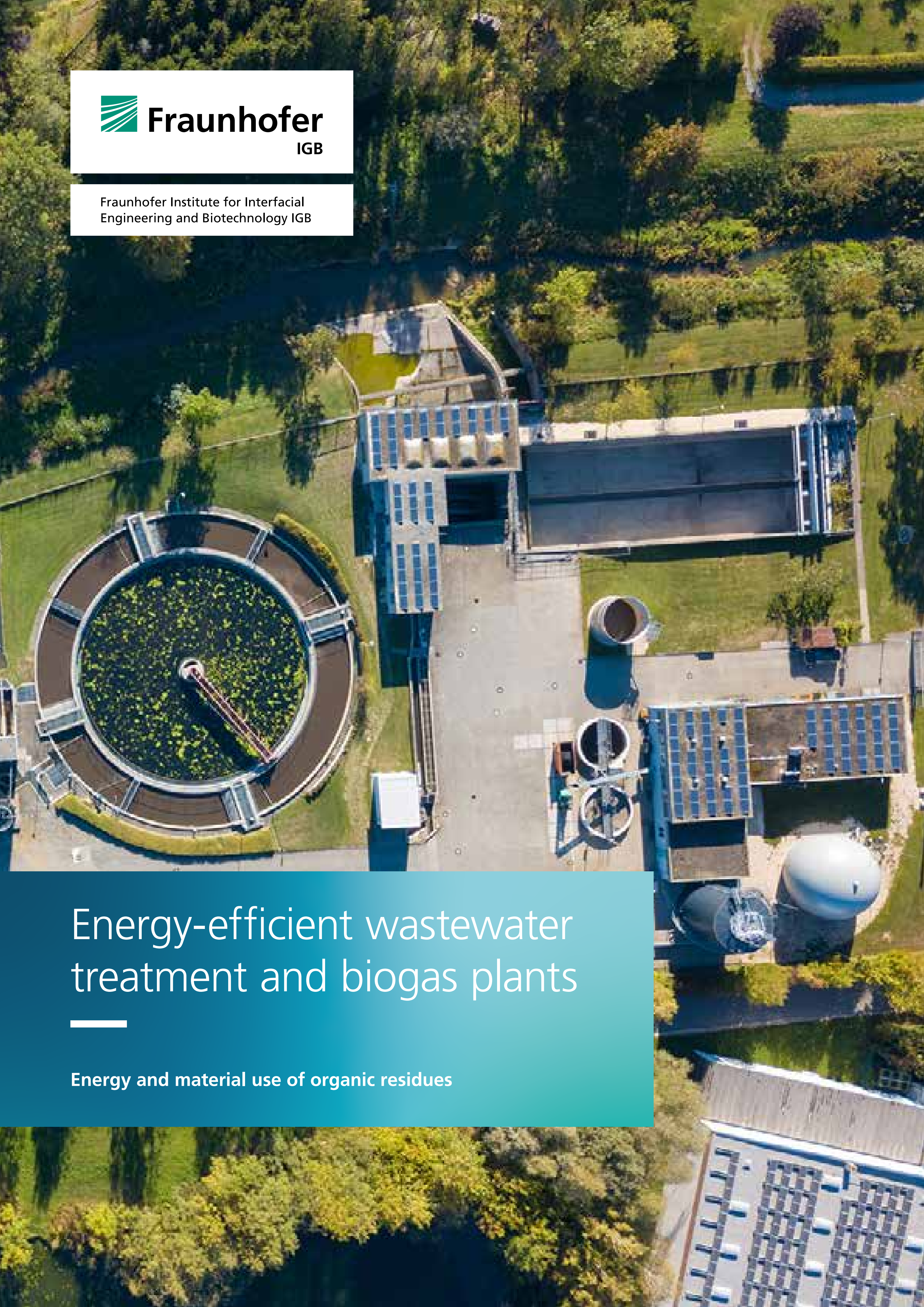


Fraunhofer IGB

Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB

Energy-efficient wastewater treatment and biogas plants

Energy and material use of organic residues

"

Shorter retention time – more biogas – reduced costs!"

Wastewater treatment plant Edenkoben, © Verbandsgemeinde Edenkoben

Energy- and resource-efficient wastewater treatment and biogas plants

In view of the finite nature of fossil and biological raw materials, it is becoming increasingly important for companies, municipalities and states to use existing resources more efficiently and intelligently and to recover ingredients for material or energy use in accordance with the circular economy approach.

top:
Digesters of the Edenkoben wastewater treatment plant, © Verbandsgemeinde Edenkoben

bottom:
Digestate storage tank of the sewage treatment plant Erbach

Anaerobic digestion to biogas

Anaerobic fermentation processes take place in the absence of atmospheric oxygen. Fermentation proceeds in various stages, each involving different bacteria. At the end of the anaerobic microbial food chain, a mixture of carbon dioxide (CO_2) and methane (CH_4) – known as biogas – is produced from the carbon content of the organic matter.

Biogas anaerobic technology has been used for a long time, also in technical dimensions, for example in the stabilization of sewage sludge or liquid manure.

Higher degradation rate and more biogas through high-load digestion of sewage sludge

The Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB has developed an energy-efficient high-load process for the fermentation of sewage sludge. It was put into operation for the first time in 1994 at the sewage treatment plant in Leonberg. In the meantime, this process is being successfully applied by four other municipal sewage treatment plants.

The outcome: The high-load digestion converts the sludge into biogas in a considerably smaller space and more cost-effectively than the conventional digestion towers. High-load digestion has also been successfully used for the anaerobic treatment of industrial biomass residues and in agricultural biogas plants.

Fundamental advantages of high-load digestion
- Shorter retention time (5 – 10 days)
- Higher biogas yield
- Enhanced degradation rate
- Smaller digestion space
- No operational problems (foaming)
- Easier to dewater
- Lower operational and disposal costs

High-load digestion

The process

top:
One-stage high-load digestion plant in Ilsfeld

bottom:
High-load digestion reactor in the workshop at the Fraunhofer IGB

The process was developed for increasing the efficiency of sewage sludge digestion and was the subject of intensive research work at Fraunhofer IGB in this regard. The high-load process is characterized by a significantly improved efficiency, short retention times and a high degree of degradation.

It is used for the anaerobic conversion of organically degradable substrates such as sewage sludge, but also of liquid manure, biowaste or other organic residues. Due to the significantly increased biogas yield compared to other processes, it is becoming increasingly attractive.

Excellent operational data compared with conventional digestion

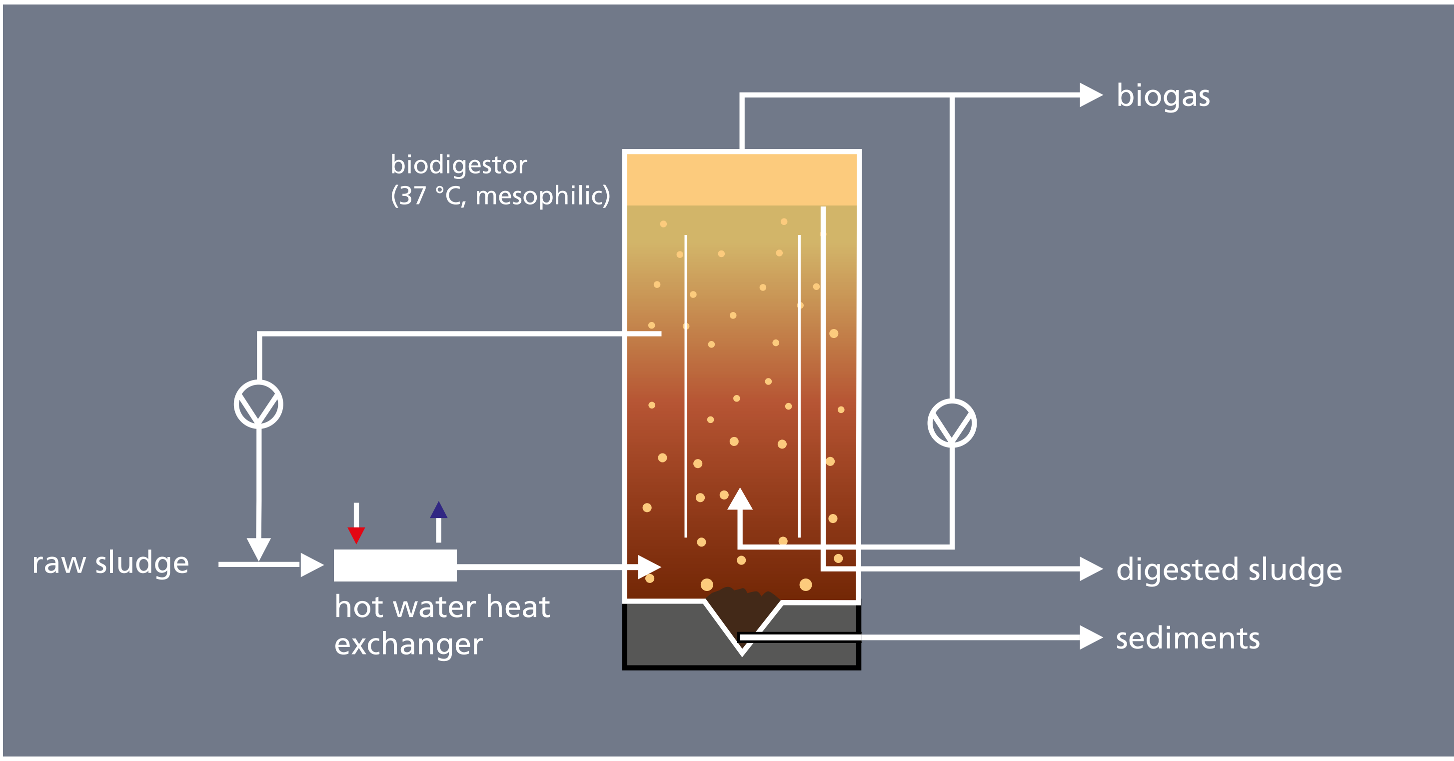
Shorter retention time
Even with a high solid content the sewage sludge only has to remain approx. 5 – 10 days in the digestion tower instead of 20 – 30 days up till now. Thus organic load rates of 8 – 10 kg TVS* / $m^3 \cdot d$ are achieved instead of only 1 – 2 kg TVS/$m^3 \cdot d$.

High biogas yield
The high-load digestion can produce up to 23 liters of biogas per PE (population equivalent) and day, depending on the quality of the raw sludge. Conventional digestion plants in contrast achieve a maximum of only 19.7 liters of biogas per PE and day on average [Haberkern et al.; Steigerung der Energieeffizienz auf kommunalen Kläranlagen Umweltbundesamt Texte Nr. 11 / 08, Dessau-Roßlau, March 2008].

The gas can be used to supply the plant with energy or can be delivered as a technically and commercially usable energy carrier.

Less organic residues
In the course of enhanced biogas production the high-load digestion also reduces the organics – by 50 to 70 percent, depending on the specific combination of processes. The organic share of the dry residual matter is now only 50 percent. As a result, far lower amounts of sludge occur, as they can be dewatered and disposed of more effectively.

Dewatering of digested sludge provides nutrient-rich filtrate for nutrient recycling
For further use or recovery of ingredients, the digested sludge is dewatered in a solid-liquid separation plant, such as a chamber filter press or centrifuge. This yields a particle-free sludge water that contains most of the dissolved nutrients (nitrogen and phosphorus) and thus can be used directly for fertilizer irrigation. Alternatively, nitrogen and phosphorus can be recovered as fertilizer. Fraunhofer IGB has developed various technologies for nutrient recovery.



Scheme of a high-load digestion reactor

* TVS = total volatile solids

Applications of anaerobic digestion processes

Energy-efficient sewage treatment

Sewage plants remove organic matter from wastewater. If the accumulating sludge decays, biogas is generated as a by-product. However, only 10 percent of the more than 9,000 sewage plants in Germany have a digestion tank. Smaller operations, especially, baulk at the costs of a new digestion tank. Instead, they enrich the sludge with oxygen in the existing activation basin, and stabilize it. Activation basins, however, require a lot of electricity and make a sewage plant the part of a municipality that eats up most electricity. At the same time, enormous energy potential is lost, since no biogas is produced. The digestion tanks of larger sewage plants are often out of date. They could considerably improve energy efficiency and cost-effectiveness by using the latest innovative technology.

Limited disposal possibilities

The disposal routes for sewage sludge from municipal wastewater treatment have already been restricted by the legislation. Landfilling is no longer possible. According to the amendment of the Sewage Sludge Ordinance in 2017, large sewage treatment plants (> 100,000 or 50,000 PE) may only spread sewage sludge as fertilizer until 2029 or 2032. The incineration of sewage sludge will continue to gain importance, prices for disposal will increase. However, the alternative of incinerating the sludge is not sustainable because wet sludge does not make a positive contribution to renewable energy production. Aerobic sludge stabilization is expensive due to the high energy demand, often insufficient and not an adequate alternative for sewage plants > 10,000 PE.

Intelligent utilization of sewage sludge as an energy carrier

The high-load digestion process developed at Fraunhofer IGB makes sewage sludge digestion a process that can, as a result of the efficient conversion of the sewage sludge contents into biogas, contribute substantially to the cost-effectiveness and energy efficiency of sewage treatment plants. The process is therefore also suited for smaller treatment plants (10,000 PE) that so far stabilize the sludge aerobically with a high power consumption.

The sewage sludge is stabilized with net energy production by means of high-load digestion, can be dewatered to a higher TS level and the residual sludge disposed of by incineration at the lowest possible cost. The regenerative energy carrier biogas is derived as a product. The thermal energy requirements of the sewage treatment plant can be covered by the biogas obtained and further expenses can be saved by means of combined heat and power generation. The high-load digestion process therefore also represents an economically intelligent alternative and considerably improves the energy efficiency of municipal sewage plants.

Energy-efficiency even for smaller sewage plants

In a cost-benefit study the Fraunhofer IGB has shown that it also pays small sewage plants to transfer to more energy-efficient processes – even if they have to invest in a sludge digestion unit. Based on a sewage plant for 28,000 inhabitants, we calculate that the plant can reduce its annual waste management costs from 200,000 euros by as much as 50,000 euros if sludge is decayed in a high-rate digestion unit with microfiltration, as opposed to treating it aerobically.

With the high-load digestion process around 60 percent of the organic matter is converted into biogas – the yield is approximately a third more than in the traditional digestion process. The biogas obtained can be used to operate the plant by means of combined heat and power generation in the block-type thermal power plant.

The two-stage high-load digestion in Edenkoben allows the wastewater treatment plant to be flexibly adapted to the high wastewater load during the vintage © Verbandsgemeinde Edenkoben

Our approach until implementation

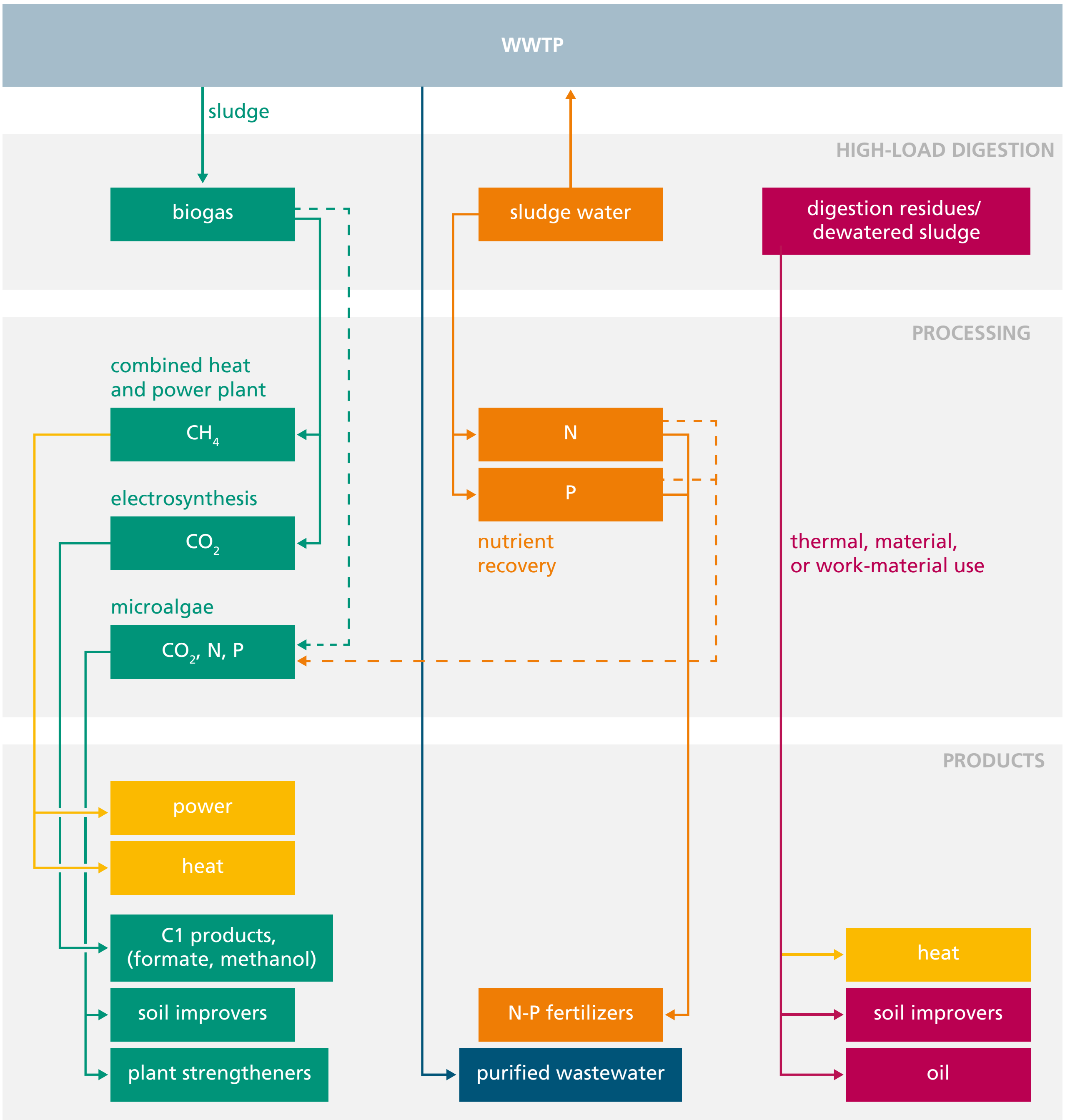
Design data at small scale

High-load digestion systems are individually dimensioned and designed with regard to their integration into the overall sludge treatment process of a wastewater treatment plant. For the successful realization of a high-load digestion, we therefore usually investigate the fermentability of the raw sludge in high-load operation beforehand on a pilot plant scale. The experiments are carried out in a small-scale plant with automated 50-liter reactors at Fraunhofer IGB. Based on the characteristic data obtained here, we design a larger-scale plant and scale up the design to an industrial scale.

Pilot plant ensures optimum know-how transfer

In addition, we can implement the high-load digestion process on a pilot scale at the wastewater treatment plant. In this case, the tests are carried out in a pilot plant consisting of a temperature-controlled biogas recirculated reactor made of stainless steel with a useful volume of approx. 2 m^3. This offers the opportunity to test the operation of a high-load digester on site and to smoothly transfer the process know-how to the operator to ensure successful implementation.

WASTEWATER TREATMENT PLANT (WWTP) AS A BIOREFINERY



Simplified illustration of the value creation in a wastewater biorefinery facility

Wastewater treatment plants as biorefinery

The circular economy is considered a key strategy for conserving resources and achieving climate targets. The constituents in wastewater from a sewage treatment plant can also be used as materials – if it is processed appropriately. The focus here is on nutrient recovery and the use of CO_2 to manufacture downstream products. These products are to be used as feedstocks in value-adding processes in order to realize a local and sustainable recycling economy.

Our high-load digestion process lays the foundation for the utilization of residual and waste materials, as it not only converts the sludge produced at a wastewater treatment plant into biogas as a regenerative source of carbon and energy, but also provides a nutrient-rich "sludge water" with the dewatering of the digested sludge and carbon-rich digestate with the concentrate as further usable material streams.

The sludge water is rich in valuable plant nutrients, above all phosphorus and nitrogen. The Fraunhofer IGB has developed various concepts for recovering the nutrients from this water produced during sludge dewatering and processing it as fertilizer. Alternatively, the sludge water can be used as a growth medium for cultivating photosynthetic microalgae that grow with CO_2 and synthesize plant-stimulating polysaccharides, for example.

This approach has been pursued since 2021 in the project "RoKKa – Sewage sludge as a source of raw materials and climate protection at wastewater treatment plants," which is funded by the EU and the state of Baden-Württemberg.

top:
Struvite recovered from wastewater can be used as a N and P slow-release fertilizer

bottom:
A pilot wastewater biorefinery plant is being set up at the Erbach wastewater treatment plant as part of the RoKKa project

Biogas from organic residues

Organic residues and biowaste also contain valuable energy. This energy is lost when it is recycled in composting plants. In addition, composting involves a high energy input for aerating the compost material. Here, too, anaerobic fermentation is an energy-efficient and cost-saving alternative for using organic materials.

Biogas from waste – alternative to natural gas

Biogas, or the biomethane purified from it, could also represent an alternative to ensure security of supply with methane ("natural gas") and reduce international dependencies. According to the German Biogas Association, there are currently around 9,600 biogas plants in Germany. With a share of eleven percent of renewable electricity generation, they supplied a good 50 terawatt hours of electricity in 2021 – as much as all photovoltaic plants in Germany (Federal Environment Agency, based on AGEE-Stat, as of 02/2022). This makes biogas an important storable supplement to volatile electricity from wind and sun.

In Germany, biogas is still mainly produced from renewable raw materials. In this context, fermentation is excellently suited for all wood-poor fresh and moist organic waste: from liquid manure and dung, to green waste and vegetable waste from municipal waste disposal, to food waste from trade and industry. Promoting the widespread use of these organic wastes should find its way into national strategies for the sustainable use of biological resources so that the cultivation of energy crops on arable land can be reduced. This would also create economic incentives for agricultural operators of smaller plants. Recently, already functioning plants have been decommissioned because the Renewable Energy Sources Act (EEG in German) remuneration ceases after 20 years of operation.

Efficient anaerobic digestion of organic residues

Anaerobic digestion processes can be used to operate plants directly at the point of origin of the residual biomass, ensuring the utilization of readily fermentable materials to produce biogas. The high-load process developed for increasing efficiency in sewage sludge digestion also promises significantly improved efficiency, short retention times and a high degree of degradation, as well as a high biogas yield, for use with organic residues.

Advantages of anaerobic digestion technology

- Production of biogas as an alternative to fossil fuels
- Contribution to climate change mitigation through reduction of greenhouse gas emissions
- Use of fermentation residues for soil improvement and sustainable phosphorus supply
- Inactivation of weed seeds, neutralization of ingredients (e. g. antibiotics) and hygienization of the residues (with thermophilic processes at approximately 55 °C)

Process development – we make more from residual materials

Fraunhofer IGB develops individual and adapted solutions for the material and energetic utilization of organic residues, which accumulate as by-products in industry and agriculture.

To this end, we are investigating the fermentative conversion of the residues on a laboratory scale with regard to their bio-methane potential. For the design of the new process according to the customer's specifications, we evaluate the various process parameters, identify weak points and optimize the process with regard to maximum product yield.

We evaluate and optimize existing biogas plants regarding their performance and energy efficiency.

With a technical and economic analysis of the production waste and by-products, we advise companies on how to make optimum use of any residual materials that arise, for example, by coupling anaerobic digestion with further conversion or recovery steps.

Optimal process control

For the design of the process, the type and composition of the substrates is crucial, since the properties of the feedstocks have the greatest influence on the degradation time. In addition to the process temperature, other important parameters we are investigating for optimal conversion of the feedstocks to biomethane are the residence time of the substrates and the organic loading rate in the reactor. The stability of the biological process is mainly influenced by the microorganisms available in the inoculum and the C/N ratio in the feeding regime, furthermore, by the availability of trace elements. Metabolic products such as ammonia and volatile fatty acids or toxins must also be taken into account in the process control.

Comprehensive analytics ensure the monitoring of the process, its optimization and the improvement of the process and energy efficiency of the plant.

Anaerobic reactor technology

Characteristic of anaerobic conversion is the low growth of biomass, since most of the energy contained in the substrates is converted into the end product: methane. Therefore, to increase the conversion rate, the active biomass must be retained and concentrated in the reactor. This can be done by immobilizing the biomass on a support material in a fixed-bed reactor or by mechanical retention in a membrane bioreactor.

Liquid raw materials can be used without further pretreatment. Suspension reactors or fixed-bed reactors are used here.

For raw materials with a high solids content, e. g. the organic fraction of municipal solid waste, food waste and lignocellulosic biomass, anaerobic solid reactors are suitable.

Fermentation tests at laboratory and pilot plant scale

Biogas plant

Additional value added in waste biorefinery

In addition to energy recovery as biomethane, organic residues can also be recycled as materials. By coupling anaerobic digestion with biotechnological or electrochemical conversion of ingredients and CO_2 according to the principle of a biorefinery, additional value-added products can be produced, for example:

- Basic chemicals
- Algae biomass
- Paper and bioplastics from fibers and solid residues
- Bio-oil
- Activated carbon and biochar
- Amino acids and other organic acids
- High-quality organic fertilizers, e. g. struvite

For feedstocks containing fibers and lignocellulose, longer residence times and suitable pretreatment, for example with various mechanical, biological or thermochemical digestion processes, lead to better biogas yields.

Substrates suitable for biomethane production

- Food waste
- Cattle/pig manure and poultry manure
- Waste/residues from beverage and food industry
- Waste/residues from biofuel production
- Energy crops, e. g. corn, cup plant (silphium), miscanthus (after sufficient pretreatment), sugar sorghum
- Combination of different substrates

Valuable phosphorus fertilizers (back), nitrogen fertilizers (right) and soil conditioners (front) can be obtained from liquid manure and fermentation residues

Demand-oriented biogas production as a contribution to the energy transition

In order to better compensate for fluctuations in power generation from the sun and wind, Fraunhofer IGB has joined forces with Hamm-Lippstadt University of Applied Sciences in the BMEL-funded NextGenBiogas project to develop a process that allows biogas to be produced flexibly and on demand. For this purpose, the anaerobic fermentation process is operated in such a way that the microorganisms involved in methane production can react quickly to changes in operating conditions.

Applied concept

The anaerobic digestion process is carried out in a two-stage system. Acid formation occurs in a first, hydrolytic stage, while biogas formation occurs in the second, methanogenic stage. In order to be able to quickly ramp up methane production in the second stage if necessary, easily convertible organic acids and alcohols are produced in the hydrolytic stage as a storage medium.

The optimum conditions for rapid and efficient acid production and thus the highest methane yield were determined in laboratory tests: The highest acid formation was achieved at a temperature of 51 °C, a pH of 5.5, and a shredded corn silage to cattle manure ratio of 50:50. In the methanogenic phase, different scenarios of flexible feeding were tested to achieve the fastest recovery of microorganisms and the highest efficiency of biogas production after selected starvation phases.

Process regulation by microbial approach

Metagenome and metatranscriptome analyses of the inoculum and samples from the two-stage system allowed us to identify the species involved in each case. This allows the process to be controlled by targeted inoculation and adjustment of the cultivation conditions.

References

Sludge digestion at wastewater treatment plants

The high-load digestion is at present being used by ten municipal sewage treatment plants in the German state of Baden-Württemberg:

- **Mittleres Glemsstal sewage treatment plant**, Leonberg, 1994: two-stage high-load digestion
- **Heidelberg wastewater treatment plant**, 2001: expansion of the egg-shaped digestion towers to include an upstream high-load stage without disabling the disposal line
- **Tauberbischofsheim wastewater treatment plant**: two-stage high-load digestion system
- **Wastewater treatment plant AZV Mittleres Wutachtal**, Schwerzen, 2007: single-stage high-load digestion for wastewater treatment plant with 10,000 PE
- **Group sewage treatment plant Schozachtal**, Ilsfeld, 2008: single-stage high-load digestion for 35,000 PE
- **Wastewater treatment plant ZWA Bad Dürrenberg**, 2012: single-stage high-load digestion for a capacity of 26,000 PE
- **Wastewater treatment plant Edenkoben**, 2016: two-stage high-load digestion for approx. 7,000 PE
- **Erbach wastewater treatment plant**, 2017: high-load digestion tower for a capacity of approx. 25,000 PE
- **Leipheim wastewater treatment plant**, 2018: single-stage high-load digestion for modernization and expansion from 16,000 PE to 20,000 PE
- **Steinhäule sewage treatment plant**, Ulm, 2020–2022: pilot plant for high-load digestion

Biogas plants

NextGenBiogas – flexible bioenergy production to stabilize power grids
Funding: BMELV | Duration: February 2019–March 2022
Within the scope of the joint project, a flexible process for the demand-oriented generation of biogas is being developed – as the key to the successful integration of biogas production into the renewable energy system.

HoLaFlor – increasing the efficiency of biogas plants by establishing high-load digestion (using corn as an example) with detection of the microorganism flora
Funding: BMEL | Duration: October 2015–December 2018
Here, we operated a biogas plant using the high-load process on a pilot plant scale and compared it with a reference plant using the conventional process. We were able to show that by using a suitable plant technology for biogas plants with significantly shorter residence times, and thus two to four times higher methane productivities can be achieved than in operation with conventional process and long residence times.

MOST – model-based process control of biogas plants: Practical tests
Funding: BMBF | Duration: October 2013 – December 2017
One goal of the project was to increase the operational safety of biogas plants by early detection of an operational malfunction. For this purpose, various operating situations were experimentally simulated on a pilot plant scale. The results show that the economic efficiency of biogas plants can be increased by reacting in time.

GOBi – holistic optimization of the biogas process chain
Funding: BMBF | Duration: June 2013 – December 2016
The aim of the project was to optimize the entire process chain of biogas production – from the cultivation of the plants to increasing the yield of biogas – with a holistic approach and to use the biomass of the plants used as fully as possible.

Organic residues

En-X-Olive – utilization of residues from olive oil production
Funding: EU | Duration: November 2008 – October 2011
Together with partners from Spain, Italy, Greece and France, we researched and demonstrated the recovery of biogas, polyphenols and fertilizers from olive oil production residues.

Wastewater biorefinery

RoKKa – sewage sludge as a source of raw materials and climate protection at wastewater treatment plants
Funding: Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg, co-financed by the EU (EFRE) | Duration: October 2021 – March 2024
This project aims to drive the turnaround to a climate-friendly wastewater treatment plant by linking various innovative processes in a value-centered manner.

from left to right:

Digester of the sewage plant Bad Dürrenberg

RoKKa project team in front of the Erbach wastewater treatment plant (© Umwelttechnik BW GmbH)

HoLaFlor: High-load process at pilot scale

Services offered

For 40 years Fraunhofer IGB has been developing biotechnological processes for the treatment of water and waste – from the microbiological fundamentals to a technical and pilot scale plant:

Integrated approach: energy generation and nutrient recovery

One focus here is materials recycling. This makes us the partner of choice for municipalities and industrial companies wishing to combine waste disposal and wastewater treatment with the use of organic residues. We have also developed various technologies for nutrient recovery from the liquid and solid residues produced during high-load digestion.

We will be glad to advise you on how to make optimum and holistic use of your residual materials! To this end, we work together with other research and development departments at Fraunhofer IGB.

Scaling from pilot plant up to industrial scale

In our pilot plants, we investigate the fermentability of various biogenic residues on a laboratory and pilot plant scale and develop concepts for large-scale implementation. Basic and detail engineering based on Fraunhofer patents is carried out by our industrial partners from the plant engineering sector.

Pilot plant for know-how transfer

To ensure a smooth transfer of know-how to the operators and a successful implementation, we can also always implement the high-load process initially on a pilot scale and operate it on site.

Services at a glance

Analytical measurements

- Comprehensive analysis (chemical and biological parameters)
- Characterization of solids and substrates: Qualitative and quantitative biogas analytics, analytics of constituents of substrates

Studies

- Feasibility studies for the production of biogas from residues
- Analysis of wastewater treatment plants and biogas plants to increase energy efficiency
- Specific analysis of processes with the aim of process improvements: Elimination of malfunctions, increase of efficiency, process optimizations
- Determination of potential to increase the performance of processes, e. g. wastewater treatment, biogas plants, sewage sludge digestion

Laboratory tests

- Investigations of sewage sludge digestion for the determination of design parameters
- Performance of fermentation tests (investigation of fermentability)
- Quantification of the biogas yield of substrates/cosubstrates
- Process development for the anaerobic treatment of organic residues, e. g. from agriculture, food processing and production
- Process development for the production of recyclables/ biogas from residues: Determination of design parameters at pilot plant scale.

Industrial implementation

- Development of planning concepts for the realization of high-load digestion on a technical scale
- Scientific support for the start-up of processes on a technical scale
- Technical implementation on pilot scale and operation on site
- Technical-scientific consulting for process improvement or commissioning of plants
- Individual, cost-saving expansion of wastewater treatment plants

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We combine biology and engineering

The Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB develops processes, technologies and products for health, sustainable chemistry as well as the environment and climate protection. For this, we rely on the combination of biological and process engineering competencies in order to provide solutions for individualized medicine, a sustainable bioeconomy and climate-neutral as well as resource-efficient circular economy. We offer our customers research and development services ranging from feasibility studies to implementing new processes in industrial practice, accompanied by a wide range of analysis and testing services. Our strengths are offering complete solutions from the laboratory to pilot scale applications.

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