Feedstocks for Anaerobic Digestion

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Abbreviations

TS ... total solids ... [%]
VS ... volatile solids ... [% of total solids]
COD ... chemical oxygen demand ... $[mg \times l^{-1}]$
C:N ratio ... carbon to nitrogen ratio ... [dimensionless]
LU ... livestock unit ... [kg]
OFMSW ... organic fraction of municipal solid waste ...
VFA ... volatile fatty acid ... $[mg \times l^{-1}]$
CSTR ... continuously stirred tank reactor ...
YG ... biogas yield ... $[m^3 \times kg^{-1}$ VS/or COD]

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Introduction

1.1 Definition of feedstock

In this paper the term feedstock is defined to include any substrate that can be converted to methane by anaerobic bacteria. Feedstocks can range from readily degradable wastewater to complex high-solid waste. Even toxic compounds may be degraded anaerobically depending on the technology applied. One requirement is that a given waste/wastewater contains a substantial amount of organic matter that is finally converted mainly to methane and CO_2.

1.2 The various substrates (feedstock) eligible for anaerobic digestion

As shown in figure 1 feedstocks for anaerobic digestion are derived primarily from one major source. Historically anaerobic digestion has mainly been associated with the treatment of animal (pig, cattle, poultry) manure and sewage sludge from aerobic wastewater treatment plants. However, in the 1970s increased environmental consciousness, accompanied by the demand for new waste management strategies and renewable energy forms, broadened the field of applications for anaerobic digestion and hence introduced industrial and municipal wastes as well. Moreover, high-rate reactor configurations and sophisticated process control devices allowed anaerobic digestion to enter areas which were dominated by aerobic systems such as the treatment of low COD-containing industrial effluents.

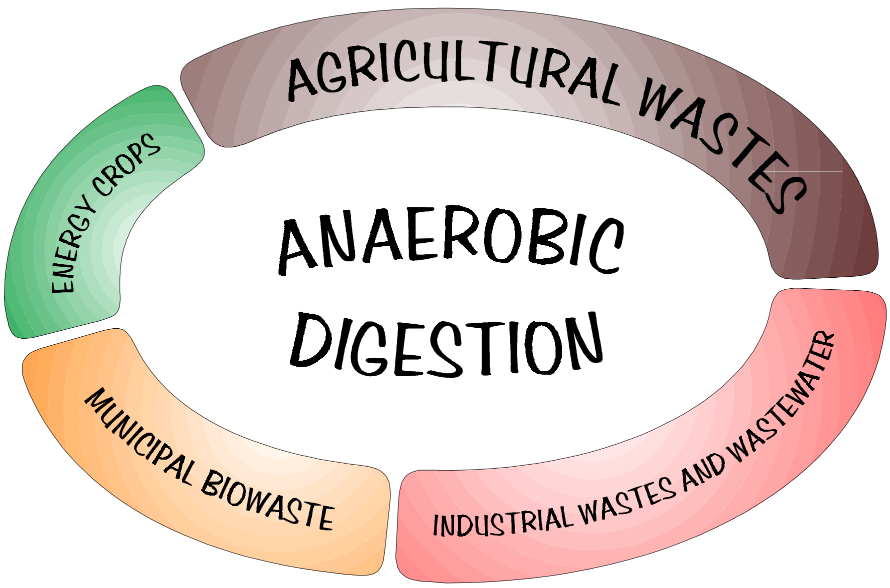

Figure 1: Sources of eligible substrates for anaerobic digestion

Recent concerns over landfilling of solid wastes stimulated engineers to consider new approaches to their treatment before disposal. For example solid and semi-solid wastes such as the organic fraction of municipal solid waste (OFMSW), currently commonly disposed of to landfills or aerobically composted, may be treated anaerobically, saving landfill space and converting the organic material partially to biogas energy.

The classification in figure 2 shows an overview of the various feedstocks assigned to the three different sources mentioned. Nevertheless, agriculture accounts for the largest potential feedstocks and most current applications. As specified in the objectives of the AD-NETT by agreement, this document will mainly focus on agro-industrial wastes, namely animal farm wastes, agricultural wastes and industrial wastes associated with agriculture and food production. Municipal solid wastes, sewage sludge and other industrial wastes are not included, unless when treated in a centralized co-disposal facility where agro-industrial wastes predominate the plant. Table 1 provides an overview of networks, programs, discussion groups, etc. dealing with further feedstocks and topics that are not covered by the AD-network.

AGRICULTURE

- **manure (cattle, pig, poultry)**
- **energy crops**
- **algal biomass**
- **harvest remains**

INDUSTRY

- **food/beverage processing**
- **dairy**
- **starch industry**
- **sugar industry**
- **pharmaceutical industry**
- **cosmetic industry**
- **biochemical industry**
- **pulp and paper**
- **slaughterhouse/rendering plant**
- **etc...**

COMMUNITIES

- **OFMSW**
- **MSW**
- **sewage sludge**
- **grass clippings/garden waste**
- **food remains**
- **etc...**

Figure 2: Survey of the various feedstocks from different sources.

Table 1: Survey of networks, programs, discussion groups, etc. dealing with various feedstocks eligible for anaerobic digestion not being covered in the AD-NETT

Name/Internet address	short description	feedstock
ALTENER Program. Waste for Energy Biomass Network http://www.nutek.se/Teknik/Altener/wfe.html	The network Waste for Energy (WfE) was created in 1995 by nine European partners with the objective of an increased use of waste for production of heat and electricity. Issues concerning municipal solid waste, wood (forestry industry residues, pulp & paper industry residues and contaminated wood residues) and biogas from anaerobic digestion are discussed. The WfE network comprises 10 European organizations.	MSW & others
Australian Biomass http://www.physics.adelaide.edu.au/~mferrare/best/biomass.htm#Australian Biomass	Development of landfill gas technology	MSW
ORCA http://www.orca.be/pubs/home.html	The organic reclamation and composting association deals with the promotion of the implementation of biological treatment, recovery or treatment of organic resources from different waste-streams, the use of good quality compost and the best use of biodegradable products to support sustainable development.	MSW & others
PRISM http://www.wrfound.org.uk/	PRISM is the information service of the World Resource Foundation (WRF). It provides information on sustainable waste management.	MSW
THERMIE http://erg.ucd.ie/res.html	THERMIE was created in order to promote and commercially implement renewable energies including photovoltaics, wind energy, energy from biomass and waste, hydroelectric, geothermal and solar thermal energy.	MSW & others
IAWQ Specialist Group: Anaerobic Digestion http://www.IAWQ.org.uk/spgroups/andig.htm	The Anaerobic Digestion Group was established in 1985. The group deals with all scientific, technological and engineering disciplines engaged in anaerobic digestion process development, application and control.	Wastewater and others

Name/Internet address	short description	feedstock
UWIN, Universities Water Information Network http://www.uwin.siu.edu/tocnoframes.html	The network disseminates information of interest to the water resources community.	wastewater
EnviroNET Australia http://www.erin.gov.au/net/environet.html	A network of environmental databases providing information on industry expertise, environmental education, research and development, cleaner production, environmental technologies, and hazardous wastes.	general
Water online http://www.wateronline.com/	Water online features the most complete online database of product and literature information for water and wastewater professionals.	wastewater
Enviroene http://es.epa.gov/index.html	Enviroene is an integral part of the U.S. EPA's web site. It provides a single repository for pollution prevention, compliance assurance, and enforcement information and databases. Covered topics are pollution prevention case studies, technologies, points of contact, environmental statutes, executive orders, regulations and compliance and enforcement policies and guidelines.	general
EREN, Energy Efficiency and Renewable Energy Network http://www.eren.doe.gov/resources/list-Digestion.html	A digestion mailing list was created to provide a forum for the discussion of anaerobic digestion as a sustainable energy resource. Topics are the cost effectiveness of anaerobic digestion, markets for biogas and other co-products, advanced technologies for biogas utilization, environmental benefits, and institutional barriers.	general
GTZ, Promotion of Anaerobic Technology http://www.gtz.de/anaerob/	This supraregional sectoral project focuses on the characterization of the potential and limitations governing the applicability of anaerobic technology to the treatment of liquid and solid wastes.	Municipal and industrial sewage and wastes
Environmental Technology and Management Centre of Expertise http://www.glam.ac.uk/schools/mech/Etmce.htm	The center was founded in order to apply research findings and expertise through partnerships with industry in the areas of environmental technology and environmental management.	compl. wastes/ wastewater

Name/Internet address	short description	feedstock
IEA Bioenergy (Task X and XIV) http://www.fri.cri.nz/ieabioenergy/home.htm	IEA Bioenergy is an international collaborative agreement which was set up in 1978 by the International Energy Agency (IEA). It attempts to improve international co-operation and information exchange between national bioenergy (RDD&D; research, development, demonstration and deployment) programmes. IEA Bioenergy promotes the use of environmentally sound and cost-competitive bioenergy on a sustainable basis, to provide a substantial contribution to meeting future energy demands.	general, MSW (task XIV)
Water Environment Web Biosolids & Solids Management http://www.wef.org/wwwboard/biosolids/wwwboard.html	Electronic discussion group	general
Waste Prevention Association http://www.rec.hu/poland/wpa/wpa.htm	WPA is a registered, non-governmental and non profit environmental organization. WPA's mission is to promote Clean Production methodology, waste reduction at source, and environmentally friendly waste management: segregation and recycling, as well as rational utilization of "historical" waste.	MSW
SEWAGE WORLD http://www.sewage.net/	SEWAGE WORLD attempts to become one of the most informative websites regarding industrial and municipal sludge treatment. It contains the most extensive list of wastewater treatment plants on the web and will be adding other subjects related to sewage and wastewater.	sewage, wastewater
CADDET Renewable Energy http://www.caddet-re.org/	CADDET provides information on full-scale commercial projects which are operating in the member countries. This information is made available through four main products: A Renewable Energy Database of full-scale projects (available on-line), a quarterly Renewable Energy Newsletter, Technical Brochure, Case Studies of selected renewable energy projects, and Reports which follow up on topics of interest.	general

1.3 The term feedstocks and its involvement in various aspects of anaerobic digestion

Feedstocks is a very comprehensive topic interacting with an array of interdependences being connected with anaerobic digestion (Figure 3). The feedstock considerably influences the reactor configuration (design and operational considerations) and has a comprehensive influence on the bacterial physiology.

From the metabolic pathway it is clear that high-solid, polymeric compounds-containing waste or wastewater requires a completely different design than readily biodegradable wastewaters, e.g. only containing volatile fatty acids. For example, lignin degradation is hardly noticeable under anaerobic conditions and cellulose breakdown can take several weeks. Hemicellulose, fat, and protein are degraded within a few days, whereas low molecular sugars, volatile fatty acids and alcohols exhibit degradation rates as short as a few hours. Moreover, the feedstock dictates the quality of the products such as biogas, anaerobic surplus sludge and the necessity of effluent post-treatment at the end of the digestion process. Since the final products of the anaerobic digestion are further processed to thermal and electrical energy (biogas) and soil conditioners (anaerobic sludge), a comprehensive assessment of the composition, purity (quality of the feedstock) is required.

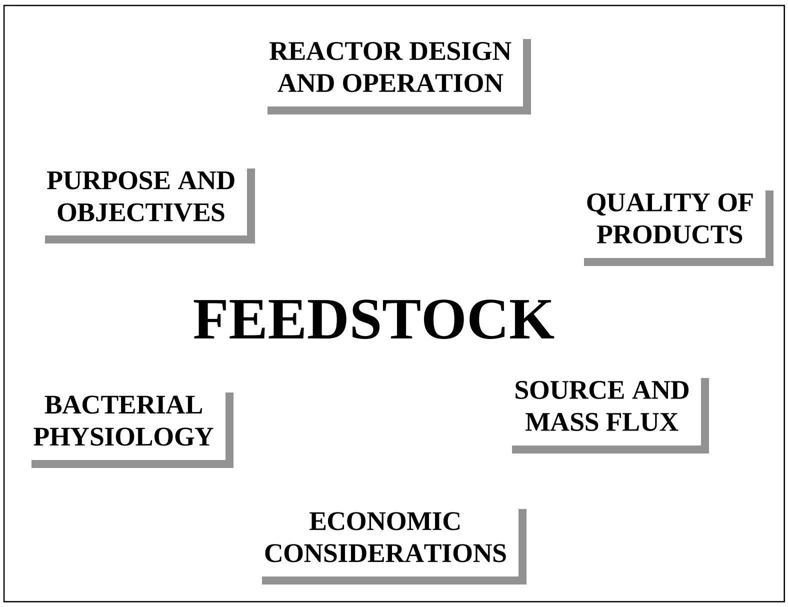

Figure 3: Feedstocks and its involvement in various aspects of anaerobic digestion

However, reflections on waste source and mass flux (compare figure 2) as well as economic considerations are also comprised. Concerning the latter, if a given feedstock requires an expensive pretreatment and/or reactor configuration, financial inputs have to be compared with all benefits (economic, environmental) of the anaerobic treatment. The feedstock may also determine the purpose and the objectives of the anaerobic treatment process. For example, the main objective of treatment of industrial wastewater treatment by anaerobic digestion is not generally the generation of methane with subsequent energy production or the quality of the anaerobic sludge as a potential soil conditioner, but the reduction of COD in the effluent as much as possible.

Digestion of the organic fraction of municipal solid waste (OFMSW) is driven by the need to reduce waste, generate useable biogas and also optimise the horticultural compost-substitue product in order to enhance the economic output of the process. For energy crops the prime driver will be the generation of biogas as a source of energy. In some cases plant biomass is pretreated and stored (i.e. silage) for the subsequent utilization as a feedstock for anaerobic digestion (Nordberg, 1997).

2 Objectives

The following technical summary cannot discuss all aspects of anaerobic digestion in detail as this would be beyond the scope of the report. In-depth studies on economic and environmental considerations, reactor design, bacterial physiology and others may be found in the technical summaries that dedicated to these topics.

This report will mainly focus on the characterization of the most important agricultural and agricultural-related feedstocks with respect to gas yield and composition, total solids and organic dry matter content, C:N ratio and NH_4-content, as well as disturbing and inhibitory compounds. The influence of these characteristics on the anaerobic process will be discussed including practical experience. A chapter will be devoted to the anaerobic co-fermentation process examining the advantages of this relatively new application.

3 Agricultural wastes suitable for anaerobic digestion

3.1 Pig slurry

Up to six varieties of the different types of animal housing are commonly in use, resulting in large variations of total solids (2 - 10 %) and organic dry matter content in manure. The excrements from pigs, particularly in units with more than 1000 animals, are commonly collected as a liquid slurry. In most cases, pigs are kept in feedlots with open floors, where the excrements are collected through slots with high amounts of liquid. The dilution of the feedstock resulting in 2 - 5 % TS makes the application of a digester system often uneconomic. In some cases, the slurry is collected using scraper systems resulting in higher dry matter contents of 5 - 10 %.

3.2 Cow slurry

Cow slurry is typically collected from feedlots by a scraper system. Straw is often added in the feedlots resulting in slight variations of total solids. Commonly little water is added for cleaning and rinsing of the cattle walkway, hence dilution with water is minimal (Table 2). As for pig slurry, cow slurry also exhibits large variations in total solids contents, depending on the animal housing system. Depending on the location and operational tradition cows often spend long periods of time grazing on pastures. Reduced overall manure collection must therefore be considered in economic evaluations.

3.3 Chicken manure

Chickens are usually kept in large scale units holding up to several hundred thousand animals. Chicken manure is characteristically high in TS contents (~ 20 %) and NH_4-N concentrations (~ 8 g x l^{-1}) (the NH_4^+-N concentration of animal slurries is generally rather high). In most cases, water dissolved ammonia is excreted. Since chickens excrete little liquid, ammonia may be found in crystalline form in the excrements. The resulting high ammonia content can lead to inhibitory effects during digestion, causing high NH_4 - emissions during manure storage in the feedlots. Keeping chickens in open feedlots typically causes considerable contamination of the manure with sand. In most digester systems sand is sediments to form a bottom layer, frequently causing operational problems and resulting in reduced reactor volumes.

3.4 Farmyard manure

On smaller farms conventional manure collection results in farmyard manure. Animals are typically kept on straw, which absorbs the excrements resulting in dry matter contents ranging from 10 to 30 % TS. The digestion of farmyard manure requires considerably higher retention times and often demands a pretreatment of the inhomogenious manure. Frequently additional operational problems, like scum layer formation, are observed. Some bedding materials like wood shavings are (due to their high lignin content) hardly degradable anaerobically and may be enriched in the digestion tank.

3.5 Harvest remains and garden wastes

Harvest residues and garden wastes, remaining on or recycled to agricultural land may also be used as feedstocks in farm digesters provided the effluent can be applied conveniently to agricultural farm land. Commonly such residues will be added as co-substrates to manure. Possible feedstocks for anaerobic digestion include plants and plant remains (e.g. leafs, corn, clover, stems etc.), spoiled or low quality fruits and vegetables, silo leachate and straw.

3.6 Energy crops

Efforts have been made to cultivate crops specifically for anaerobic digestion (biogas collection) purposes. This could be of interest for countries where energy costs are high, while sufficient agricultural land in mediate climate is available. Even in Europe, where agricultural over production occurs, anaerobic digestion of energy crops might be a possible alternative for using fallow areas. However currently energy crops for anaerobic digestion have not reached any significance in the EU. In some cases investigations have been reported using pretreated plant biomass (i.e. silage) for anaerobic digestion in farm digesters (Nordberg, 1997). The silage can be stored over prolonged periods of time and used for biogas production when energy is required.

3.7 Waste and wastewater from agriculture related industries

Huge amounts of agricultural raw materials are processed in the food industries. During processing, wastes and wastewater are produced. These could often be recycled as co-substrates in agricultural digesters. The resulting anaerobic sludge could then be applied as a fertilizer on agricultural land. Typical agro-industrial wastes and by-products include protein and sugar containing whey from the dairy industry or slops from fruit juice processing and alcohol distilleries. Various other crop and plant residues from industrial processing, often used or treated via other routes or landfilled, may also be treated anaerobically. Such residues can be added as co-substrates to manure or slurry digestion, provided the transport of the industrial waste can be organized on a rational basis.

3.8 Assessment of the various feedstocks

The average volume of faeces and urine largely differ from one type of animal to another and mainly depend on their age and lifeweight. For comparison, the general "livestock unit" (LU) is accepted widely. One LU represents a live weight of 500 kg and equals to 1 cow, 6 fattening pigs or 250 laying hens. Table 2 provides the average weights, excrement volumes and corresponding dry matter contents. According to the biogas yields, one LU of cow, pig or chicken produce in average 0.75, 0.60 or 12.5 m^3 biogas per LU.

Table 2: Animal manure generation characteristics

Animal	Life weight [kg]	Volume $[l * d^{-1}]$	Total Solids [%]
Dairy cow	500	55	11-12
Pregnant cow	500	45	11-12
Fattening cattle	250-400	19	8.7
	400-500	24	12
Fattening pig	15	1.0	-
	70	4.6	5.6
	125	4.0	9.5
	170	14.9	-
Laying hen	1.8	0.1	10 - 30
Fattening hen	0.9	0.9	10 - 30

In a recent survey undertaken by the ALTENER Energy from Waste Network (EfW), the total amount of agricultural manure in the 15 EU countries was estimated to be $1{,}124 \times 10^6$ tonnes in 1993, including 887×10^6 tonnes from cattle and 237×10^6 tonnes from pig livestock. The annual amount of industrial organic waste in the same study was estimated to be 35.04×10^6 tonnes. In addition there were 46.9×10^6 tonnes organic matter in municipal solid waste (OF/MSW). The distribution in the respective countries is presented in figure 4. Figures from the statistical office of the European Union (Burton, 1997) for livestock animal numbers in selected EU countries, indicate the quantities of cattle and pig manure calculated by the EfW network are of the right order. In addition, this report estimates the livestock animal numbers for sheep and laying hens. The resulting manure quantities are calculated with the following average yields per day and per animal and presented together with the estimations for cattle and pig manure from the reported network in figure 5.

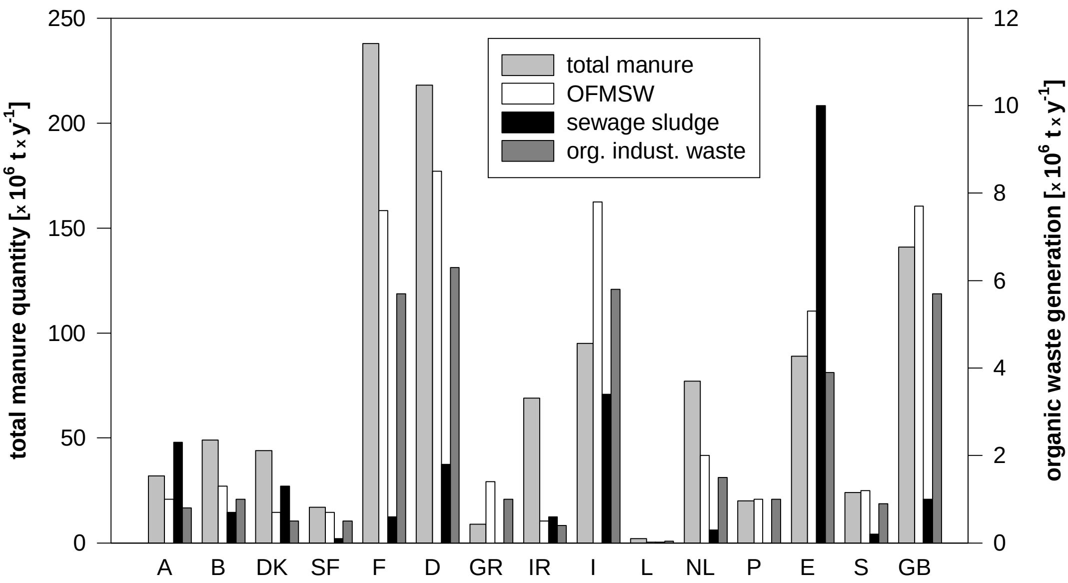

Figure 4: The amount of organic waste accumulation in the 15 EU countries

Most of the existing agricultural biogas plants are operated exclusively with manure. It is reported that in Germany a yearly quantity of 150 - 180 x 10^6 m³ animal waste is produced (Metzger, 1994). Only a minor part of this huge amount is currently treated in agricultural anaerobic digesters. Assuming that the whole amount of animal wastes could be digested with an average biogas yield of 0.25 m³ x kg^{-1} VS, a total biogas amount of 1.6 - 1.8 x 10^9 m³ could be produced in Germany.

For Germany more detailed figures on possible amounts of specific co-substrates like brewery spent grains, fruit and potato slops, fat slimes, rendering wastes, garden and yard wastes are available (Fuchs, 1994).

In Austria, the total amount of agricultural feedstocks for biogas plants (OFMSW excluded) is estimated to be 0.9 x 10^6 tons TS per year (Kunyik *et al.*, 1996). Only about 5 x 10^3 tons (~0.5 %) are considered to be currently digested in approximately 51 agricultural Austrian biogas plants.

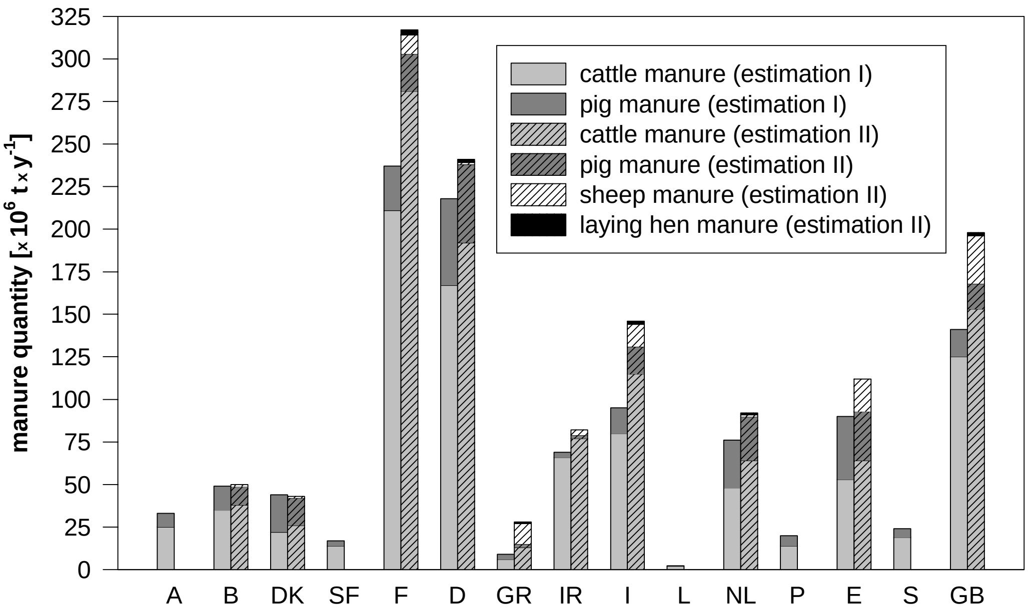

Figure 5: Estimations for animal manure accumulation in the EU (after EU Waste for Energy Network, 1997 (estimation I); Burton, 1997 (estimation II; calculation factors: pigs = 5 kg x d^{-1},
cattle = 35 kg x d^{-1}, sheep = 3 kg x d^{-1}, laying hens = 0,1 kg x d^{-1}))

4 Main characteristics of the various feedstocks and their impact on the anaerobic digestion process

4.1 Substrate composition

The feedstocks for anaerobic digestion vary considerably in composition, homogeneity, fluid dynamics and biodegradability. In intensive animal farming, the excrement are commonly collected as a slurry. Pig and cow slurries are reported to contain dry matter contents in the range of 3 to 12 %. Chicken manure contains 10 to 30 % TS. (Braun, 1982; Wellinger, 1991). The dry matter content of other agricultural wastes and by-products varies widely. Some agro-industrial wastes may contain less than 1 % TS, while other contain high TS contents of more than 20 % (see table 4).

Commonly, the biodegradable organic matter content ranges from 70% to > 95% of the dry matter content. Substrates with dry matter organic contents less than 60 % are rarely considered as valuable substrates worthwhile for anaerobic digestion.

The overall nutrient ratio in waste materials is of major importance for the microbial biodegradation process. The C:N-ratio in wastes can vary in a considerable wide range between ca. 6 (eg. animal slurries) and more than 500 (eg. wood shavings). For optimum degradation a C:N:P-ratio of 100:5:1 is recommended.

The water content of slurries can change seasonally and may be influenced by different operational conditions (dilution, etc.). High water containing substrates not only unnecessarily increase the digester volume, but also raise the heat input per m^3 waste required, resulting in unfavorable process economics. On the other hand, high TS contents dramatically change the fluid dynamics of substrates, often causing process failure due to bad mixing behavior, solids sedimentation, clogging and scum layer formation. As a rule of thumb for conventional CSTR - digester types, the optimum TS - concentration will be in the range of about 6 - 10 %.

Furthermore the distribution of organic macromolecules like proteins, fats and carbohydrates in the feedstock is of great importance, as their degradation leads to the formation of Volatile Fatty Acids (VFA), the main substrates for bacteria of the last two stages of anaerobic digestion. In particular, high fat contents increase VFA considerably, whereas high protein content leads to large amounts of ammonia (NH_4^+).

VFA and ammonia are not only formed through bacterial metabolism during degradation. They can already be present in considerable amounts in the influent, depending on the type of feedstock. Animal manure (3-5 $g \times kg^{-1}$) and especially chicken manure (15-20 $g \times kg^{-1}$) initially contain high concentrations of ammonia. Distillation slops and evaporation condensates may contain very high amounts of VFA as well.
A survey of possible compounds in the different feedstocks with some examples and effects are given in table 3. Table 4 shows examples of the most common wastes treated in digestion including important waste properties.

Table 3: Sources, composition and biodegradability of anaerobic feedstocks

Compounds	Sources	Examples	Anaerobic Biodegradability	Disturbing effects	Inhibitory effects
Carbohydrates Sugars Starch Cellulose	beets, corn potatoes, maize, etc. straw, grass, wood	sugar beet processing chips & starch processing farmyard manure, harvest remains	excellent excellent poor - good	foaming lignine incrustation	pH decrease [2)]
Proteins	animals & animal products	milk processing, pharmaceutical industry	excellent	foaming	pH decrease [2)], ammonia increase [3)]
Fats	animals & animal products	slaughterhouses, rendering plants	excellent [1)]	scum layers, poor water solubility	VFA increase [3)], pH decrease [2)]
Volatile Fatty Acids (VFA)	fats, grease, oils, evaporation condensates	rendering plants, oil mills	excellent [1)]	poor water solubility of fats and oils	specific inhibition of diff. bacteria groups
Trace organic compounds	pesticides, antibiotics, detergents	pharmaceutical industry, manure	poor	foaming	antibiotic reactions
Inorganic material	salts, food additives, silica gel (filtration)	slaughterhouses, manure, food & pharm. industry	no	precipitation [4)], sludge formation	
Sand, Grit	stable walls & floors	manure	no	precipitation, tube blocking	
Metals	packaging material, process remains	OFMSW, industry	no	blocking, precipitation	
Plastic	packaging material	OFMSW, industry	no	flotation	
Heavy metals	metal refining, batteries	OFMSW, industry	no		toxic reactions

[1)] necessity for high retention times; [2)] depending on buffer capacity; [3)] inhibition depending on pH value; [4)] can have positive effect through elimination of sulfide

Table 4: Characteristics and operational parameters of the most important agricultural feedstocks

Feedstock	Total Solids TS [%]	Volatile Solids [% of TS]	C:N ratio	Biogas Yield [3] [$m^3 * kg^{-1}$ VS]	Retention Time [d]	CH_4 Content [%]	Unwanted substances	Inhibiting substances	Frequent problems	Refe-rences
Pig slurry	3-8 [4]	70-80	3-10	0.25-0.50	20-40	70-80	Wood shavings, bristles, H_2O, sand, cords, straw	Antibiotics, disinfectants	Scum layers, sediments,	(3), (4), (22), (24)
Cow slurry	5-12 [4]	75-85	6-20 [1]	0.20-0.30	20-30	55-75	Bristles, soil, H_2O, NH_4^+, straw, wood	Antibiotics, disinfectants	Scum layers, poor biogas yield	(3), (4), (22), (24)
Chicken slurry	10-30 [4]	70-80	3-10	0.35-0.60	>30	60-80	NH_4^+, grit, sand, feathers	Antibiotics, disinfectants	NH_4^+-inhibition, scum layers,	(3), (15)
Whey	1-5	80-95	n.a.	0.80-0.95	3-10	60-80	transportation impurities		pH-reduction	(3), (22)
Ferment. slops	1-5	80-95	4-10	0.35-0.55	3-10	55-75	undegradable fruit remains		high acid conc., VFA-inhibition	(3), (22)
Leaves	80	90	30-80	0.10-0.30 [2]	8-20	n.a.	soil	Pesticides		(3), (22)
Wood shavings	80	95	511	n.a.	n.a.	n.a.	Unwanted material		Mechanical problems	(3), (22)
Straw	70	90	90	0.35-0.45 [5]	10-50 [5]	n.a.	Sand, grit		scum layers, poor digestion	(3), (22)
Wood wastes	60-70	99.6	723	n.a.	∞	n.a.	Unwanted material		poor anaerobic biodegradation	(3), (22)
Garden wastes	60-70	90	100-150	0.20-0.50	8-30	n.a.	Soil, cellulosic components	Pesticides	poor degrad. of cellulosic comp.	(3), (22)
Grass	20-25	90	12-25	0.55	10	n.a.	Grit	Pesticides	pH-reduction	(3), (22)
Grass silage	15-25	90	10-25	0.56	10	n.a.	Grit		pH-reduction	(3), (22)
Fruit wastes	15-20	75	35	0.25-0.50	8-20	n.a.	Undegradable fruit remains, grit	Pesticides	pH-reduction	(3)
Food remains	10	80	n.a.	0.50-0.60	10-20	70-80	Bones, plastic material	Disinfectants	Sediments, mechanical problems	(18)

[1] depending on straw addition; [2] depending on drying rate; [3] depending on retention time; [4] depending on dilution; [5] depending on particle size; n.a. = not available

4.2 Disturbing components

Fluid dynamics and hence degradation behaviour as well as the biogas yield are considerably affected by components such as straw, wood shavings, inorganic matter like sand, glass, metals or polymeric components like plastics etc. These unwanted materials often cause process failures (e.g. phase separation, sedimentation, flotation etc.) and much emphasis must be placed on avoidance of these components upstream of the digesters. In particular long straw particles and slime components in pig and cow slurry can cause considerable scum layer formation which is difficult to control during digestion. However depending on the reactor type and especially on the particle size of straw, the disturbing effect may be reduced and straw can even considerably improve the biogas yield. Sand input, often occurring with chicken slurry, causes a reduction of the digester volume due to its rapid sedimentation, which results in process failures.

Frequently disturbing components are introduced with co-substrates such as biogenic wastes (glass, plastics etc.) or industrial slops (salts, fats etc.). As a consequence wastes containing high amounts of these components should be considered carefully and preferably pre-sorted whenever possible. Once they are introduced into the digester it is more or less impossible to properly control the digestion process.

4.3 Inhibitory components

The initial concentration of volatile fatty acids (VFA) varies with the type of slurry but also with the waste handling and storage conditions. The VFA concentration in pig slurry is higher than in cow slurry. Usually the VFA - content of animal slurries does not cause inhibitory effects, but fast degradation of organic macromolecules like proteins, fats and carbohydrates in agro-industrial wastes may increase VFA concentrations to levels that cause reactor imbalances, especially in combination with low pH-values. However, microorganisms may adapt to high VFA concentrations (~ 5,000 mg $\times$ l^{-1}). Due to the fast biodegradation of organic wastes the VFA-content in anaerobic digesters can become very high, frequently resulting in start-up problems with digesters. Shock loads of VFA normally do not affect the process, if the pH buffer capacity is sufficient and if the micropopulation is not inhibited or weakened by other effects.

Other inhibitory substances e.g. antibiotics, pesticides and disinfectants in the feedstock have been reported to affect the biodegradation in some cases and hence the biogas formation rate. Toxic components e.g. pesticides sometimes occur in crop or harvest residues but have no widespread significance. Inhibiting antibiotic concentrations occasionally have been reported in livestock manure but are only of minor significance.

Inhibitory substances are more frequently associated with agro-industrial wastes. Components like NH_3, H_2S, NO_3^-, fatty acids etc. usually result during processing of high protein or sugar and lipids containing industrial wastes and byproducts.

End products like NH_3 or H_2S may cause gradually increasing inhibitory effects during digestion and caution is required in order to prevent this, especially in combination with high pH values. In particular chicken manure and in some cases also pig slurry, as well as protein containing agro-industrial wastes can evolve inhibitory amounts of free ammonia. But as in the case of VFA, microbial adaptation is possible to high ammonia concentrations beyond 2,000 $mg \times l^{-1}$.

Toxic heavy metal concentrations in animal manure, agricultural and agro-industrial wastes are usually of little concern; but even the occurence of toxic heavy metal concentrations in some cosubstrates does not necessarily result in inhibitory effects, as dilution with the main substrate will reduce its toxicity. In every case of heavy metal occurence, it is not only their microbial inhibitory effects which have to be considered, since even low concentrations prevent the application of sludges as fertilizer on agricultural land.

4.4 Biodegradability

Provided the nurient composition is of similar value, the specific biogas yield of organic wastes may vary from 0.15 to 0.9 $m^3 \times kg^{-1}$ VS (compare table 4). However, the degradation rates of waste organic matter can vary significantly with the substrate composition, e.g. protein-, carbohydrate-, and fat content. Fats are reported to provide the highest biogas yields; however, at the same time, due to their poor bioavailability, require the highest retention times. Carbohydrates and proteins show the fastest conversion rates. For example digestion of pig slurry results in higher biogas yields and methane contents than cow slurry. This is mainly due to a slightly higher fat content. Table 5 shows that the total solids of animal slurries in general contain only very small amounts of fat, while the protein content is somewhat higher. The main components in animal slurries are corbohydrates. Depending on the chemical and physical composition of the waste, the resulting overall degradation rate of organic matter varies between less than 20 % to over 90 %.

Table 5: Chemical composition (in % of total solids) of animal slurries (after Wellinger, 1984; Robbins *et al.*, 1989; Varel *et al.*, 1977; Hobson *et al.*, 1974)

Feedstock	Fat	Protein	Carbo-hydrates	Cellulose	Hemi-cellulose	Lignin	Inorg. residues
Cow slurry	3.5-7.5	13.7-15.6	59.9-62.1	14.5-25.0	2.0-19.3	6.8-9.0	16.0-29.0
Pig slurry	7.0-12.3	16.0-28.9	53.8	10.3-22.9	17.1-20.8	3.7-10.1	17.3-27.0

4.5 Waste handling and digestion properties

The mode of waste generation, the arrangement of waste collection, transport and occasionally required pretreatment, strongly influence the overall process course. Long transport distances, as well as high required storage capacities have ditrimental effects on the overall process economics.

Numerous wastes require effective pretreatment strategies prior to digestion. Common procedures include removal of non-degradable componets (wood, plastics, sand, metals, glass etc.), grinding or cutting of bulky material and finally homogenizing of the waste organic matter. Cosubstrates, particularly ones such as biogenic wastes, garden wastes or kitchen and restaurant waste, often require expensive pretreatment procedures.

Hygienic considerations are also a particular concern in co-digestion. For example slaughterhouse wastes, food remains or flotation sludges, slurry from chicken, pigs and cattle may contain pathogens depending on their origin and state of health. Most countries have their own specific legislation concerning maximum concentrations of indicator organisms, but also limiting concentrations for heavy metals and other toxic substances which will be reported in the AD-NETT technical summary on “legislation”.

Demuynck *et al.* (1984) concluded that in theory the effect of pathogen reduction by anaerobic digestion is significant for bacteria, lower for viruses and poor for parasitic eggs. The same results were found by Bendixen (1994). As temperature is an important parameter controlling pathogens, thermophilic digestion significantly improves their reduction and produces an effluent almost free of pathogenic agents (Aitken, 1992).

Finally the feedstock composition, together with local soil, climate and legal conditions, may influence the potential for recycling of the residual anaerobic sludge to agricultural land, and any required post-treatment of the anaerobic effluent.

4.6 Cofermentation

During the last decade numerous non-agricultural organic wastes have been introduced to farm digesters as cosubstrates. The additional feedstocks applied are mainly derived from agro- and food industries as well as from municipalities (biogenic wastes). Typical feedstocks are:

- food remains from large kitchens, hospitals, etc.
- flotation slimes, fat separation sludges, spent edible oils etc.
- animal wastes from slaughterhouses and rendering plants (blood, paunch and stomach contents, fat)
- organic wastes from the food processing industry (fruit and vegetable remains, distillation slops, olive oils wastewater, fish processing wastes)
- organic wastes from the biochemical industry (fermentation slops)
- organic wastes from textile industries (wastewater)
- organic wastes from the pharmaceutical industry (press cakes, spent tissues, contaminated eggs, spent blood plasma) and

- source separated, organic fraction of municipal solid waste (OFMSW).

Some possible feedstocks have been intensively evaluated in laboratory- and pilot scale at the Institute for Agrobiotechnology (IFA) in Tulln, Austria. The main characteristics of these cosubstrates are listed in table 6.

Table 6: Digesting properties of various possible cosubstrates as investigated at the Institute for Agrobiotechnology, Tulln, Austria

Feedstock	Total Solids [%]	Volatile Solids [% of TS]	Biogas Yield [$m^3 * kg^{-1}$ VS]
Animal blood	9.7	95	0.65
Homogenized animal carcasses	33.6-38.8	90-93	1.14
Rumen contents	14.3	88.5	0.35
Gut and stomach contents	16.5	82.5	0.68
Animal fat (rendering plant)	89-90	90-93	1.00
Food remains	26.2	90-97	0.48
Spent eggs	27.1	92	0.97
Fermentation slops	1.8	98 [1)]	0.78

[1)] COD [$g * l^{-1}$]

Typically cosubstrates are digested in combination with animal manure as the predominant substrate. In most areas, farmers are allowed to process cosubstrates, provided the final waste sludge can be applied to their own land.

It has been shown frequently that the performance of digesters could be considerably improved by means of cosubstrate addition. Table 7 shows some examples of cosubstrates digested in a technical scale. As can be seen up to 80 % cosubstrate addition are applied in some cases in agricultural digesters.

Table 7: Examples of cosubstrates applied in large scale agricultural digesters

Cosubstrate	Biogas plant	Total Solids[%]	Biogas yield [$m^3 * kg^{-1}$ VS]	Cosubstrate addition [%]	References
OFMSW	Hof Lechner, D	20-35	n.a.	35	(26)
Various [1)]	10 centralized biogas plants, DK	n.a.	0.03-0.10 [2)]	14-37	(7)
Slops	Spradau, Twistringen, D	n.a.	0.028-0.033 [2)]	n.a.	(15)
Fish oil	Broby, DK	n.a.	n.a.	n.a.	(15)
Fat remains	Laukenmann, D	n.a.	n.a.	n.a.	(15)
Industrial vegetable remains	Brüederhof, Dällikon, CH	n.a.	0.018 [2)]	75-80	(9)
Slaughterh. wastes, flotation sludges	Finsterwalde, D	n.a.	n.a.	30	(12), (15)
Flotation sludge, rumen contents, bloodwater	Lingen, D	n.a.	n.a.	n.a.	(12)
Flotation sludge, vegetables	Meier, D	7,5	0,036 [2)]	35 flot. sludge 28 vegetables	(13)
Blood plasma	IFA-Tulln, A	20-40	0.40-0.60	10	(3)

[1)] abattoir wastes, fish processing waste, flotation sludge, bleaching clay
[2)] biogas yield per kg total wet influent
n.a. = not available

5 Summary and conclusion

Feedstocks for anaerobic digestion can be derived from various agricultural, industrial and municipal sources. For the current considerations agricultural and agriculture-related wastes from industry and communities are considered exclusively. Aspects of industrial wastewater and biogenic waste digestion are treated in numerous other EU and international work programmes and associations.

Feedstock is a comprehensive term interacting with a multitude of aspects in anaerobic digestion. Not only bacterial physiology, reactor design and operation but also aspects of end-product quality and utilization as well as economic and legal conditions have to be considered.

Among the agricultural wastes, pig and cow slurry, chicken manure and framyard manure are of primary importance. Harvest residues and garden wastes can be applied to anaerobic digestion in principal, but in most cases are treated through traditional routes for composting, soil conditioning and fertilizer purposes. Energy crops so far have not gained any significance in the EU countries, although the storage and application of silage can be of regional significance as a possible alternative using fallow areas.

Waste and wastewater of agriculture-related industries and communities originate from the food-, fermentation-, pharmaceutical and biochemical industries. Food remains from large kitchens, spent edible oils, fats and biogenic wastes from municipalities are frequently digested together with agricultural feedstocks like pig or cow slurry.

The feedstocks for anaerobic digestion considerably vary in qualitative and quantitative composition, homogeneity, fluid dynamics and biodegradability. When selecting wastes for digestion, the total solids content, the percentage of volatile solids, the C : N - ratio and the biodegradability have to be carefully considered. As a rule of thumb, wastes containing less than 60 % of volatile solids are rarely considered as substrates for anaerobic digestion. Con-ventional CSTR type of digesters reliantly operate at total solids contents between 6 - 10 %.

Frequently wastes contain numerous disturbing and inhibiting components. Among the most unwanted components are straw, wood shavings, sand, glass, metals and plastics. Since such matter often causes process failures, more emphasis should be drawn to avoid these components upstream of the digesters.

Inhibitory components, metabolites and products like volatile fatty acids, ammonia and H_2S have to be carefully controlled, especially using chicken manure or, in some cases, pig slurry. Other inhibitory components such as pesticides, antibiotics, disinfectants are rarely reported to be problematic. Heavy metals usually are not present in toxic concentrations in agricultural feedstocks.

The type of waste generation, the arrangement of waste collection, transport and occasional required pre-treatment strongly influence the overall process course. Long transport distances as well as high required storage capacities have detrimental effects on the overall process economics. Numerous wastes require effective pre-treatment strategies prior to digestion. Common procedures include removal of non-degradable components (wood, plastics, sand, glass etc.), grinding or cutting of bulky material and finally homogenizing of the waste organic matter. In the case of codigestion hygienic considerations should be taken into account. In particular, slaughterhouse wastes, food remains or flotation sludges may contain pathogens depending on their origin and state of health, but slurry from chicken, pigs and cattle may also contain pathogens.

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