
**Sludge recovery, recycling, treatment
and disposal — Requirements and
recommendations for the operation of
anaerobic digestion facilities**

*Valorisation, recyclage, traitement et élimination des boues —
Exigences et recommandations pour l'exploitation des installations de
digestion anaérobie*

STANDARDSISO.COM : Click to view the full PDF of ISO 19388:2023



STANDARDSISO.COM : Click to view the full PDF of ISO 19388:2023



COPYRIGHT PROTECTED DOCUMENT

© ISO 2023

All rights reserved. Unless otherwise specified, or required in the context of its implementation, no part of this publication may be reproduced or utilized otherwise in any form or by any means, electronic or mechanical, including photocopying, or posting on the internet or an intranet, without prior written permission. Permission can be requested from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

Contents

Page

Foreword	v
Introduction	vi
1 Scope	1
2 Normative references	1
3 Terms, definitions and abbreviated terms	1
3.1 Terms and definitions	1
3.2 Abbreviated terms	3
4 Fundamentals	3
4.1 Boundaries	3
4.2 Principle	4
4.3 Pre-treatment	5
4.3.1 General	5
4.3.2 Physical pre-treatment	8
4.3.3 Chemical pre-treatment	9
4.3.4 Enzymatic hydrolysis	9
4.4 Digester	9
4.4.1 Shape	9
4.4.2 Configurations	10
4.4.3 Mixing system	11
4.4.4 Heating system	14
4.4.5 Operating temperature	14
4.4.6 Line description	14
5 Digestion performance	15
5.1 Feedstock composition	15
5.2 Feeding characterization	15
5.3 Evaluation of the potential production of methane	16
5.4 Assessment of foaming risks	19
5.5 Rheological properties	20
5.6 Prediction of biogas quality	20
6 Operating performance	21
6.1 Pre-treatment	21
6.1.1 General	21
6.1.2 Shock loading or digester over-loading	22
6.1.3 Inadequate or excessive heating	22
6.1.4 Commissioning, start-up	22
6.1.5 Mixing efficiency and hydraulic retention time	24
6.1.6 Gas system	25
6.1.7 Gas monitoring	26
6.1.8 CH ₄ production	26
6.1.9 Process monitoring	26
6.1.10 Return liquors	27
6.2 Digestate quality and characteristics	27
6.2.1 Process efficiency	27
6.2.2 Dewaterability	28
6.2.3 Biogas quality	28
6.2.4 Biogas quantity	28
6.2.5 Biogas conditioning	29
7 Process safety — Trouble shooting	30
7.1 Pressure control	30
7.2 Stop of CHP machines	30
7.3 Odour management	30
7.4 Foaming	30

7.5	Corrosion.....	31
7.6	Struvite deposits.....	31
7.7	Sand and grit removal.....	31
Annex A (informative) Stabilization of sludge.....		32
Annex B (informative) Chemical parameters of ammonium — pKa values of NH₃/NH₄⁺		35
Bibliography		36

STANDARDSISO.COM : Click to view the full PDF of ISO 19388:2023

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 275, *Sludge recovery, recycling, treatment and disposal*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Anaerobic digestion of sewage treatment plant sludge is an increasing market at world scale. It presents advantages for sludge treatment in terms of sludge volume decrease, organic matter recycling and energy recovery.

Standardization of conditions of operation is therefore a main issue to ensure an efficient development of anaerobic digestion treatment. Anaerobic digestion process is subject to appropriate safety measures because it can represent many risks. Safety parameters are included in risks analyses (e.g. HAZOP).

Therefore, the objectives of this document are:

- to reduce volatile solids, mitigate odours production and generate biogas;
- to obtain good process stability and performance;
- to maximize qualities of by-products: digestate quality, biogas quality for different uses (injection of upgraded biogas into the gas grid, liquefied storage, fuel reuse, electricity and heat production);
- to perform safe and reliable operation: industrial safety for piping and automatism network and biogas equipment is in particular an important issue;
- to reduce emission of greenhouse gasses, especially of methane.

Anaerobic stabilization does not mean sludge sanitization: pathogens reduction is limited to 1 log to 3 logs. Higher reduction can only be obtained with specific conditions of temperature and residence time which are not discussed in this document.

Sludge recovery, recycling, treatment and disposal — Requirements and recommendations for the operation of anaerobic digestion facilities

1 Scope

This document establishes requirements and recommendations for the operation of the anaerobic digestion of sludge in order to support safe and sufficient operation of anaerobic digestion facilities to produce sufficient biogas and control by-products qualities.

In particular, conditions to optimize mixing within the reactor and appropriate control systems management for safe and reliable operation are described in this document. Performance of the processes in terms of biogas and digestate production are presented depending on type of technologies available on the market. Blending sludge with waste (co-substrate) and mixing the sludge with organic wastes to increase digester loading are also considered.

This document is applicable to decision-makers and operators in charge of an anaerobic digestion system.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1 Terms and definitions

3.1.1

acetoclastic methanogenic microorganism

anaerobic microorganism which use acetate as a main substrate

3.1.2

anaerobic digestion

anaerobic process which achieves two equally important functions, the anaerobic stabilization of substrate and the production of energy through conversion of substrate into biogas

3.1.3

biochemical methane potential

BMP

volume of methane generated during the sample degradation referred to the mass of the sample of biosolid and expressed in normal conditions of temperature (0 °C) and pressure (1 013 hPa)

3.1.4

digestate

digested sludge

remaining effluent from the anaerobic digestion process including solid fraction and liquid fraction

[SOURCE: ISO 20675:2018, 3.19]

3.1.5

digester gas

biogas

gas mixture generated during anaerobic digestion consisting mainly of methane and carbon dioxide

3.1.6

feeding

process of adding substrate into an anaerobic digester

3.1.7

hydrolysis

biological, chemical, thermal or physical transformation of solid chemical oxygen demand into dissolved chemical oxygen demand by reaction with water

3.1.8

phase

distinct metabolic pathways

EXAMPLE Two-phase digestion: hydrolysis/acidogenesis followed by acetogenic/methogenic.

3.1.9

readily degradable substance

substance which is easily and completely degradable by microorganisms

3.1.10

sludge age

solids retention time in a reactor

Note 1 to entry: The common unit is d.

3.1.11

stabilization

process in which organic substances are converted to materials that are not biodegradable or are slowly biodegradable

3.1.12

stage

consecutive part of a process

EXAMPLE Two-stage digester, i.e. a primary digester followed by secondary digester for completing processes.

3.1.13

substrate

feedstock containing degradable organic components

3.1.14

volumetric organic load

mass of substrate, measured as total solids, volatile solids, biochemical oxygen demand or chemical oxygen demand, fed per digester volume and day

3.2 Abbreviated terms

ATU	allyltiourea assay
BMP	biochemical methane potential
BOD	biochemical oxygen demand
CAPEX	capital expenditure
CHP	combined heat and power
COD	chemical oxygen demand
ECP	extracellular polymer
FOG	fats, oils and greases
HRT	hydraulic retention time
ITHP	intermediate thermal hydrolysis process
OUR	oxygen uptake rate
OPEX	operational expenditure
SOUR	specific oxygen uptake rate
SRT	solids retention time
TS	total solids
VFA	volatile fatty acids
VS	volatile solids

4 Fundamentals

4.1 Boundaries

[Figure 1](#) describes the system configuration of the anaerobic digestion. In this document, the focus is oriented on anaerobic digester operation and pre-treatments.

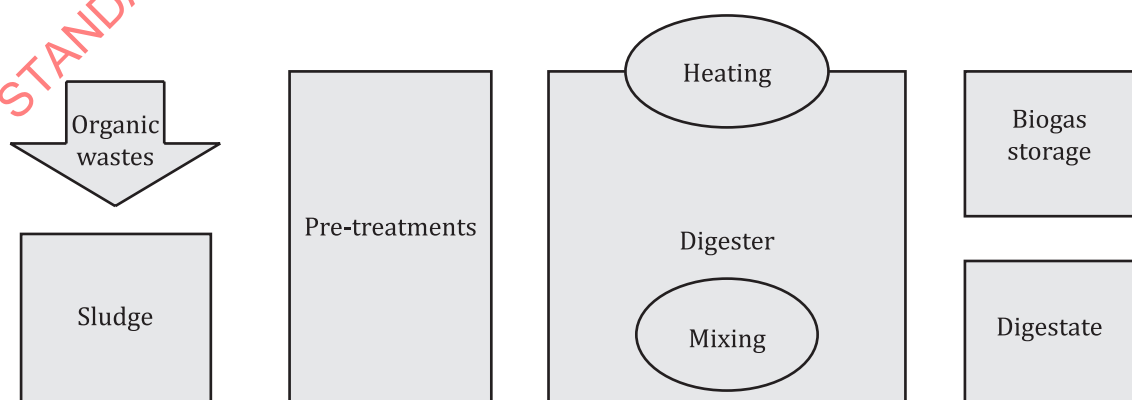


Figure 1 — Typical system configuration of anaerobic digestion

4.2 Principle

Anaerobic digestion is a cornerstone process of wastewater treatment operations, wherein solid waste streams can be effectively treated and resources recovered. Anaerobic digestion usually requires primary sludge. Most of the digester gas is generated from primary sludge. Secondary or tertiary sludge can also be stabilized, but they should be (usually mechanically) thickened prior to anaerobic digestion. The pervasive rollout of activated sludge-based wastewater treatment processes in particular throughout the 20th century, necessitated digestion processes to effectively stabilize the large volumes of generated waste activated sludge. The key purpose of anaerobic digestion during wastewater treatment is to achieve disintegration and destruction of the degradable sludge solids fraction in order to reduce this fraction and to reduce the mass and volume of the sludge material after dewatering or drying.

This treatment recovers useful resources such as combustible digester gas (methane) and nutrients in the digester sludge. Anaerobic digestion involves microbial decomposition of the organic constituents present in wastewater sludge (i.e. proteins, carbohydrates and lipids) in the absence of dissolved oxygen. Microorganisms involved in anaerobic digestion comprise a complex consortium of microbes, with different metabolic properties and physicochemical requirements. The key products of anaerobic digestion, apart from digested and stabilized solids rich in phosphorus include water containing high levels of ammonia and alkalinity, and a biogas which comprises principally methane (typically 60 % v/v to 70 % v/v) and carbon dioxide (typically a volume fraction of 30 % to 40 %), with other minor constituents including hydrogen, nitrogen, hydrogen sulfide and siloxanes. Digester gas composition depends on substrate quality. It can be different for industrial sludge or where co-substrates are added.

Anaerobic digestion transfers energy from solids to digester gas (methane). Only a very small amount of energy is used for the production of biomass. Theoretical calculation gives 0,35 m³ methane with an energy content of 3,5 kWh per kg of COD removed.

Anaerobic digestion is performed through four distinct biological steps, namely hydrolysis, acidogenesis, acetogenesis and methanogenesis; an additional pre-treatment stage may be added prior to hydrolysis for feedstocks containing solid particles in order to breakdown solids to smaller particles which are more amenable to hydrolysis.^[50]

- Hydrolysis: Hydrolysis generates soluble organic components (e.g. sugar) from volatile solids which microorganisms can absorb through their cell membranes. Hydrolysis is usually the rate-limiting step during the digesting process.
- Acidogenesis: Hydrolyzed compounds formed during the hydrolysis step are further converted to a mixture of short-chain volatile fatty acids (e.g. acetic acid, propionic, butyric and valeric acids), alcohols, esters, sugars and other simple organic compounds (e.g. carbonic acid) by a diverse array of microorganisms called acidogens. The relative proportion of the different metabolic co-products (H₂ and CO₂) depends on the substrate quality as well as the operating conditions.
- Acetogenesis: Products of acidogenesis are further transformed to acetic acid, CO₂ and H₂ by acetogenic microorganisms. Acetogenic microorganisms are relatively slow growing compared to the acidogens, such that careful process control and stable digester operation is required to avoid excessive acid accumulation and concomitant pH drop which can lead to digester upsets or process failure. Nevertheless, the slowest growing microorganisms are the methanogens.

Some minor route such as syntrophic acetate oxidation performed by methane microorganisms (oxidation of acetate into H₂ and CO₂) can occur and be prevalent when stressful conditions are encountered (e.g. high concentration of ammonia resulting from high ammonium concentration, high pH and high temperature).

- Methanogenesis: This final stage generates methane from either acetate or hydrogen by methanogenic microorganisms (Archae). Usually acetate is the main source for the production of methane (approximately 70 %) via so-called acetoclastic methanogens, with the remaining approximately 30 % of generated methane being generated from hydrogen-utilizing methanogens. The balance between methane generation from acetate and from hydrogen is variable depending on operating conditions and substrate characteristics. Methanogens are slower growing than both

the acidogens and acetogens, and are also susceptible to environmental stresses in the form of pH and temperature imbalance, toxic or inhibitory substances such as free oxygen, or disruptions of nutrient supply.

This succession of steps shows two points of attention in order to optimize anaerobic digestion operation.

- a) Methanogenic microorganisms (mainly acetoclastic methanogens) are the slowest to grow because their substrate and their end products have a small energy difference (i.e. they gain little energy). In addition, they are most sensitive to inhibition.

Methanosarcina have a maximum growth rate of 0,3 d⁻¹ and *Methanothrix* have a maximum growth rate of 0,1 d⁻¹.^[8] According to the Monod equation, the growth rate depends on the substrate concentration. The Monod equation is given in [Formula \(1\)](#):

$$\mu = \frac{\mu_{\max} \times C_s}{K_s + C_s} \times \frac{K_i}{K_i + C_i} \quad (1)$$

where

μ is the growth rate, in d⁻¹;

$\mu_{\max}$ is the maximum growth rate at unlimited substrate concentration, in d⁻¹;

K_s is a constant, in g/l, depending on the kind of microorganism and its substrate; if $C_s = K_s$, then $\mu = 1/2 \times \mu_{\max}$;

K_i is a constant, in g/l, depending on the kind of microorganism and its inhibitor; if $C_i = K_i$, then $\mu = 1/2 \times \mu_{\max}$;

C_i is the inhibitor concentration, in g/l;

C_s is the substrate concentration, in g/l.

- b) Hydrolysis is the velocity-limiting process step during the digesting process. In preferably heated raw sludge storage tanks some biological hydrolysis takes place. Particulate COD is turned into dissolved and easily degradable COD.

Two stage digestion occurs in a highly loaded first-stage digester followed by a less loaded second-stage digester; the microorganism in both stages can be the same. A two-stage digestion (mesophilic and mesophilic) is more efficient than a single mesophilic reactor because the distribution around the mean retention time is tighter.

4.3 Pre-treatment

4.3.1 General

Substrate thickening is usually the first pre-treatment process. The fed substrate should have a solids concentration (30 g/l to 80 g/l) in accordance with the anaerobic digester operating conditions. This concentration should reach 150 g/l to 250 g/l in case of co-digestion of sludge and other organic waste. Concentration of either sludge or organic waste, or both, shall be performed by gravity or mechanical thickening.

Additional pre-treatments improve anaerobic digestion performance leading to either an increase of organic volumetric organic load or an increase of gas yield, or both. These pre-treatments are preferably designed to enhance sludge hydrolysis which is the velocity limiting step of anaerobic digestion. Fine screening of all fed substrates is generally recommended to remove coarse material, such as hygienic and cosmetic products and plastic matter. Removal of sand and grit reduces abrasion and wear of mechanical equipment and deposit formation in pipelines and channels, and accumulation of grit in anaerobic digesters.

Advantages and drawbacks for different types of treatment before anaerobic digestion are presented in [Table 1](#).

The full-scale estimations represented in [Table 1](#) are average values which depends on the process characteristics.

STANDARDSISO.COM : Click to view the full PDF of ISO 19388:2023

Table 1 — Advantages and drawbacks for different types of treatment before anaerobic digestion

Pre-treatment technique	Type of sludge	Hydrolysis rate (k _{hyd})	Biodegradation	VS removal	Dewaterability of digestate	Return load (NH ₄ -N)	Biogas yield	OPEX	CAPEX	Reference
Physical pre-treatment										
Thermal < 100 °C, time application < 24 h (pasteurization)	Mixed sludge	+	±	±	±	--	±	++	++	[44]
Thermal > 100 °C	Mixed sludge and excess sludge	++	++	++	+	-	++	++	+++	[25]; [26]; [28]; [29]; [30]; [34]; [35]; [36]; [37]; [38]; [39]; [41]
Mechanical (pressure homogenizer, ultrasonic and mechanical disintegration)	Mixed sludge	+/++	+	+/++	±	-	+	+/++	+/++	[47]; [45]; [40]; [46]; [26]; [33]; [32]
Chemical pre-treatment										
Alkaline hydrolysis	Mixed sludge (industrial and municipal)	++	+	++	-	-	±	++	±	[7]
Oxidation (O ₃)	Mixed sludge	++	+	++	+	-	+	++	++	[45]
Biological pre-treatment										
Enzymes	Mixed sludge	+	±	±	+	-	±	+/++	±	[31]; [43]; [26]
Key + : improvement (+ low, ++ medium, +++ high) - : degradation (- low, - medium, -- high) ±: no significative change The signs (±) used in this table derive from full-scale anaerobic digestion data with or without pre-treatments.										

A new excess biological sludge treatment configuration has been developed which consists of an ITHP. The potential benefits of this new configuration are volatile matter reduction, enhanced biogas production and a significant increase of the dewatered digested sludge dryness^[27].

4.3.2 Physical pre-treatment

4.3.2.1 Thermal hydrolysis

As hydrolysis is the rate-limiting process step, pre-hydrolysis of thickened raw sludge in a heated and agitated blending and storage tank improve the overall process performance. Hydrolysis can also be achieved through high-thermal pre-treatment (between 80 °C and 200 °C), with or without the addition of chemicals (acidic or caustic). Degradation and digester gas production is increased and dewaterability of the digestate is improved.

High thermal hydrolysis processes can employ direct steam injection into the sludge hydrolysis tank in order to reach temperatures in the range of 140 °C to 170 °C (higher temperatures shall be avoided in order to limit production of refractory COD). Average pressure is around 4 bars¹⁾ to 6 bars and the usual retention time under these conditions of temperature and pressure is 30 min. Heat recovery commonly include two or three reactors: one for preheating and homogenization, one for reaction, and one for cooling and heat recovery, respectively.

Hydrolysis can also be enhanced with a combination of thermal and alkaline processes. They require often lower temperature and addition of chemicals. The temperature is usually around 70 °C and pH varies from 10 to 12. In comparison to sole thermal hydrolysis alone, the operating temperature and pressure are lower, which is the main interests of this configuration.

4.3.2.2 Sanitization

Pasteurization is the most common technology in case of added organic substrate which needs to be sanitized (e.g. feedstock originating from animal waste). The feedstock is quickly heated at a temperature of minimum 70 °C for a minimum of 1 h. In case of feedstock originating from animal waste, the particle size should not exceed 12 mm to ensure that the whole matrix is properly hygienized. Heat recovery is commonly included; usually three reactors are provided: one for heating, one for reaction time and one for cooling and heat recovery.

4.3.2.3 Compression or decompression — Pressure homogenizer

The use of rapid vacuum conditions of up to 200 bars (e.g. 20 MPa) in a dedicated reactor (e.g. cavitation chamber) to facilitate the destruction of microorganisms and polymers structures by combining large pressure drop, turbulent eddies and shear forces, and make the sludge more feasible to the anaerobic biodegradation.

4.3.2.4 Ultrasounds pre-treatment

Ultrasound treatment operates through cavitation phenomenon inducing local spots of high pressure and temperature. The use of high intensity ultrasounds, at a frequency of approximately 20 kHz breaks down cell walls, releasing additional structural polymers and intracellular organic contents and intracellular organic content by fractionating the organic material to make it readily biodegradable. A fraction of sludge, generally thickened or dewatered from 6 % to 12 % of dryness, is introduced into the ultrasonic vessel, this fraction is usually around 30 % and affects mainly biological sludge. The other interest of ultrasonic treatment is the destruction of filamentous bacteria in the upstream digester.

4.3.2.5 Mechanical disintegration

Mechanical pre-treatment is used to destroy cells of the biological sludge. The content of the cells becomes easily degradable. Disintegration increases biogas generation. Common systems use,

1) 1 bar = 0,1 MPa = 105 Pa; 1 MPa = 1 N/mm².

high pressure nozzles or milling. Only (ball) mills are systems for mechanical pre-treatment unless decompression is also taken as a mechanical treatment.

4.3.3 Chemical pre-treatment

4.3.3.1 Oxidation by ozone or hydrogen peroxide

Chemical treatment with oxidation agents mainly aims on the destruction of unsaturated fatty acids in the cell membrane of microorganisms. Solubilisation of organic complex matters including microorganisms by strong oxidation is carried out in a separate and dedicated tank. Literature gives a dose of ozone injected around 0,1 kg O₃/kg TS.

4.3.3.2 pH variation

Acid or alkaline chemicals are added to the sludge in a chemical conditioning tank in order to enhance degradability of volatile solids. pH modification can be coupled with thermal or mechanical pre-treatments (see 4.3.2). Alkaline chemicals are more commonly used. The hydrolysis rate increases proportionally with the concentration of H⁺ or OH⁻ ions. It causes the cleavage of carbohydrates, proteins and other biopolymers and thus dissolution of the cell wall.

4.3.4 Enzymatic hydrolysis

Selected enzymes are mixed with sludge in order to accelerate hydrolysis of slowly biodegradable organic compounds into small compounds easy to convert into methane. Enzymes act as a catalyst of hydrolysis reaction and are not consumed in the anaerobic digestion process but washed out with the digestate without impact on environment. They are biologically degradable and therefore not harmful to the environment. Main types of enzymes are cellulase, hemicellulase, protease, lipase and DNase. Operating conditions are strictly dependant on the enzyme used. Usually the mixture of enzymes is added either directly into the digester or via a pump into the feed line.

Enzymes can be *in situ* produced in a dedicated hydrolysis reactor with specific conditions of temperature and pH [see 4.2 b)]. These exo-enzymes are produced by hydrolysing bacteria.

Temporary addition of enzymes may be useful if a digester is upset. Continuous addition of enzymes is not economical because they are washed out with the digested sludge.

4.4 Digester

4.4.1 Shape

Sludge is usually digested in a more or less continuously fed and mixed reactor (CFMR) in one or more steps. The main features of these continuous stirred tank reactors (CSTR) include the tanks, mixers, covers and heating systems.

There are different types of anaerobic digesters and configurations. There are wide variations of digester shapes, from shallow cylindrical digesters (so called pancake digesters) with or without floating cover to egg-shaped digesters. Digester equipment, in particular their mixing systems, depends on digester geometry.

There are single-stage and two-stage digester systems (e.g. mesophilic and mesophilic), the latter offering a higher degradation rate per unit volume. There are additional processes used in combination with anaerobic digestion, for example, disinfection, disintegration or hydrolysis processes (see 4.3). There are processes to remove phosphate from anaerobic digesters in the form of digesters (magnesium-ammonium-phosphate) in order to avoid operational problems in the digester and downstream equipment and to recover phosphorous. Operational requirements depend on the type of digester, process configuration and coordination.

Characteristics of the feedstock can influence decisions on the kind of system used, in particular solids concentration.

There are additional operational considerations: anaerobic digestion at wastewater treatment plants needs to be very reliable because raw sludge is generated continuously.

The common digester shapes include but are not limited to the following list:

- a) Shallow, cylindrical, flat bottom tanks with a height to diameter ratio below 1:2: Such tanks are, for example, common in the US. They can be equipped with a floating cover to retain the biogas, or a fixed cover. Mixing is usually done with external recirculation (e.g. jet mixing), multiple draft tube mixers or multiple injection point gas mixing. Removal of deposits is required every few years.
- b) Cylindrical, flat bottom tanks with a height to diameter ratio of at least 1:1: Such tanks are common in Europe, for example, in France and Germany. Digester mixing is usually achieved with mechanical mixers or multiple point biogas injection.
- c) Cylindrical tanks with a top dome and bottom cone with a ratio of cylinder height to diameter of about 1:1: The top dome serves to concentrate scum on a small surface from where it can be removed. Since fine screens have become common in preliminary works, this design is less common in some countries. Digester mixing is done through external sludge recirculation (for small digesters), a central mechanical draft tube mixer or peripheral biogas injection.
- d) Egg-shaped digesters were developed in Germany and are used in other countries too: They are used at medium to large plants. They are mixed with either a central mechanical draft tube mixer or through peripheral gas mixing, or both.

4.4.2 Configurations

Conventional digesters are designed to have a SRT equal to the HRT. The extended SRT digestion process which has greater SRT than HRT done by thickening the digestate and then recycling it back to the digester. But that is not well adapted to highly concentrated sludge due to the difficulty to have adapted thickening equipment and risk to lose anaerobic conditions. Anaerobic digestion can be designed as either single, two stages or even multi-stages digesters.

Two-stage digestion is usually limited to plants equal or higher than a total population of 20 000 inhabitants. The two digesters can be operated under the same mode or the second one can be operated as a gravity thickener and sludge returns from the bottom of the second digester to the first digester in order to increase SRT over HRT.

Another configuration called two-phase digestion is designed and operated in order to separate and optimize the main biological steps, for example, hydrolysis and partial acidogenesis occurring in the first reactor and methanogenesis in the second. Main advantage is to apply optimal operating conditions for each phase, for example, thermophilic condition for enhancing hydrolysis or increasing pathogen inactivation in the first phase and mesophilic in the second phase. SRT and mixing conditions shall be specific and adapted for each phase.

Volume of single digester is calculated to provide usually an HRT or SRT in the range of 16 d to 30 d. The overall SRT or HRT of two-stage digestion is usually in the range of 15 d to 22 d and for the two-phase process, volume can be reduced to 2 d or 4 d of HRT depending on the size of the plant and the quality of the sludge for the first phase and around 10 d or 15 d for the second one. In case of mixture with organic waste, the recommended TSH / TSS can be around 35 d to 45 d, even more (up to 60 d when mixed with, for example, manure with high straw content or cereal residues).

The advantages and drawbacks of each common digester configuration is presented in [Table 2](#).

Table 2 — Main advantages and drawbacks for three digester configurations

	Advantages	Drawbacks
Single digester	low capital expenditures; easy to operate; low sensitivity to feedstock variations	high HRT; big volume
Two-stage digesters (primary followed by secondary digester)	great biological stability in the second stage; low SRT and HRT; great stability regarding feedstock variations; decreased anaerobic digester total volume; increased VS degrada- tion and digester gas production	high CAPEX
Two-phase digesters (two distinct metabolic pathways)	short SRT/HRT; great biological stability; great stability regarding feedstock varia- tions; possible sanitization in case the first phase is thermophilic with a certain mini- mum batch period	less easy to operate than the single digester; high CAPEX; large footprint; large risk zone around the digesters

Digesters are usually made of concrete or steel. The choice of material depends on the size and the shape of the digester. Above the minimum sludge level, concrete or steel shall be protected against corrosion.

Efficiency of digestion systems can be enhanced by additional pre-treatments (see 4.3).

4.4.3 Mixing system

4.4.3.1 General

Even if natural mixing occurs in anaerobic digesters thanks to gas bubble rising and thermal convection, additional mixing is required. Mixing prevents stratification within digesters and it also ensures uniform conditions (temperature, concentration of substrate, etc.) throughout the entire volume.

Adequate mixing permits treatment of raw sludge with a solids concentration of up to 10 %. The higher the sludge concentration, the higher is its viscosity and the higher is the required mixing energy. In case of mixing with biowaste or for dewatered sludge, the dryness at the feed can reach 20 % or slightly more.

Digester mixing has the following objectives:

- fast and even distribution of the raw sludge (substrate) into the bulk of the digested sludge within the digester;
- avoiding of concentration and temperature gradients within the digester;
- acceleration of mass and temperature transfer;
- prevention of dead zones, short-circuits, deposits and scum layers;
- acceleration of biogas release;
- avoidance of disturbances or interruptions of digester operation.

Sufficient mixing is essential to keep most of the digester volume long-term active and to prevent the need for periodic digester emptying or the need to employ divers to remove solids deposits. Intensive digester mixing avoids the need for additional digesters and reduces maintenance costs. The quality of digester mixing can be determined with tracer tests (e.g. with addition of lithium). Nevertheless, the mixing power should rather be too high than too low to obtain a controlled balance between foaming and homogeneity criterion.

The following equipment is commonly used for digester mixing:

- external recirculation pump (including jet mixing);
- draft tube mixers (either mechanical or with biogas injection);

- internal propeller mixers;
- biogas injection (through peripheral nozzles and/or hanging gas lances). The choice of the mixing equipment depends on the size and shape of the digester. There are digesters which are equipped with more than one mixing system, for example, with a draft tube mixer at its centre and gas injection to its periphery.

NOTE Tanks with a rooftop mixer require a rigid roof structure to support the mixer.

4.4.3.2 External pump recirculation

External sludge recirculation through pumping is commonly sufficient for small digesters with a volume of up to 500 m³ (see EN 12255-8^[4]) and even then, only if the digester has a steep conical bottom. Some larger digesters can also be equipped with such a system. This system is simple and inexpensive, but energy-inefficient. The digester volume should be recirculated about 10 times per day. This requires a power-density of about 6 W/m³ to 10 W/m³. Most of the introduced energy is wasted to overcome pipe friction and only a small portion is introduced into the digester as kinetic energy.

The energy efficiency can be improved by providing nozzles (as with the jet-mix system) to increase the introduced kinetic energy, however such internal nozzles can clog and cannot be cleaned without taking the digester out of operation. Such systems are more reliable if the raw sludge is fine-screened. Jet mix systems employing several nozzles can be used for flat bottom digesters and digesters larger than 500 m³.

External sludge recirculation cannot guarantee complete digester mixing and prevention of dead zones.

4.4.3.3 Draft-tube mixers

Draft-tube mixers comprise a large diameter vertical pipe extending from near the digester's bottom to near the sludge surface. In its upper end, an impeller is turning, either drawing sludge up through the tube or driving it down. The position of the tube needs to be secured by rods or ropes.

There is a kind of draft tube mixer employing gas injection near its lower end to drive sludge up through the tube (like a mammoth pump).

A single central draft tube mixer is often installed in tall egg-shaped digesters, where they are quite effective. The sludge is conveyed from the surface of the digester via the central tube to the bottom in a spindle-shaped flow pattern. In cylindrical digesters, a number of draft-tube mixers are needed, usually one in the centre and four to eight in the periphery, depending on the diameter of the cylindrical digester. This makes the system expensive.

Draft-tube mixers also require a turnover of about 10 times the digester volume per day. In comparison to external sludge recirculation, the friction losses are smaller. The power density is 3 W/m³ to 6 W/m³, and, if the sludge has a high viscosity, up to 10 W/m³ can be needed.

Mechanical draft-tube mixers require an almost constant sludge level of ± 15 cm. This makes them rather unsuitable for two-stage digestion system where the sludge level in the first digester depends on the viscosity of the sludge flowing from the first to the second stage.

Because digesters with draft tube mixers require a near constant sludge level, the sludge level cannot be lowered when digester foaming occurs. Draft-tube mixers should therefore not be installed where heavy sludge foaming is expected.

4.4.3.4 Propeller mixers

Propeller mixers can be used for small to medium-sized digesters, to make possible their removal without interrupting the digester operation.

Large, vertically and centrally mounted, slowly rotating mechanical mixers have been used in Europe for about 25 years in tall cylindrical digesters. They have large rotors driving the sludge down onto

the bottom of the digester and then radially outward above the bottom. The velocity above the bottom should be at least 0,3 m/s. The power density of such mechanical mixers varies from 2 W/m³ to 10 W/m³, depending on the digester shape and the sludge viscosity. The power density can reach 20 W/m³ for a mixture of sludge and biowaste with a high dry matter content (20 % or more).

For several years, derived from agricultural methanization, small digesters have been equipped with propeller mixers which are installed in the digester wall, driving the sludge diagonally and tangentially down. Such mixers are installed through sloped pipes extending to above the sludge level; their rotors have a small diameter and turn fast. Such systems are quite inefficient because they create a lot of turbulence but not much thrust for the sludge movement.

Submerged rotors have been used for a few years to save costs. They drive the sludge in a horizontal and tangential direction. They are installed on vertical rods and can be pulled out by pulling their chains.

The required power density of mechanical mixers depends on the sludge viscosity and on the hydraulic conditions within the digester. The smaller the rotors of mechanical mixers are and the faster they rotate, the lower is their capability to drive the sludge through the digester and the lower is thus their energy efficiency.

It should be considered that ragging can occur on all equipment which is installed within digesters, such as rotor blades, rotor shafts, rods, ropes and chains. Precondition for the use of mechanical mixers is thus fine-screening of the raw sludge.

4.4.3.5 Gas mixing

Gas mixing has been successfully used for many decades. Digester gas is compressed and periodically introduced near the bottom of certain sections of the digester, for example, on one half or a quarter. The introduced gas drives the sludge in this subclause up creating a rolling sludge movement throughout the digester.

The large gas bubbles create turbulences and prevent the formation of scum layers on the sludge surface. However, gas injection can increase sludge foaming.

There are various kinds of gas injection equipment. Most common are hanging gas lances in flat bottom cylindrical digesters and peripheral gas nozzles in egg-shaped or conical bottom digesters.

The gas is usually not injected continuously but intermittently with high power density into certain zones of a digester. For this reason, a single gas compressor can serve several digesters. Common injection times are 16 h/d into a first stage digester and 8 h/d into a second stage digester.

Friction losses in the gas pipelines are low and the introduced gas bubbles transfer almost their entire compression energy into kinetic sludge movement energy. Depending on the sludge viscosity, the power density is 3 W/m³ to 10 W/m³ while the gas is introduced.

The above given power densities refer to a common municipal raw sludge with a dry solids content of up to 7 %. Regardless of the mixing system, a higher power density may be required if the dry matter content, and/or viscosity of the raw sludge, is higher. Because it is usually not possible to predict the dry solids content and the viscosity of the sludge which will be fed in the distant future, it is recommended to install a high-power mixing system. As long as such a high power density is not needed, the mixing system can be operated intermittently to save power consumption.

It should also be noted that the power density alone is a poor criterion to determine the mixing intensity. At first, it does not take into account the system's energy efficiency, and secondly, the thrust force of a system is also important. A fast turning small rotor can consume the same power as a large and slow turning rotor, but it cannot generate the same thrust and thus not the same sludge movement.

4.4.4 Heating system

To maintain the digester temperature at the required conditions, it is necessary to heat sludge which is done on influent/recirculated sludge entering the digester via direct heating by steam blowers (or injectors) or indirect heating by heat exchangers.

In a direct heating system, high-temperature steam is introduced into sludge. It is injected in the form of small steam bubbles into recirculated sludge.

Condensing steam transfers a substantial amount of enthalpy. To prevent overheating and damaging the bacteria, high sludge turbulence is needed where steam is injected. Steam addition increases the water content of the sludge, but usually by not more than 5 %. The equipment for steam injection is inexpensive but requires de-ionization of the boiler's make-up water.

In indirect system, heat exchangers are generally used on a recirculation loop on digested sludge to heat sludge with hot water. Hot water can be produced from boilers running with part of the produced biogas or from heat generated in CHP-systems which is usually sufficient for digester heating (at least if the raw sludge is sufficiently thickened).

Heat exchangers for indirect heating can be of various shapes, tubular or spiral. The choice depends on economical aspect or on preventing clogging risks.

The heating system is designed to heat the influent and recirculated sludge but also shall compensate the losses through digester walls, roof and bottom.

4.4.5 Operating temperature

Three types of digestion exist, depending on the operating temperatures:

- psychrophilic, at room temperature: up to 25 °C;
- mesophilic, between 30 °C and 45 °C;
- thermophilic, above 45 °C.

The choice of the operating temperature is a function of the feedstock to digest, the cost for heating but also the end use of the digestate.

Psychrophilic anaerobic digestion is rarely used due to the low kinetics and, consequently, the need of large sludge retention time, that means a very large specific volume.

Mesophilic systems allow more robust bacterial populations compared to thermophilic systems mainly in terms of either resistance or adaptation to inhibitors or changes of operating conditions.

Thermophilic digestion may be chosen for space reduction due to faster kinetics and in case of co-digestion with organic waste (requiring sometimes disinfection). The characteristics of digestate in terms of odour and dewaterability are commonly poorer. It is important to consider that thermophilic digestion doesn't allow to meet regulations in terms of pathogens removal without special design in order to maintain a minimum residence time of all biosolids (e.g. batch or plug flow hydraulics).

4.4.6 Line description

Anaerobic digestion requires pumping, heating, mixing operations, all interconnected. Three distinct parts can be considered: the inflow, the outflow and the volume within the digester.

- The digester inflow is a mix of (potentially pre-treated) raw sludge pumped from the storage tank and recirculated sludge from the digester. This inflow is pumped through the heat exchanger before entering into the digester at the operating temperature. The inlet flow rate is calculated to ensure an appropriate hydraulic retention time within the digester and is equal to the outflow plus the overflow.

- The entire volume of the digester should be mixed to homogenize the inflow and the digested sludge within the digester.
- Biogas is collected at the top of the digester and is partly stored for future usage and partly burnt to produce heat for the heat exchanger. When raw sludge is pumped into a digester the same volume of digestate overflows from the digester (or another digester in case of two-stage digestion). There should be at least two overflow pipes: One from the digester bottom and another one from below the minimum sludge level. Using one or the other overflow, the solids content in the digester can be controlled. In addition, an always open emergency overflow pipe shall be provided defining the maximum sludge level in the digester.

5 Digestion performance

5.1 Feedstock composition

The composition of feedstock influences directly the digestion performance. In general, the percentage of volatile solids is a good parameter to assess the biodegradability of a feedstock but the nature of the organic matter can affect drastically the part of VS which can be hydrolyzed and consequently produce biogas. For instance, 55 % to 70 % of primary sludge volatile solids can be converted into biogas whereas for biological sludge the value drops to 30 % to 45 % depending on the organic load of wastewater treatment line.

One way to be more accurate is to characterize the feedstock in terms of percentage of major organic components (FOG, proteins, carbohydrates and COD/VS ratio).

The comparison of these components for biogas production gives the following order FOG > hydrolysable carbohydrates > proteins > long chain carbohydrates.

The [Table 3](#) shows the order of magnitude of various organic waste composition.

Table 3 — Order of magnitude of various organic waste composition

	Fat-oil-grease	Proteins	Carbohydrates
	%	%	%
Primary sludge	20	20	60
Waste activated sludge	5	50	45
Municipal solid waste	25	15	60
Raw dairy manure	15	10	75
Sugar beet	—	10	90
Corn silage	5	15	80
The values in this table are expressed in a percentage of the volatile suspended solids.			

Special attention shall be given to the carbon-to-nitrogen ratio (C/N) in order to prevent inhibition by NH_3 . Ratio C/N in the range of 20 to 30 is suitable for avoiding inhibition phenomenon. Effect of temperature should also be taken into consideration, the higher the temperature, the higher the threshold of C/N ratio is. In the same way, operators shall be careful with the sulfur content of the feedstock either to avoid inhibition of methanogenesis or high H_2S concentration into the biogas, or both, requiring specific treatment before final use.

A BMP test (see [5.3](#)) can be performed to evaluate the potential production of biogas.

5.2 Feeding characterization

The digestion system has to be designed to handle the maximum loading. Either the various tests or analysis selected for substrate characterization, or both, should be determined under consideration of the digestion system's characteristics. If digestion of industrial sludge is needed, or if substantial

volumes of co-substrate are added, BMP tests should be performed. For common municipal sludge, testing is usually not required.

5.3 Evaluation of the potential production of methane

When the substrate to be treated is not available, for example, when a new wastewater treatment plant is built, it is necessary to use data from similar systems in order to estimate degradation of VS and biogas production. This is usually possible for municipal wastewater treatment plants, but more difficult for bio-waste treatment facilities.

For municipal wastewater treatments plants, the production of primary and secondary sludge solids and their VS content need to be estimated anyway. Based on these data the potential for VS degradation and biogas production can be derived.

It may be assumed that about 70 % of the VS in the primary sludge and about 30 % to 45 % of those in the waste activated sludge are readily degradable.

The technical degradation ratio in anaerobic digesters depends mainly on the following conditions:

- single or two stage digestion;
- temperature in the digesters;
- anaerobic sludge age (means sludge retention time) in the digesters;
- mixing quality of the digester content;
- presence or not of inhibitors.

The hydrolysis rate k_H , in d^{-1} , for aerobic and anaerobic degradation depends on the process temperature T , °C, as given in [Formula \(2\)](#):

$$k_H = 0,045 \times 1,072^{(T-10)} \quad (2)$$

In a continuously fed and ideally mixed reactor, the technical degradation rate η depends on the hydrolysis rate k_H and the sludge age t_s , in d, [\[22\]](#) as shown in [Formula \(3\)](#):

$$\eta = \frac{k_H \times t_s}{(1 + k_H \times t_s)} \quad (3)$$

In a two-stage process, the overall degradation η_{tot} is as given in [Formula \(4\)](#):

$$\eta_{tot} = \eta_1 + (1 - \eta_1) \times \eta_2 \quad (4)$$

The degradation ratio η or η_{tot} should be minimum 85 % and is usually above 90 %.

If a digester is not well mixed, the sludge age t_s is calculated with a smaller long-term active volume.

The gas yield of degraded primary sludge VS is about 0,95 Nm^3/kg and that of secondary sludge solids is about 0,85 Nm^3/kg . It should be noted that the gas yield is expressed as dry gas at normal conditions (1 013 hPa and 0 °C). The methane content is about 64 %.

When the substrate to be treated is available, it is possible to investigate its degradation and methane potential with a BMP test.

BMP tests should be performed in a sealed and dark vessel having a representative volume (e.g. >0,5 l). The content can be well stirred and shall be kept at the temperature the digester is designed for. Depending on the laboratory equipment, the headspace for biogas can vary between 15 % and 40 %. The applied substrate/inoculum ratio depends on the type of substrate [\[51\]](#)[\[52\]](#).

A representative sample of organic substrate to be tested and microorganism's consortium (inoculum) are mixed in a sealed vessel in absence of free oxygen. The inoculum should be taken from an active anaerobic digester and should contain a highly diverse microbial community able to digest a large variety of organic molecules. In addition, the inoculum should have a low endogenous methane production [28].

The BMP is the volume of methane generated during the sample degradation referred to the mass of the sample of biosolid and expressed in normal conditions of temperature and pressure (0 °C, 1 013 hPa).

The sample shall be representative of the feedstock to be tested and homogenized before it is introduced into the vessel. The inoculum is sampled from an operating anaerobic digester which is fed with similar substrate, for example, from a digester at a municipal wastewater treatment plant or from an agricultural biogas plant. In case of inoculum not adapted to the organic substrate to be tested, it can be necessary to perform successive BMP, until the lag period is below one day and similar curves are obtained.

A nutrient solution (see Table 4) and a pH buffer can be added in order to avoid limitation and inhibition. The pH should be in the range of 6,5 to 8.

Table 4 — Example of nutrient solution in concentration

Nutrient	Concentration g/l
NH ₄ Cl	26,6
KH ₂ PO ₄	10
MgCl ₂ · 6H ₂ O	6
CaCl ₂ · 2H ₂ O	3
FeCl ₂ · 4H ₂ O	2
CoCl ₂ · 6H ₂ O	0,5
MnCl ₂ · 4H ₂ O	0,1
NiCl ₂ · 6H ₂ O	0,1
ZnCl ₂	0,05
H ₃ BO ₃	0,05
Na ₂ SeO ₃	0,05
CuCl ₂ · 2H ₂ O	0,04
Na ₂ MoO ₄ · 2H ₂ O	0,01

The ratio between the organic sample and the inoculum is dependent on the forecasted degradability of substrate. It should be preferentially between 1 g to 2 g of sample VS per gram of inoculum VS.

In parallel to the BMP test, two other tests should be carried out, one to assess the inoculum activity by adding a reference substrate (e.g. acetate) and one to quantify the endogenous production of the inoculum which is deducted from the volume produced by the sample test.

The biochemical methane potential, expressed in Nm³·kg⁻¹_{VSsubstrate} or Nl·g⁻¹_{VSsubstrate} is calculated with Formula (5):

$$\frac{V_s}{M_s} - \frac{V_0}{M_0} \quad (5)$$

where

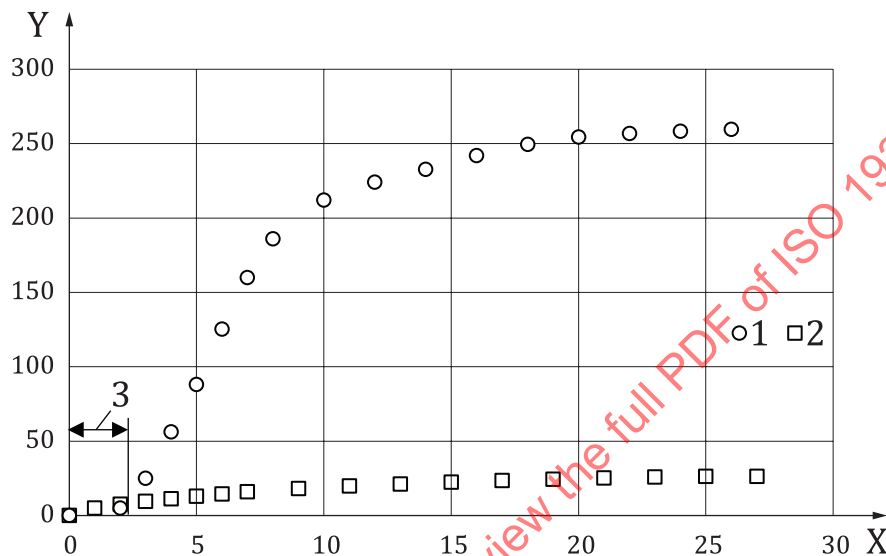
V_s is volume of methane (at normal conditions) produced from the sample and the inoculum in the BMP test, expressed in cubic meters or litres;

V_0 is volume of methane (at normal conditions) produced from the inoculum in the reference test, expressed in cubic meters or litres;

M_0 is mass of volatile solids in the inoculum used in the reference test, expressed in grams or kilograms;

M_s is mass of volatile solids in the sample added to the BMP test expressed in grams or kilograms.

The generated gas is collected in an expandable container, for example, in an inverted water (pH < 2) sealed glass vessel. Every day, the methane production is monitored and recorded. The results are plotted as shown in [Figure 2](#).



Key

- X number of days
- Y volume of methane (NI)
- 1 sample
- 2 inoculum endogenous
- 3 lag phase

Figure 2 — Typical graph from a BMP test

The graph represents a first order degradation after a lag phase. First order degradation is described with [Formula \(6\)](#):

$$\frac{dc}{dt} = -k_H \times c \quad (6)$$

where c is the concentration of readily degradable volatile solids.

Integration results in [Formula \(7\)](#):

$$c = c_0 \times (1 - e^{-k_H \cdot t}) \quad (7)$$

where c_0 is the initial concentration of c , in kg/m³.

The methane production is as given in [Formula \(8\)](#):

$$V_G = c_o \times Y_G \times (1 - e^{-k_H \cdot t}) \quad (8)$$

where Y_G , in $\text{Nm}^3 \cdot \text{kg}^{-1}_{\text{VSsubstrate}}$, is the specific methane yield per kilogram of volatile solids degraded.

Of course, the measured methane volumes are corrected for pressure, temperature and humidity.

This curve should show gradual approximation to the final value $V_{G\infty} = c_o \times Y_G$.

Conventional mathematical regression analysis can be used to assess the best values for c_o , k_H and Y_G .

Because some methane is still generated from volatile solids in the seed sludge, a parallel BMP test shall be performed with seed sludge alone. The methane volumes generated from the seed sludge is deducted from the overall methane volumes of the test.

As [Figure 2](#) shows, there is a lag phase. The seed sludge needs some time to adapt to the substrate's composition, unless the seed sludge has already been well adapted to the substrate. If there is a substantial lag time, the measured methane production is too low. The adaptation times of the seed sludge to the various substrate components differ, for example, the adaptation time to different proteins is longer than that needed to degrade carbohydrates. For this reason, BMP tests should be repeated several times, using the digested sludge from a prior test, until the lag phase is very short. Consequently, it can take several months until reliable values can be determined.

BMP testing can also be used to assess the potential for digester foaming which is usually a consequence of the presence of hydrophobic filamentous bacteria, such as microthrix or nocardia. If digester foaming is expected, this problem needs to be addressed during design of the digesters and their equipment (see [5.4](#)).

The biogas yield and methane concentration from carbohydrates, organic fats and proteins is well known (see [Table 5](#) and [5.6](#)).

It is possible to analyse the content of these components in the substrate and in the digestate to distinguish their specific degradation rates. Then, it is possible to calculate the biogas production and methane content.

Table 5 — Biogas and methane yield of substrate components

Substrate	Digester biogas production per degraded mass unit $\text{Nm}^3 \cdot \text{kg}^{-1}_{\text{VSdegraded}}$	Methane content in the digester biogas %	Methane production per degraded mass unit $\text{Nm}^3 \cdot \text{kg}^{-1}_{\text{VSdegraded}}$	Energy content MJ/kg
Carbohydrates	0,79 to 0,83	50	0,39 to 0,42	15,1
Organic fats	1,27 to 1,43	68 to 70	0,86 to 1,00	36,0
Proteins	0,70 to 0,72	71	0,5 to 0,51	18,4

5.4 Assessment of foaming risks

Foam is an important issue for anaerobic digestion management.

There are several reasons for digester foaming:

- introduction of foaming filamentous bacteria with waste activated sludge into the digester (e.g. microthrix or nocardia);
- uncontrolled addition of compounds with high foaming potential (e.g. grease, oils, chemical surfactants, biological surfactants).

Foaming can be exacerbated by unstable operating conditions such as highly variable loading rates or not appropriate mixing.

5.5 Rheological properties

The knowledge of these physical properties can help to allow the prediction of sludge behaviour when handled and submitted to almost all treatment, storage and utilization or disposal operations.

In particular, rheological properties are a key parameter for the design and operation of anaerobic digesters because the energy required for pumping or ensuring homogenous mixing is highly dependent on sludge viscosity. Generally speaking, viscosity rises exponentially with the solids concentration and decreases with temperature and degree of stabilization.

Studies confirmed that rheological measurements can be useful for assessing and governing the agitation and mixing efficiency of the medium and also mass exchanges between the solid, liquid and gaseous phases in anaerobic digesters^[13], and as indicators of biological changes in anaerobic digestion.^[14]

Sludge are generally non-Newtonian, temperature dependent, shear thinning and stress yielding (thixotropic) fluids.

More detailed information is given in [Annex A](#).

5.6 Prediction of biogas quality

Especially in case of co-digestion with other organic waste, attention shall be focused on the presence of pollutants which shall be removed before biogas conversion into energy. Predicting the concentrations of gas contaminants is essential for the design of the entire process.

According to the extended Buswell equation^[22] the composition (in percentage of components) of biogas after anaerobic digestion can be derived from the chemical proportion of the initial substrates entering into a digestion process.

Each substrate or mixture of substrates results in different biogas compositions with varying levels of CH₄, CO₂, NH₃ and H₂S (see [Table 6](#)).

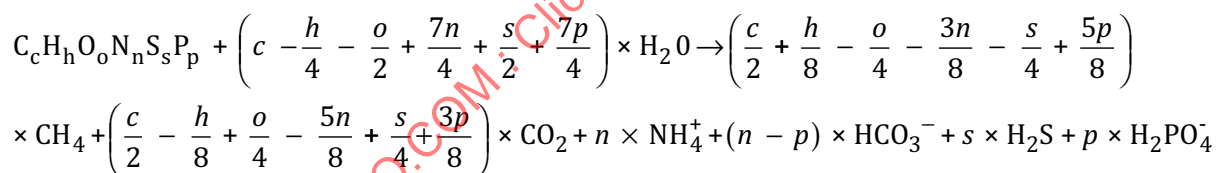


Table 6 — Biogas composition for three substrates

Substrate	Volumetric percentage of CH ₄	Volumetric percentage of CO ₂	Volumetric percentage of NH ₃	Volumetric percentage of H ₂ S
Carbohydrates	50 %	50 %	—	—
Fats	71 %	29 %	—	—
Proteins	38 %	38 %	18 %	6 %

This type of theoretical calculation gives only a rough result and in case of poorly characterized substrate or new mixture, the only way is to perform BMP tests and to characterize biogas composition.

6 Operating performance

6.1 Pre-treatment

6.1.1 General

In general, the feed pre-treatment technologies are focused on achieving the following objectives:

- Reducing feedstocks volume and increasing in digester capacity by pre-thickening of the raw sludge prior to digestion, the raw sludge should be pre-thickened prior to anaerobic digestion, preferably to a DS ratio between 4 % and 8 %;
- Avoiding toxic, inhibitory and unwanted substance for digester: Wastewater qualities and quantities of the connected industry shall be investigated; on-site pre-treatment of effluents can be required; fine-screening and effective grit removal is essential for long-term reliable digester operation; co-substrates, if accepted, can require pre-treatment (e.g. septic sludge needs to be screened).
- Reducing digester maintenance and clean up: Fine screening and grit removal are required.
- Homogenizing the feedstock mixture: An agitated blending tank for gravity thickened primary and mechanically thickened secondary sludge may be needed.
- Solid contents control, temperature control etc. of the feed for digestion process: To save digester volume and heating energy, the raw sludge should be pre-thickened prior to anaerobic digestion, preferably to a DS ratio between 4 % and 8 %. The thickened raw sludge can be pre-heated in a blending and storage tank so that hydrolysis begins.
- Enhancing biogas production from the digester: The basic requirement for enhanced digester gas production is stable process operation (even temperature and good mixing). Good primary treatment increases the primary to secondary sludge ratio (but there are limitations where N-removal is required). The longer the anaerobic sludge age, the more volatile solids are degraded. With a given digester volume, the sludge age can be increased by raising the solids concentration of the digestate in the digester. This can be done by using the upper digester headspace and temporarily operating the digester as a gravity thickener (it is best done in a two-stage system). Hydrolysis of the raw sludge also increases digester gas production. Addition of readily biodegradable co-substrate also increases digester gas production. However, it can affect the dewatering of the digestate and increase the mass of sludge to be removed.
- Increase the accessibility and biodegradability of volatile solids in the digester.
- Increasing sludge hygienization by removing high pathogen levels from feedstocks: Mesophilic anaerobic digestion reduces common pathogens by 1 to 2 logarithmic units (i.e. by a factor of 10 or 100). Generally, pathogen reduction is better with two stage than in single stage digestion because the retention time distribution curve is narrower. Thermophilic digestion at 55 °C can achieve sufficient disinfection (i.e. pathogen reduction by over 5 logarithmic units) if it is designed for a minimum retention time (of every particle) of 23 h. This requires batch operation with heat recovery and commonly a two-stage thermophilic/mesophilic process or a simple thermophilic anaerobic reactor (single stage). The most common process for sufficient pathogen reduction (disinfection) is pre-pasteurization at 70 °C for minimum of 1 h. This is also commonly a batch process with heat recovery. Thermal digestate drying (e.g. in belt dryers) can also achieve disinfection. This is also the case for solar drying in warm climates, provided that the temperature and retention time of the sludge are sufficient. In these warm climates, long-term storage (at least one year) of dewatered digestate has been shown in some cases to be sufficient to ensure disinfection. Sludge can also be disinfected by adding sloughed lime (to liquid sludge) or quicklime (to dewatered sludge). In the first case, a pH of minimum 12 should be maintained over a period of 3 months to 1 month. In the second case, a pH above 12 and a temperature of 50 °C should be maintained for 6 h. The higher the ratio of primary to secondary sludge, the better dewaterable is the digestate. The higher the degradation ratio, the smaller is the solids' mass in the digestate. Both effects lead to a smaller digestate mass. Drying the sludge further reduces its mass and disposal costs. Drying should be carried out when

high temperature conditions are available at low cost. Land application is the most ecological and economical method of sludge reuse, but it requires a low concentration of pollutants.

6.1.2 Shock loading or digester over-loading

Well operating digesters can sustain shock loads because of their strongly buffered condition. In practice, it is not easy to upset a digester by overloading. Organic shock overloading to a digester generates more VFA than the methane producing bacterial consortium can consume, for example, this is the case when additional easily biodegradable organic waste is fed to the digester. Depending on the composition of the feed, shock loading or overloading can lead to increased VFA and biogas production, and cause foaming problems^[25]. This can also happen if there is no blending tank or a blending tank with insufficient mixing for the various types of feed, such as sludge, FOG and food wastes before digester. A sudden change in feed composition or feeding mix can also upset the operational condition.

It is important to insist that digesting is strictly dependent on the operation of the wastewater treatment plant. Digester overloading can happen as a consequence of internal or external issues at the water train operation, for example, heavy rainfalls can flush into the plant large quantity of settled solids. This excess is removed and fed to the digester which can lead to mass and hydraulic overloading.

6.1.3 Inadequate or excessive heating

This can result from the inability to maintain a stable temperature inside the digester causing temperature and density gradients resulting in foaming problem. The temperature can vary between summer and winter, but temperature changes should be limited to 1 °C per week in order to allow adaptation of the microbial community.

6.1.4 Commissioning, start-up

6.1.4.1 General

Digesters shall be tested for water tightness. The digester is filled with water or wastewater to its brim. Three days shall be allowed for the saturation of concrete surfaces. Then, the water temperature shall be measured and recorded near the top, at about centre level and near the bottom.

After another day the digester is filled to the brim again and the required water to refill it shall be measured. Again, the temperatures at the three levels shall be measured and recorded. The water volume shall be corrected according to the average temperature difference at the beginning and the end of the test (expansion or contraction of water with rising or falling temperature).

The volume of water required to refill the digester shall not differ from $\pm 0,1$ % of the digester volume.

The digester gas system shall be tested for gas tightness. It is filled with air up to the design gas pressure (i.e. near the pressure when the lowest set pressure relieve valve opens). The pressure in the system shall be recorded. The air temperature within the gas system shall also be measured and recorded at several points. The ambient air pressure shall also be measured and recorded. The internal gas pressure shall be corrected for changes in ambient air pressure and temperature.

The corrected air pressure in the gas system shall not decrease by more than 3 % during a three-day testing period.

6.1.4.2 Testing

The performance of digester mixing systems can be investigated with a tracer test under operating conditions. However, such tests are only useful after several years of operation.

An example of tracer is lithium which is inert to the biology and has very low adsorption and absorption properties to the sludge.

A batch of tracer is fed with a batch substrate volume within less than 30 min. The mixing system(s) shall be operating continuously while no further substrate is fed. Sludge samples are taken every 10 min from the sludge recirculation line and analysed for their tracer concentration. Mixing shall be assumed to be completed when the tracer concentrations in the samples remains within a range of ± 5 %. The true digester volume can deviate from the volume derived from the drawings. This concentration is compared with the ratio of fed tracer mass and the sludge volume in the digester. This comparison allows to quantify the active digester volume. The higher the final tracer concentration in the samples, the smaller is the digester's active volume.

Further continuation of the test allows analysis not only of dead digester volume but also of short circuiting. For this procedure, it is very important to exactly determine the substrate feeding volumes during the test period which extends over a time which is at least equal to the mean hydraulic retention time. By substrate feeding, an equal amount of digested sludge, and with it some tracer, is displaced from the digester (through its overflow). The tracer in the digester is thus gradually diluted. Samples are taken every day and the curve of the tracer concentrations is plotted.

This curve is compared with curves calculated through modelling of digesters with various dead volumes and various degrees of short-circuiting. There are computer programs available for this purpose.

The digester heating system shall be tested during normal operation. Precondition is that the heating water (or steam) flow as well as the sludge flow through the heat exchangers and the volume of substrate feeding can be accurately determined. The temperature of the sludge and of the water upstream and downstream of the heat exchanger shall be measured (preferably with conventional mercury thermometers). The temperature of the fed substrate and of the digester content shall be determined, as well as the ambient temperature.

There are two heat balances to be established: One for the heat exchanger(s) and another one for the entire digester system. Comparison of the two heat balances allows estimation of the digester's heat losses.

6.1.4.3 Start-up

The digester is completely filled with a mixture of wastewater and sludge which is then heated to the target temperature (mesophilic or thermophilic).

Then seed sludge from another digester is fed. Preferably its volume should be about 10 % of the digester volume. During start-up, careful monitoring of the digestion process is necessary. This allows overflow of very thin sludge and accelerates the built-up of the sludge inventory within the digester.

After sludge seeding, 10 % of the daily design substrate volume is fed. The start-up time varies from one digester to another. For example, every day substrate feeding can be increased by about 5 %, i.e. after a week to $0,1 \times 1,05^7 = 14$ % and after a month to about $0,1 \times 1,05^{30} = 43$ % of the design load. 100 % of the design load can be reached from 1,5 month to 6 months.

If 20 % seed sludge is available, the design load can be reached from 1 month to 4 months. If the seed sludge is well adapted to the substrate, the start-up can increase with a 10 % of substrate feeding per day, which reduces the start-up period from 1 month to 3 months.

During start-up, particularly careful monitoring of the process is necessary. The digester's temperature should be kept within a range of ± 1 °C. The concentration of volatile organic acids and alkalinity should be determined at least every week. Their ratio should be maintained below 0,4. The pH-value is a poor indicator and can usually be ignored. Addition of caustic chemicals is usually not necessary.

In case that the ratio of volatile organic acids to alkalinity should increase above a value of about 0,4, substrate feeding should be reduced until this value drops below 0,4.

To limit the emission of greenhouse gases (CH_4 , CO_2), the biogas should be recovered upon start-up and either treated or burnt, or both. As soon as the digester gas is inflammable the digester shall be closed and the biogas burned in a flare or used in the boiler.

6.1.5 Mixing efficiency and hydraulic retention time

Depending on the used methodology (static or dynamic tracing study), different performance indicators can be determined (see 6.2.1):

- active digester volume: It is gradually reduced by the formation of dead volume, by deposits of mineral matter, for example, sand and grit; when deposits reach a certain limit, depending on the design volume reserve, dredging should be carried out;
- short-circuiting: It is also a result of poor digester mixing and can occur when the distance between the point where new substrate is fed and the point where digested sludge overflows is too short. For this reason, the sludge overflows should be provided at the top and sludge feed lines to the bottom so that the raw sludge can be fed far away from the overflow.

Some short-circuiting is inevitable even in completely mixed digesters because the hydraulic retention time is not a fixed value but a distribution; if a single digester has a mean hydraulic retention time of 20 days approximately 5 % of the fed sludge has a retention time of less than a single day; if a two-stage digestion system has a mean hydraulic retention time of $7 + 7 = 14$ d, only 2 % of the fed sludge has a hydraulic retention time of less than a single day; this is the reason why two-stage systems are far more efficient than single stage digesters.

An inert tracer is usually employed to determine the mixing characteristics of the reactor. Any inert material that can readily be detected quantitatively and does not disturb the flow pattern of the reactor can potentially be used as a tracer (see 3.1 and 6.1).

Among inert tracers, lithium chloride is frequently used and widely accepted. Lithium chloride is well suited as a tracer in wastewater applications because this element is not commonly found in wastewater, it has limited adsorption in organic matter and it can also be measured relatively easily.

Figure 3 describes the evolution of lithium chloride concentration inside the digester against time. First peak represents a short cut effect (the higher the concentration is, the higher the short cut is) and the final concentration allows the calculation of the dead volume consisting mainly of sand and large particles deposit.

$$V_{\text{active}} = \frac{M_{\text{Li}}}{C_{\text{Li},t\text{final}}}$$

where

V_{active} is the active volume of digester;

M_{Li} is the mass of lithium that is injected;

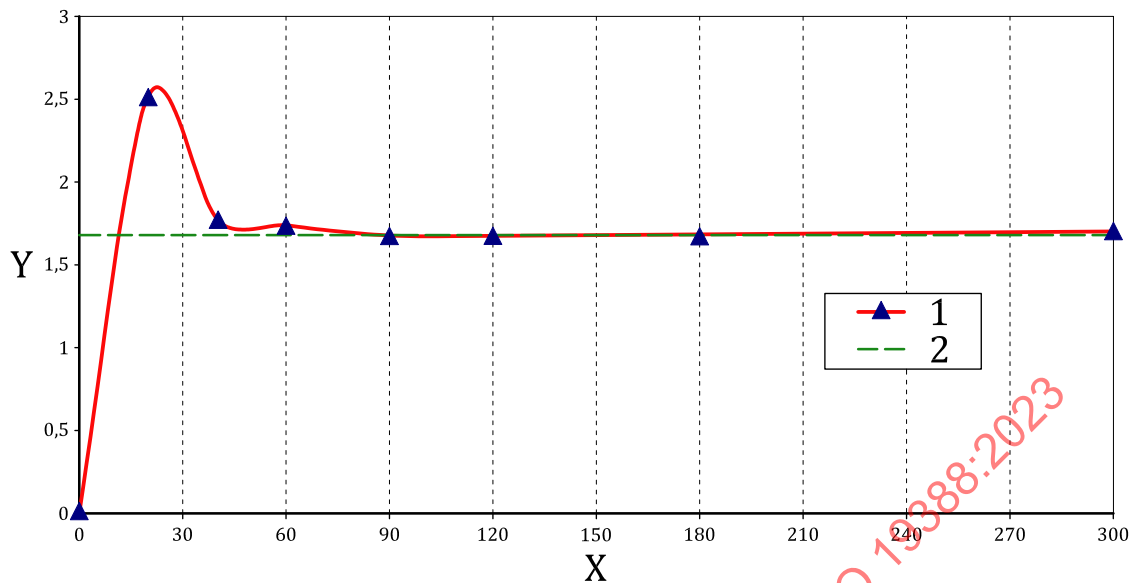
$C_{\text{Li},t\text{final}}$ is the average final concentration of lithium.

$$V_{\text{dead}} = V_{\text{total}} - V_{\text{active}}$$

where

V_{dead} is the dead volume of digester;

V_{total} is the total volume of digester.

**Key**

X time (min)

Y lithium concentration (mg/l)

1 lithium

2 asymptote

Figure 3 — Example of static tracing study with lithium chloride**6.1.6 Gas system**

As a safety means, gas shall be released through pressure relief valves if the gas pressure rises above a maximum limit. Gas is released when the gas system is clogged or when the gas holder is full.

To prevent this from happening, the gas volume in the gas holder shall be monitored and the gas flare operated before the gas holder is completely full.

The gas pressure in the headspace of digesters shall also be monitored and an alarm activated when the pressure rises to a limit which shall be well below the gas release pressure of the pressure relief device on top of the digester. Such an alarm requires immediate operator response, for example, bypassing of clogged gas filters and their cleaning.

Condensate traps that are not gas tight under all circumstances are not acceptable.

The usual reason for gas filter clogging is intrusion of foam into the gas system. Foam sensors on digesters are thus necessary. Foam traps or water spraying systems provide only limited safety. If the foam level has risen to the gas hood, other actions are required:

- addition of anti-foam agents: They should not be added for an extended time period because they contain non-degradable mineral oils contaminating the digestate;
- lowering the sludge level which requires the possibility to do so: Foam can only rise to a certain height because it collapses under its own weight; this means that digesters need to have various, at least two, overflow levels, and the digester mixing system shall be able to operate independent of the sludge level (mechanical draft tube mixers cannot do so) and it must be possible to recirculate sludge to and from point below the lowest sludge level;
- reduction of input sludge concentration.

The sludge in the digester is saturated with biogas depending on its pressure. The sludge at the bottom of a digester thus contains more biogas than the sludge near the sludge surface. Good digester mixing releases gas because sludge is frequently moved from the bottom to the surface and vice versa. Nevertheless, the pressure drops when sludge overflows. This pressure drop is high when sludge overflows from the bottom through a rising pipe.

Biogas released from overflowing sludge causes not only odour nuisance and corrosion, it is potentially toxic. Both main components of biogas lead to global warming, the comparative impact of methane is about 25 times greater than carbon dioxide.

For all these reasons, the emission of biogas from digestate needs to be prevented. This requires the need for covered post-thickeners and storage tanks and the connection of their headspace with the gas system. It also requires an enclosed overflow system on top of the digesters which is connected to the gas system.

6.1.7 Gas monitoring

Biogas generation should be measured with a suitable flow meter and the daily production should be recorded. Measurement of methane content, although optional, is useful. Monitoring the production rate is a relative indicator of the stability of the digestion process (gas composition is more useful), as fluctuations in substrate feeding cause variation of the biogas production. Unfortunately, gas flow meters are more or less reliable. It is therefore recommended to also monitor either the power or the heat generation, or both, from the biogas.

6.1.8 CH₄ production

CH₄ production is practically measured by gas flowmeter and CH₄/CO₂ analysis.

Special attention should be given to the right position of the flowmeter to avoid errors due to vapour content or dynamic perturbations.

In case of discrepancy between VS loading and measured CH₄ production, operators shall validate the measurement of CH₄ production, using two different methods:

- accordance with the volatile solids reduction (1 kg of VS digested gives approximately 900 l of biogas). In theory, mineral matters load should remain constant between the inlet and the outlet of the digester. Nevertheless, mineral matter is deposited in the digester;
- calculation using the results obtained from the BMP tests. BMP data are processed in a model in order to move from batch to continuous system and to include the distribution of retention times.

The first method is based on rapid calculation whereas the second one requires modelling.

6.1.9 Process monitoring

For process monitoring, various parameters need to be monitored.

- The pH-value of the digested sludge should be above 6,5. But the pH-value is a weak monitoring parameter. As long as there is enough alkalinity, the pH-value is rather constant. When the alkalinity is depleted, the pH-value drops like a stone, but then it is too late for preventive actions.
- It is better to analyse the alkalinity for process stability: it should be between 2 g (or 20 mmol/l) and 4 g (or 40 mmol/l) CaCO₃/l.
- VFA, as acetate equivalent, is the best indicator for sufficient stabilization: it should be below 0,5 g (or 8 mmol/l) acetate/l. VFA as such are not inhibiting, only their non-dissociated form is; the ratio of non-dissociated to dissociated VFA rises when the pH-value drops (pK_a = 4,7 for acetic acid). This is the reason why a pH-value below 6,5 is critical.

- The ratio of VFA/ Alkalinity should be maintained below 0,4 (or 0,4 mol/mol) to provide for a sufficient safety buffer preventing pH decrease.
- The digestate buffer system depends on the CO_2 and NH_4^+ concentrations and VFA. The pKa values at 35 °C of the $\text{HCO}_3^-/\text{CO}_2$ and $\text{NH}_3/\text{NH}_4^+$ buffer systems are 6,31 and 8,95 respectively. The alkalinity is a measure for the strength of the buffer systems.
- Ammonia: Free ammonia, non-ionized NH_3 is the toxic form for microorganisms populations and high ammonia concentrations can be inhibiting. Ammonium is generated by the degradation of proteins.

The balance between NH_4^+ and NH_3 is pH and temperature dependent (see [Annex B](#)). Concentration of ammonia increases when pH rises when the protein content of the substrate is high, when the substrate is highly concentrated or when the digestion process is thermophilic. The higher the temperature is, the higher is the inhibition. See [Annex B](#) for additional information.

Usual ammonium concentrations in municipal anaerobic digesters are about 1 g/l to 2 g/l, so they are not critical. However, it can become critical for thermophilic anaerobic digestion, for systems with high sludge concentration (e.g. with thermal pre-treatment), when the feeding sludge is strictly biological and when additional organic waste rich in proteins is fed to the digester.

Ammonia inhibition affects mainly acetoclastic methanogenic microorganism. Nevertheless, some digesters can work at higher ammonium concentration due to a switch in metabolic pathways where acetate is oxidized into H_2 and CO_2 and subsequently converted into methane, these two steps are made by other methane microorganisms.

Operators shall take into consideration free ammonia inhibition when either sludge composition or operating conditions, or both, can favour high ammonium release.

- temperature: depending on the operating conditions (psychrophilic, mesophilic, thermophilic);
- biogas quality:
 - CO_2 concentration: 30 % to 40 %;
 - CH_4 concentration: 60 % to 70 %;
 - Calorific value: 35,8 MJ.m⁻³ for CH_4 ;
 - stabilization (see [Annex A](#)).

6.1.10 Return liquors

Additional loads of ammonium to the wastewater treatment system: Up to 20 % of the nitrogen load of the incoming wastewater can be added with the returned sludge water from the sludge dewatering system. In case of thermal pre-treatment, be aware of non-biodegradable COD increasing the COD concentration of return liquors and potentially toxic compounds created during the high thermal process.

6.2 Digestate quality and characteristics

6.2.1 Process efficiency

About 85 % of the readily degradable solids are degraded. For municipal sludge this means that about 50 % of the volatile solids should be degraded.

Where the digestion performance is doubtful, a BMP test can be performed with the digestate (no inoculum is needed in this case). This test determines how much digester gas can be additionally generated from the digestate and how much potential for generation and emission of the greenhouse gases CH_4 and CO_2 remains (see [Annex A](#)).

6.2.2 Dewaterability

The effectiveness and cost of sludge management operations are strongly affected by its volume and, consequently, by its water content or DM concentration. Thickening and dewatering are therefore important steps in the total sludge processing train and have serious technical and economic impact on subsequent operations.

Confusing and contradictory data can be found in literature about the effect of anaerobic digestion on sludge dewaterability. Some experiences showed a clear worsening of dewaterability^[9], some an improvement of dewaterability^[10], others a negligible influence.^[11]

Main factors which are affected by anaerobic digestion and that, in their turn, influence sludge dewaterability (polymer demand, dewatered sludge dryness) are the microbial ECP (due to a different level of degradation of ECP carbohydrate and protein fractions), the particle size (small particles are preferably destroyed by anaerobic digestion, but can also be formed in stressed digester conditions) and the volatile-to-total solids content ratio (lower ratios seem to improve dewaterability).

In all cases, digestate dewaterability showed to be more sensitive to changes in digester operating conditions (chemical or thermal pre-treatment) than digestion itself. Generally, the dewatered sludge mass from anaerobic digestion can be about 1/3 lower compared to aerobic sludge.

6.2.3 Biogas quality

Monitoring the composition of biogas allows for the detection and control of digester process instabilities. It is also used for monitoring the gas quality dependent on its use, such as in cogeneration engines (i.e. combined heat and power units) and gas turbines.

Gas analysers can be either fixed or portable and provide measurement of a number of gases, such as the following:

- methane – CH₄: from 55 % to 75 %;
- carbon dioxide – CO₂: from 25 % to 45 %;
- hydrogen sulfide – H₂S: from 0 ppm to 2 000 ppm;
- 1 ppmV of H₂S = 1,394 mgH₂S/m³;
- oxygen – O₂: traces;
- hydrogen – H₂: from 10 ppm to 200 ppm;
- total Cl: from 0 µg/m³ to 3 000 µg/m³;
- ammonia – NH₃: from 0 µg/m³ to 200 µg/m³;
- siloxane: from 200 µg/m³ to 300 000 µg/m³.

Laboratory testing of biogas (according to ISO/IEC 17025^[2]) allows a more extensive analysis which can be used periodically or for process investigations.

6.2.4 Biogas quantity

Accurate measurement of biogas quantity is recommended for monitoring and understanding anaerobic digestion performance. For example, it can be used in calculating biogas yield related to the mass of volatile organic material fed to the digester expressed in Nm³ t⁻¹ VS.

Continuous monitoring is typically undertaken with thermal or ultrasonic flow meters. In general, a large variety of devices can be applied for measuring biogas production/volume:

- orifice flow meters;

- ultrasonic flow meters;
- fluidistor oscillator probes;
- turbine flow meters;
- vortex flow meters;
- hydro dynamic pressure probes before and after;
- thermal flow meters;
- diaphragm gas meters or bellows gas meters.

Measuring biogas flow can be challenging dependent upon the type of device used and the variability of biogas quality, such as moisture content and impurities. Consideration should therefore be given to device operating requirements, such as biogas quality, maintenance and installation.

6.2.5 Biogas conditioning

Biogas conditioning is undertaken so that it meets gas quality requirements and emission standards for its intended use, such as in cogeneration engines (CHP) and gas turbines. Poor biogas quality can lead to increased maintenance and impact on the performance of recovery systems. Conditioning typically includes the removal of moisture, hydrogen sulfide and siloxanes.

Biogas leaves the digester saturated with water vapour. Condensate traps integrated into the biogas system are used to remove condensed water at low points as the gas cools. Gas drying can be used to remove moisture and reduce siloxanes.

Hydrogen sulfide is always present in biogas at varying concentrations (up to 6 000 ppm depending on the location). It can form a corrosive acidic solution causing end use maintenance and performance issues and can induce overpass of the SO_2 threshold in the exhaust gas of combustion engines. If the H_2S concentration is high, frequent oil changes of gas engines are required. Removal is also required to meet specific emissions standards. Techniques for its removal include dosing a ferric solution in the digestion process, biogas filtration or carbon filtration.

In the case of a direct treatment inside the digester, the methods employed are:

- Iron chloride dosing to digester. Iron chloride can be added to the raw sludge or injected directly inside the digester; cautions shall be taken to prevent corrosion by injecting iron chloride in a well-mixed zone and by using a corrosion resistant material pipe (e.g. PVC). Sulfur is precipitated by iron into a black complex FeS .
- The principle is to inject small quantity of air or pure oxygen into the digester in order to partially oxidize sulfides to elemental sulfur without inhibiting methanogenesis. This injection can be done directly into the digester tank roof but due to risk of elemental sulfur deposits it is preferable to provide air or oxygen into the recirculation loop. This operation needs to be carefully controlled for safety reasons.

External dedicated treatments are also applicable. The main aim is to transfer sulfur from the gas phase to a liquid phase by absorption or to a solid phase by adsorption or chemical reaction. The process consists in injecting biogas at the bottom of an activated carbon tower through which it passes, or injecting the biogas against the flow of the absorbing liquid.

- Chemical treatment: High pH value of the caustic solution induces the transformation of H_2S into the soluble form HS^- . HS^- is bound by the cation Na^+ , K^+ , ... present in the solution.
- Biological treatment: Biological treatment of H_2S is based on the specific metabolism of bacteria from the genus *Thiobacillus* group: oxidation of sulfide to elemental sulfur or sulfate. Biological reaction can be performed into a single biological filter bed or into two units consisting of an absorption tower and a bioreactor.

- Activated carbon: Biogas flows through the activated carbon bed. Sulfides are adsorbed first and then oxidized to elemental sulfur which adsorbs on the surface of the activated carbon granules. The frequency of bed replacement and lifespan depend on its adsorption capacity.
- Absorption on limonite: Biogas flows through the ferrous oxide bed. Hydrogen sulfide reacts with the ferrous oxide to form ferrous sulfide complex. The capacity of the bed can be extended by intermittent aeration transforming sulfides into elemental sulfur. As for activated carbon, the frequency of bed replacement and lifespan depend on its adsorption capacity.

Siloxanes are a group of organic silicon compounds of varying molecular weight that can be present in biogas. The siloxane concentration can be as high as 70 mg/Nm³ biogas under normal conditions. Manufacturers of gas engines typically require a maximum silicon concentration of 5 mg/Nm³ biogas under normal conditions. Common technologies for siloxane removal are activated carbon filters or gas cooling. Should there be a need to meet very low levels of siloxanes, such as for combustion engines with an exhaust catalyst or for micro-turbines, then a multi-stage treatment can be required.

A cost benefit analysis should be undertaken to appraise the economic value of conditioning required for a specific biogas end-use.

7 Process safety — Trouble shooting

7.1 Pressure control

Controlling pressure in the gas space of an anaerobic digester above the local atmospheric pressure is a key parameter for safety operation. Adapted devices such as pressure or vacuum relief valves with flame arrestor or stopper can be used. To avoid clogging, water-filled syphons within the digester can be used.

7.2 Stop of CHP machines

If the cogeneration units are stopped, a flare shall be provided to burn the biogas produced and avoid the need for additional storage volume. Operation of the gas flare is dependent on the filling volume of the gas holder. Its operation starts when the gas holder is almost full. In some cases, it is possible to use a boiler to burn excessive gas. The design of the gas storage and gas utilization systems shall be such, that operation of the gas flare is restricted to exceptional circumstances.

7.3 Odour management

Odour emissions are mainly due to problems with the operation of the digester and are a sign of unstabilized digestate and/or biogas leaks. Emission of biogas to the atmosphere should be prevented. Emission can be smelled because digester gas contains some very odorous H₂S. Odours can be continuously monitored with special device such as electronic H₂S sensor equipped with threshold alarm. The design of the gas storage and gas utilization systems shall be such, that operation of the gas flare is restricted to exceptional circumstances.

7.4 Foaming

In order to keep digester foaming under control, the following preventive and control strategy can be adopted: Daily variations in volatile solids loading (organic load) to the digesters should be limited if possible to 10 %. Better performance can be obtained from feeding digester as continuously as possible, especially with FOG, food and organic wastes. Insufficient or improper digester mixing is a wide-spread concern and can contribute to foam production. Co-digestion with high strength waste can further add to this problem. That is why digester mixing system should be selected carefully considering the optimum mixing requirements as well as mixing performance. Further prevention can be added by installing foam sensor, foam removal devices (e.g. surface spraying), foam trap on gas line and protection to the pressure release valves.