo duration). The investigations were carried out in full-scale farm (V = 100 m^3) and municipal sewage sludge digesters (V = 620–9000 m^3), together with cattle manure (12% total solids [TS] content), or sewage sludge (6% TS content), using a mesophilic working temperature of 35°C. Reactors were fed regularly once per day. Additional investigations were made in stirred-tank pilot plants (V = 4.4–6.6 m^3) and laboratory-scale fermentation test apparatus (Fig. 2) at 35°C.

To estimate the biogas yield, the biowaste substrates were homogenized (Ultraturrax) and diluted (tap water) to a theoretic maximum volatile fatty acids (VFA) content of 1000–1500 mg/L. Standardized seed sludge from sewage sludge digestion was applied for the fermentation test experiments. Blank values without substrate addition were used for the characterization of seed sludge and measurement of blank biogas yield. After inoculation, the batch fermentation tests were carried out over several weeks until no more biogas was formed. The biogas volume was measured daily, and the cumulative gas volume after completion of the batch test was used to calculate the biogas yield.

Subsequently, the adopted batch test experiments were further fed on a continuous basis, using a gradually increasing substrate dosage. The required HRT for stable operation and maximum biogas yields were calculated for all specific biowastes tested.

The digestion was characterized by estimating the biogas yield and composition (CH_4, CO_2, H_2S), the in- and outflow chemical oxygen demand (COD), TS, volatile solids (VS), pH, metabolic VFA, and total Kjeldahl and NH_4 content. All analyses were done in duplicate. If appropriate, the

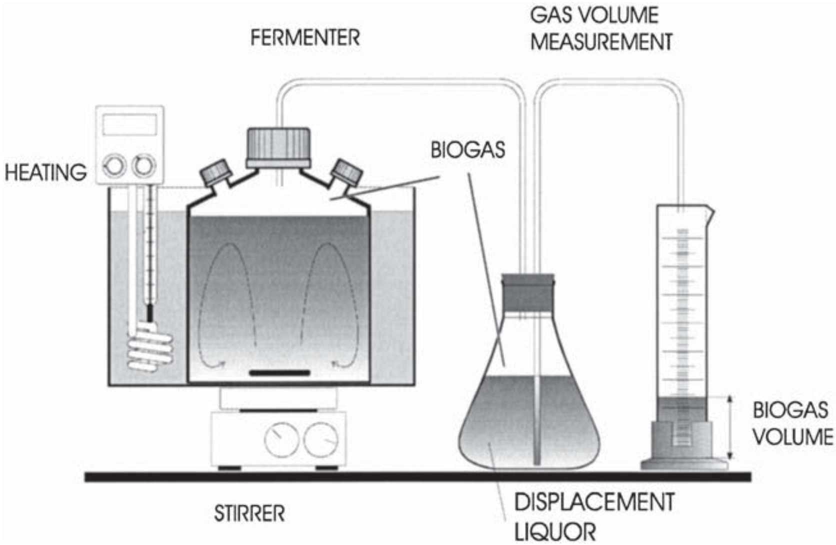

Fig. 2. Standard test equipment for methane fermentation testing, with stirred fermentor, thermostat (35°C), and biogas liquor displacement measurement.

heavy metal content of the input substrate as well as the output (digestate) was analyzed (data not shown). All analyses were done according to the German Standard Operations *(24)* on a daily to weekly basis.

Results and Discussion

Continuous fermentation tests for a large variety of potential cosubstrates were carried out (Table 2). All tests were inoculated using 25% standardized digested sewage sludge from municipal sewage treatment. Diluted substrates were added at startup of the experiments, and continuously increased portions were added depending on the course of digestion. The metabolic VFA concentration was controlled and kept below 1000 mg/L of VFA (as acetic acid). As can be seen from Table 2, most pure and mixed cosubstrates proved to be well suited for anaerobic digestion, resulting in biogas yields up to 1.36 m^3/kg of VS_{added}. Because of the varying physical properties (such as solubility, particle content, viscosity), the required HRT for reliable operation and optimum biogas yields from the various biowastes varied between 14 d and more than 2 mo.

Table 3 surveys the conditions and results of the codigestion experiments performed in full-scale municipal sewage sludge plants, in pilot plants using sewage sludge or cattle manure as base substrate, and in a laboratory experiment using high COD-containing press water from source-separated municipal biowaste separation (pretreatment). The addition rate of the cosubstrates investigated ranged from 4 to 30% (v/v). The cosubstrate addition in all cases was increased gradually, permanently controlling the digester performance by measurement of the biogas yield,

Table 2
Biogas Yields as Measured in Batch Fermentation Tests with Diluted Substrates[a]

Biogenic waste	Biogas yield in batch tests ($m^3/[kg \cdot VS_{added}$)	Minimum HRT in continuous fermentation (d)
Animal fat	1.00	33
Flotation sludge	0.69	12
Stomach and gut contents	0.68	62
Blood	0.65	34
Food leftovers	0.47–1.1	33
Food leftovers (fast food)	0.693	35
Rumen contents	0.35	62
Primary industrial sewage sludge	0.30	20
Secondary sludge (municipal)	0.2–0.35	20
Egg residues (pharmaceutical)	0.97	45
Blood plasma	1.36	45
Fermentation slops	0.85	35
Molasses distillery slops	0.42	14
Maize distillery slops	0.4	21
Potato distillery slops	0.47	10
Market waste	0.90	30
Municipal biowaste (source separate collection)	0.40	27
Biowaste (31%) + sewage sludge (69%)	0.54	30
Maize (whole corn)	0.648	20
Potato waste (chips residue)	0.692	45
Potato waste (peelings)	0.898	40
Waste edible oil	1.104	30
Chipboard manufacturing wastewater	0.893	14

[a]Required minimum residence times were estimated in continuous fermentation tests. All tests were performed in laboratory-scale fermentation test equipment at 35°C. VS_{added} = biogas yield referred to the amount of VS added.

biogas composition, VFA, pH, COD degradation, and NH_4 formation. As can be seen from Table 3, by adding cosubstrates, the digester biogas productivity could be increased between 80 and 400%.

Comprehensive investigations were carried out using poultry slaughterhouse flotation sludge in pilot plant, sewage sludge codigestion experiments (Table 4). Flotation sludge is collected during wastewater treatment in slaughterhouses and contains high concentrations of residual proteins (blood) and lipids from poultry slaughtering. The mean TS content of the flotation sludge used in the experiments was 12% (w/v), of which 96% represents organic components. The mean total Kjeldahl nitrogen was 3.5 g/L, NH_4 content was 0.4 g/L, and COD was 125 g/L. Flotation sludge was added at gradually increasing ratios of 5, 10, and 20% during the 160-d experiment. The corresponding influent COD concentration was

Table 3
Survey of Codigestion Experiments Performed
with Different Cosubstrates in Austrian Full-Scale Sewage Sludge Digesters and in Pilot Plants at the IFA, Tulln, Austria[a]

Reactor type	Digester volume	Sewage sludge P_G ($m^3/[m^3 \cdot d]$)	Cosubstrate addition (% [v/v])	Total P_G ($m^3/[m^3 \cdot d]$)	Increase in P_G (%)	Ref.
Sewage sludge digester, Schwechat	2×4500 m^3	0.5	15% Fat scraper contents, leather fleshings	1–1.3	100–160	*29*
Sewage sludge digester, Tulln	620 m^3	0.5	4% Plasma protein residues	0.9	80	*29*
Sewage sludge pilot plant, Graz	4.4 m^3	0.47	5–20% Poultry slaughterhouse flotation sludge	0.9–1.5	90–220	*30*
Cattle manure pilot plant, IFA Tulln	6.2 and 100 m^3	0.17	10% Plasma protein residues	0.68	400	*25*
Sewage sludge pilot plant, IFA Tulln	6.6 m^3	0.49	11% Biowaste, 4% food leftovers	1	100	Unpublished results, IFA Tulln
Laboratory experiments, IFA Tulln	2 L	0.6	30% Source separated biowaste (press water)	1.6	160	*29*

[a] P_G = biogas productivity related to the reactor volume.

Table 4
Results of Codigestion of Poultry Slaughterhouse Flotation Sludge in Sewage Sludge Pilot Plant Graz (V = 4.4 m^3)

Duration of experiment (d)	Flotation sludge addition (% [v/v])	HRT (θ) (d)	COD influent (g/L)	VFA (mg/L)	NH_4 content (g/L)	COD effluent (g/L)	COD degradation (%)	Specific biogas yield (m^3/[kg·COD])
0	0	20	40.5	220	0.9	5.1	85.8	0.28
35	5	20	56.4	180	—	16.5	66.4	0.43
52	10	20	74.6	980	1.25	28.4	59.9	0.35
78	20	20	93.1	1800	1.7	28.5	68.3	0.46
160	20	30	102.3	232	—	29.6	70.8	0.60

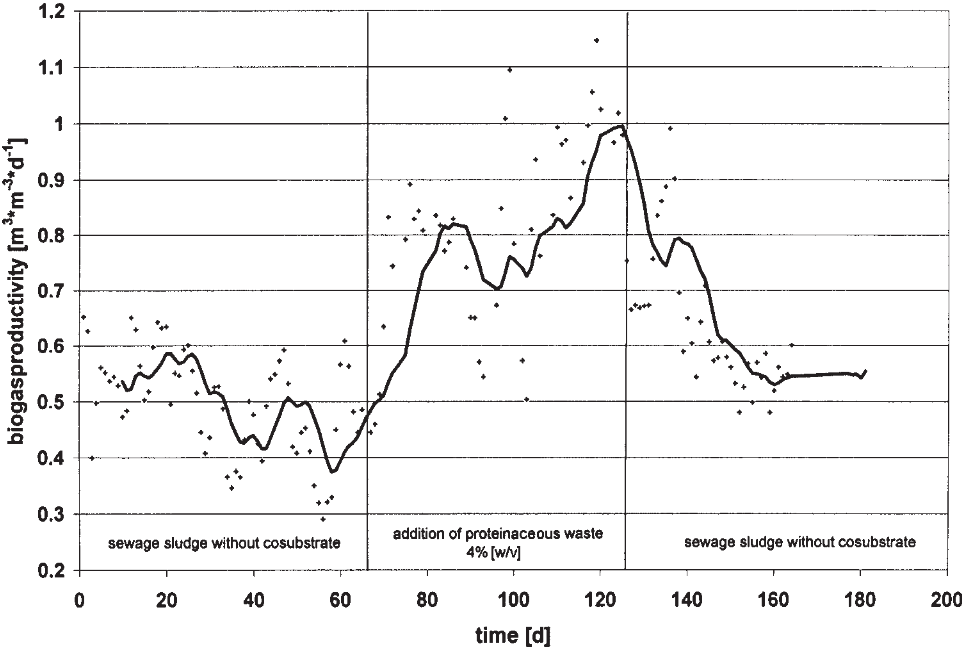

Fig. 3. Average course of biogas productivity ($m^3/[m^3 \cdot d]$) without and with continuous addition of 4% (v/v) plasma protein waste, to full-scale ($V_F = 620\ m^3$) municipal sewage sludge digester.

40.5–102.3 g/L. As can be seen from Table 4, an increase in the flotation sludge ratio was followed by an immediate increase in VFA concentration from about 100–200 to 1000–2000 mg/L (calculated as acetic acid). After an increase in the hydraulic residence time from 20 to 30 d, the VFA content stabilized again at about 232 mg/L. The COD degradation efficiency was nearly 90% in the case of using sewage sludge solely and decreased to about 60–70% when adding increasing rates of flotation sludge. The effluent COD value therefore increased from 5.1 to 16.5–29.6 g/L and the NH_4 content from 0.9 to 1.7 g/L. Nevertheless, the specific biogas yield could be increased from 0.28 to 0.6 $m^3/kg\ COD_{added}$. This corresponds to an increase in digester productivity between 90 and 220% (cf. Table 3).

Further pilot plant codigestion experiments carried out with cattle manure as a base substrate proved the good suitability of proteinaceous waste materials for agricultural codigestion applications (Table 3). The continuous addition of 10% (v/v) plasma protein residues increased biogas productivity by 400%. The experiments are described in detail by Brachtl *(25)*.

Source-separated municipal biowaste (11% [v/v]) and food leftovers (4% [v/v]) were investigated in pilot plant sewage sludge codigestion experiments at the Institute for Agrobiotechnology (IFA) Tulln, Austria (cf. Table 3). Laboratory experiments using 30% (v/v) press water from source-separated municipal biowaste separation in a sewage sludge

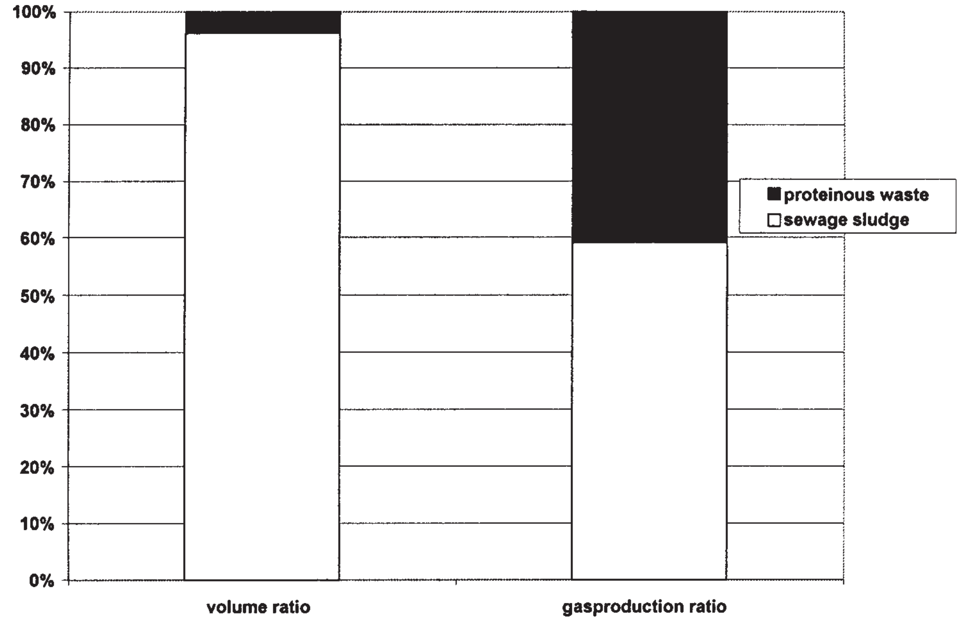

Fig. 4. Cosubstrate ratio (4% [v/v], plasma protein waste) and respective resulting biogas production ratio, in full-scale (V = 620 m^3) sewage sludge codigestion experiment.

codigestion increased biogas productivity by 160%. More results are described by Grasmug et al. *(26)*. Both investigations are still in progress and will be reported later in detail.

In a full-scale sewage sludge codigestion experiment using pharmaceutical plasma protein waste, biogas productivity increased from 0.5 to 0.9 m^3 (m^3·d) (Fig. 3). The course of biogas productivity was followed over 6 mo. As can be seen in Fig. 3, the amount of biogas produced could nearly be doubled. The continuous addition of 4% of the substrate volume as plasma protein waste was the reason for more than 40% of the overall biogas yield (Fig. 4). The HRT was 20 d at a mesophilic temperature of 35°C.

In a further full-scale demonstration experiment, 15% fat scraper contents and proteinaceous leather fleshings from leather processing were added to the 9000-m^3 municipal sewage sludge digester of the city of Schwechat, Austria (cf. Table 3). The continuous addition of cosubstrate again resulted in an increase in biogas productivity between 100 and 160%.

Conclusion

As the result of several upcoming European waste treatment and environmental protection guidelines, huge amounts of source-separated biowastes will accumulate for further treatment and recycling in the future. In agriculture as well as in municipal sewage digestion, an increasing number of existing or recently built full-scale installations are therefore occasionally using cosubstrates. Anaerobic codigestion in many cases turned out to be advantageously suited for treatment and remarkable biogas recovery of various organic wastes. Nevertheless, further research is required for a proper and reliable use of organic wastes in digesters as well as for proof of the suitability of digestate recycling on arable land.

Especially proteinaceous wastes can cause inhibiting effects on methane fermentation, owing to NH_3 release during digestion. Furthermore, depending on reaction conditions, in some cases, owing to hardening effects, fat-containing wastes can be barely bioavailable. The acceptance of those wastes therefore must be evaluated carefully from case to case. For these reasons, at IFA numerous possible cosubstrates have been investigated in laboratory-scale fermentation tests and further evaluated for the purpose of codigestion. Most waste materials turned out to be excellently digestible. Nevertheless, depending on the biowaste characteristics the required mean residence times for achieving maximum biogas yields varied considerably between 10 and 62 d. Increased attention has to be attributed to pretreatment requirements (homogenization, mixing, dilution) and pollutant removal (plastics, metals, stones). Based on comprehensive digestion testing, pilot- and full-scale codigestion experiments were performed, using sewage sludge as well as cattle manure as a base substrate. Provided that the ratio of added cosubstrates was within the limits of 5–15%, no major detrimental effects on the digestion process could be observed from the wastes considered.

As long as the physical pollutant content (e.g., plastics, metals, sand) of the cosubstrates applied is negligible, no major additional digestion equipment costs for pretreatment, homogenization, and pumping are required. The sludge separation properties were not observed to be influenced detrimentally by the additional digestion of cosubstrates. The standard equipment of sewage treatment plants in most cases meets the requirements of codigestion sludge dewatering. The benefits from the additionally recovered biogas in such cases considerably decrease waste treatment costs. Nevertheless, it has to be taken into account that, because of increased sludge loadings, the residual COD and the NH_4 concentration in the digestate can be increased considerably, thus causing higher wastewater posttreatment costs. The sludge composition, and hence its final land use, can be influenced considerably by the cosubstrate composition and must therefore be carefully considered from case to case. Especially if the digested sludge is used as fertilizer and soil conditioner in agriculture, potential hygienic and contamination risks can emerge from specific biowastes. Risky wastes (e.g., slaughterhouse wastes, food leftovers) are therefore a matter of upcoming EU guidelines *(27,28)* forbidding risky materials in digestion or demanding a thermal hygienization prior to land application.

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