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Implementation of anaerobic digestion facilities in the food and beverage industry

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Implementation of anaerobic digestion facilities in the food and beverage industry

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Cover graphic: Biogas plant using slaughterhouse waste at Frimesa Agroindustry in Medianeira, Brazil (reproduced with the kind permission of Frimesa Cooperative)

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EXCECUTIVE SUMMARY

Food and beverage production is based on the processing of agricultural biomass. For this reason, the by-products from the food and beverage industry can be very valuable feedstocks for anaerobic digestion. This report focuses on the integration of a biogas plant to the production facilities. In such scenarios either residues, wastes, by-products or wastewaters can be used as feedstock. It is important to pursue a cascading utilisation concept which prioritizes re-use and food/feed application of the by-products prior to energy utilisation. Biogas is an attractive option, since food and beverage production are energy intensive, and biogas is a multi-purpose energy carrier. The utilization of the renewable gas reduces the carbon footprint of the production process.

The report provides detailed feedstock characteristics and gives a guide to the food and beverage industry on how a biogas project should be pursued and which typical questions arise. As a practical report a variety of international examples of biogas plants that are integrated into the food and beverage industry are shown: meat industry, breweries, distilleries and potato processing sites. Typical plant details are given such as: location and operating company, investment, biogas production, energy utilisation and reactor size and type.

1. Scope of this technical report

Anaerobic Digestion (AD) is a state-of-the-art technology for treating wastewater, organic waste, industrial by-products or agricultural residues and by-products as a feedstock. Aside from the effects of stabilizing the feedstock by means of microbial degradation a regenerative energy source is produced, the biogas.

Biogas is graded as a carbon neutral energy source and offers a wide range of stationary and mobile applications. Accordingly, there are nowadays various types of AD systems in operation throughout the world, in different industry branches, like pulp and paper, beverages, chemicals, food, meat, milk and pharmaceutics.

This technical report describes the implementation possibilities of AD facilities at the production sites of the food and beverage industry´s facilities.

This technical report is intended to

- Support with basic information on AD issues,
- Encourage in starting an AD project,
- Facilitate with profiles of operating AD projects,
- Highlight critical aspects within the course of an AD project,
- Give a helping hand in the decision-making process.

This technical report finds its target groups in

- Companies interested in regenerative energy sources,
- Companies interested in resource efficient production,
- Companies interested in environmentally friendly treatment of residual material or wastewater,
- Decision makers and stakeholders being active within environmental sector, resource efficiency sector, and greenhouse gas emission sector.

AD technology can offer a financially beneficial solution to reduce the company's costs for waste disposal and energy consumption, while lowering its emissions and associated carbon charges at the same time. Quality and quantity of the overall benefit need to be defined and evaluated for each single installation.

Technically reliable AD facilities are installed globally and are state of the art. However, due to individual and specific conditions within the food and beverage industry, they still need to be tailor-made solutions. Therefore, the economics and reliability of AD facilities are dependent on consideration of individual, on-site related parameters and feedstock characteristics.

This technical report emphasises on the details which need to be considered when installing an AD facility at an industrial production site. If done right, AD technology opens the possibility for a reliable solution to increase the efficiency of resource utilization, energy consumption, and waste or wastewater management. Not at last, the overall efficiency increase should lead to a cost and greenhouse gas emission reduction.

1.1. Why the food and beverage industry?

The agricultural industry and especially the food and beverage industry is one of the world's largest manufacturing sectors. In the EU it comprises 289,000 companies and is with 4.5 million employees the leading employer. Together with the automotive, machinery and equipment industries it is a major contributor to the European economy. In 2018, the EU food and beverage industry generated a turnover of €1,093 billion and a value added of €222 billion. With an investment of €41 billion in 2018, it represented the industry with the highest capital spending in the manufacturing sector (FoodDrinkEurope 2021).

Aside from these amounts of turnover and products a variety of potential substrates for AD as well as emissions emerge from the food and beverage industry. There are substantial mass streams of residues, waste, wastewater and last but not least direct greenhouse gas (GHG) emissions. GHG emissions occur during the initial production of agricultural raw material and feedstock, whilst processing at the production site and whilst or after utilization of the products by the customers. The industry is increasingly steered towards reduction of the emissions by customers and authorities.

Focusing on the production site´s emissions the food and beverage industry depicts a promising industrial sector for the enhancement of AD installations. Food and beverage industries process organic feedstock of a high quality, containing hardly any pollutants, inhibitory substances or disturbing material. The produced by-products, residues and wastes represent a wide range of organic, microbially degradable material: solid, pasty or liquid by-products, residues and wastewater with organic load. All these materials are suitable to be used as feedstock for AD installations respectively for producing biogas.

1.2. Why AD facilities for the food and beverage industry?

Generally, the primary interest of the industry in installing AD facilities focuses on the reduction of treatment costs for waste and wastewater, as well as in the reduction of energy costs by using the generated biogas. The reduction of GHG emissions comes along due to substitution of fossil fuels by utilizing biogas instead. There are also a wide range of ecological and social benefits closely linked to an AD installation at industrial production facilities – AD fits well into Circular Economy concepts. Figure 1 illustrates the interaction of agricultural feedstock production, industrial production, human consumption and energy supply:

- The agricultural feedstock production, respectively primary production, depends on fertilizers for crop production as well as for animal breeding. Digestates provide nutrients and recalcitrant organics thus increasing soil fertility. Agricultural residues like corn stover and by-products like manure are a well-known feedstock for AD plants.

- The industrial production of food and beverages also produces by-products and residues which can be utilized in cascades e.g. spent grains can go first as feedstock into animal husbandry, then the manure into AD and the digestate is used as fertilizer. If the by-product or residue is not suitable as fodder within animal husbandry, such as potato peels, it can be used directly as feedstock for AD plants.

- The trade and consumption of food and beverages is responsible for organic leftovers and organic waste, which both can be treated aerobically by composting or anaerobically in AD plants.

- The energy demand for production facilities in regards of mobility, heating or electricity can be (partly) covered by the regenerative energy source biogas from AD plants.

- Costs of disposal of waste and wastewater streams can be reduced due to mass reduction and reduction of concentration of organic carbon.

Another worthwhile end-product of AD plants next to biogas is the effluent from the digesters, the digestate. Digestate is an organic fertilizer, ready to use without pre-treatment in crop production.

By closing the loop, the resource and energy efficiency within the production processes increases significantly, as vice versa the water and carbon footprint decreases substantially. Quality and quantity of these effects vary widely and need to be evaluated for each installation individually.

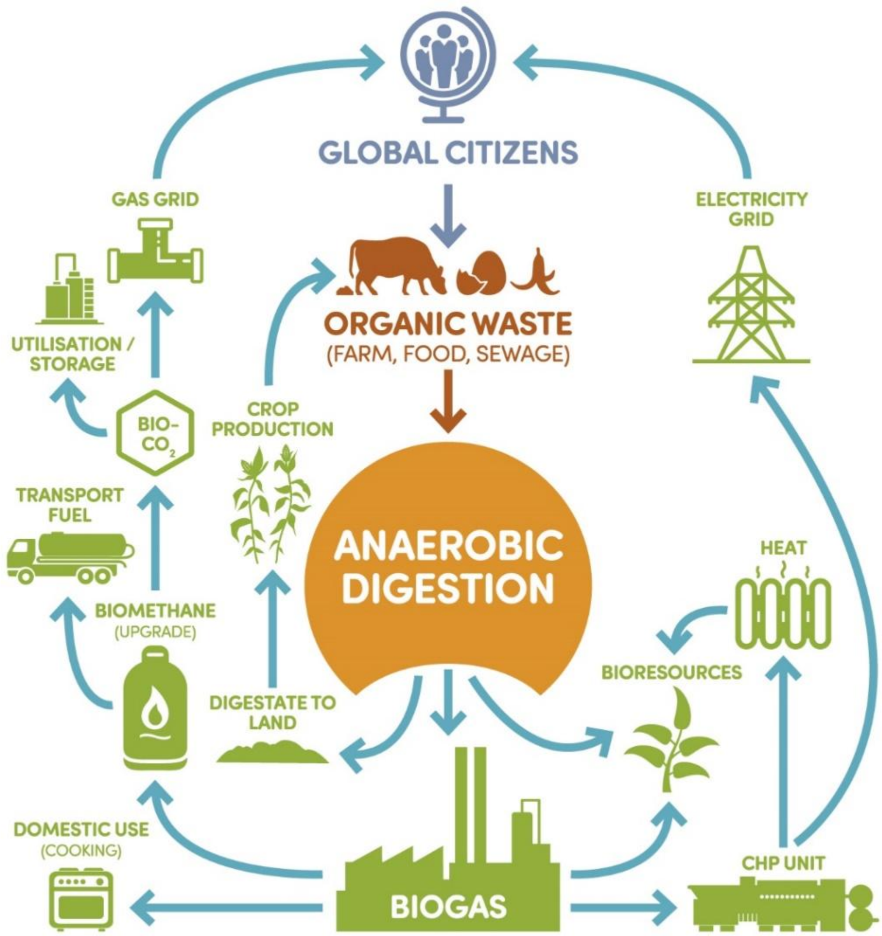

Figure 1 Interactions between agriculture, food processing, food and feed consumption and energy supply (reproduced with the kind permission of the World Biogas Association)

1.3. General aspects on reducing GHG emissions by using biogas

In addition to the impact of AD on the Circular Economy or Energy Efficiency, greenhouse gas emission reduction plays an important role when producing and utilizing biogas. Organic waste materials discharged in landfills produce landfill gas by means of anaerobic degradation which is emitted into the atmosphere if not collected properly (Zhu et al., 2009) thus contributing to the global warming. If organic waste is degraded prior to disposal in a closed reactor under controlled conditions emissions can be reduced significantly. The burning of the methane releases only carbon neutral carbon dioxide (Ward et al., 2008, Khalid et al., 2011), as in contrast to fossil fuels biogas contributes far less to the greenhouse effect, ozone depletion and acid rain (Nath and Das, 2004).

With respect to greenhouse gas (GHG) emissions, the food and beverage industry contributed 85 megaton (Mt) CO_2 equivalent emissions per year in 2020 (FoodDrinkEurope 2021).

The Greenhouse Gas Protocol Corporate Standard (2015) distinguishes GHG emissions within production processes as Scope 1, Scope 2 or Scope 3 emissions to help delineate direct and indirect emission sources and improve transparency. These emission categories are defined as follows:

- Scope 1 emissions: direct GHG emissions, e.g. emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc. or emissions from chemical production in owned or controlled process equipment. Direct CO_2 emissions from the combustion of biomass are not included in Scope 1 but are reported separately.

- Scope 2 emissions: indirect GHG emissions, e.g. regarding electricity use, emissions from the generation of purchased electricity consumed by the company.

- Scope 3 emissions: other indirect emissions that are a consequence of the activities of the company, but occur from sources not owned nor controlled by the company, e.g. emissions associated with the extraction and production of purchased materials, transportation of purchased fuels, use of sold products and services.

Producing and utilizing biogas in stationary or in mobile applications has to offer several benefits for the food processing companies regarding the reduction of GHG emissions, e.g.:

- Burning biogas directly on site for heat and steam production reduces the demand on fossil fuels, thus reducing Scope 1 emissions.

- Utilizing biogas in a combined heat and power unit (CHP) reduces the amount of energy to be bought or supplemented otherwise, reducing Scope 1 or 2 emissions.

- Upgrading biogas to biomethane which is used as fuel for vehicles reduces the demand on fossil fuels in transport and logistics, thus reducing Scope 1, 2 or 3 emissions.

- Substituting chemical fertiliser by commercialising the digestate reduces Scope 3 emissions.

Therefore, an AD plant can support the company in reducing Scope 1, 2 and 3 emissions by substituting fossil fuel-based heat, electricity or transport. Further, closing the nutrient cycle by providing the AD plant's effluent as organic fertilizer reduces emissions as well. Similarly, as the AD plant on site has to be planed and installed individually, the quantity and quality of synergistic effects by biogas production and utilization on the industry´s GHG reduction have to be determined and evaluated for each installation individually.

1.4. A selection of motivations for starting an AD project

The food and beverage industry focusses on the cost-efficient provision of products, not necessarily on treating wastewater, by-products and wastes. Still, the latter is mandatory and costly so that pathways for handling wastewater, by-products and waste are usually settled and well-rehearsed, as in examples given below:

- The company gets paid (or pays) for the utilization of organic by-products and residues as a secondary feedstock for feeding animals.

- The company pays for the treatment of its wastewater in a municipal wastewater treatment plant.

- The company pays for the collection and shipping of by-products and residues to external recycling or treatment facilities.

Points of connection and borders between production and post-treatment are clearly defined, benefits and costs are well known. Therefore, a particular motivation or driver, outweighing the financial risk and risk of increasing effort of a new investment, is essential to encourage a company to re-design its production, specifically its wastewater and waste management.

There is no simple answer to how this motivation must look like, since the reasoning for an on-site treatment of organic residues or waste streams in an AD facility is complex. The branches and production sites have highly individual characteristics. Besides the internal drivers for change, the external requirements as e.g., changing prices or regulations play a role. Potential drivers can be:

- Changing legislation regarding GHG emissions
- Changing legislative restrictions for waste/wastewater handling,
    - E.g., changing regulations for reuse as a secondary feedstock
- Changes in cost – revenue structure
    - Rising prices on the energy market,
    - Increasing costs for the waste/wastewater treatment,
    - Decreasing revenue on the secondary feedstock market,
- Security of supply - reliance on external sources:
    - Dependency on fossil fuels,
    - Dependency on volatility of connected markets,
- Low efficiency in the feedstock´s utilization,
- Environmental issues,
- Change of the production capacity, resp. modification of production processes,
- Expansion of the products´ portfolio,
- Change of the marketing strategy,
- Socio-economic expectations from customers of the company.

As a matter of fact, not every aspect mentioned above has the same importance within each sector, each company or each facility. But at the end of the day the company's focus will be condensed to economically driven results, the reduction of costs and the increase of revenues will be decisive criteria for the decision.

AD installations connected to production sites of the food and beverage industry can be part of new concepts, meeting these expectations. An AD installation needs to be integrated and part of the overall solution, it is neither an end-of-the-pipe nor a one-fits-all solution. An AD installation always has to be developed tailor made, individually designed - paying attention to the detail within the overall system and upstream and downstream processes.

2. Aspects of industrial AD applications

The following chapters shall summarize the basics of AD (Chapter 2.1), introduce selected conceptual (Chapter 0) and technical (Chapter 2.3) aspects for AD installations in the food and beverage industry and take a look onto the reduction of GHG emissions (Chapter 1.3). The latter can be achieved by implementing AD installations, preferably embedded in a holistic concept of combined energy and environmental technologies.

2.1. General aspects of AD

AD is a biological process that is naturally occurring in swamps, rumen and landfills (Braun 1982; Bischofsberger et al. 2005). In the absence of oxygen, microorganisms metabolize organic compounds. The degradation process involves a series of metabolic reactions, the four main interdependent pathways being hydrolysis, acidogenesis, acetogenesis and methanogenesis (Braun 1982). The pathway of AD results in the gaseous end-product biogas, a mixture of methane and carbon dioxide.

Biogas consists of 50-85 vol.-% methane (CH_4), 12-50 vol.-% carbon dioxide (CO_2) and trace gases like water (H_2O), hydrogen-sulphide (H_2S), ammonia (NH_3) and hydrogen (H_2). The calorific value of biogas depends on its CH_4 content and is being calculated based upon a calorific value of 9.94 kWh/m³ CH_4. The calorific value of biogas with 55% CH_4 results accordingly in 5.47 kWh/m³ Biogas, equivalent to 0.53 L fuel oil.

After some cleaning, namely dewatering and desulfurizing, the produced biogas can be utilized on site in combined heat and power plants (CHP) to provide heat and electric energy. Both energy forms can directly substitute fossil fuels or reduce the demand for electricity from the grid, especially at times of peak power demands.

Another option is the cleaning and upgrading of the biogas to natural gas quality. This so-called “biomethane” can be utilized in all applications as natural gas, most often as fuel for vehicles, like trucks or forklifts. Feeding the biomethane into the gas grid is another option and state of the art (see also Figure 1).

Besides the gaseous end-product biogas, there are also solid and liquid forms of end-products of the process, named effluent, digestate or digested slurry. The digestate, in particular when containing high content of organic solids and nutrients, can be used as organic fertilizers. Valuable nutritional components within the digestate are nitrogen, potassium, phosphorus or sulphur in significant concentrations. Usually the digestate is “ready-to-use” and therefore ready to spread onto the fields directly, without any pre-treatment. For large plants the logistics of the distribution and the storage until season for spreading on agricultural land might be a challenge.

Another option is the direct or indirect discharge of digestion effluent into waterbodies. The effluent of anaerobically treated wastewater needs to be further treated aerobically to meet the legislative restrictions for discharging it into waterbodies. This aerobic treatment can be done on site in an additional process step, or more commonly, be treated at a municipal wastewater treatment facility. As the price of wastewater treatment is amongst other dependent on the content of organics the AD process reduces these costs.

2.2. Conceptual aspects of industrial AD applications

Anaerobic microbial conversion of organic matter into biogas as a regenerative energy source is a well-established, technically mature, state-of-the-art process. Any organic material other than lignin- might it be solid, pasty or liquid - can be converted into biogas by microbial degradation under anaerobic conditions. The primary aim of AD in industrial applications is the treatment of residues for reducing the biological activity of the material, gaining an energy carrier, and reducing downstream treatment or disposal effort, respectively, costs.

Digesting solid or pasty by-products from the food and beverage industry takes place on the food and beverage production site or in external co-digestion facilities, not directly located on the food and beverage production site. By-products with high total solid content have less volume und usually higher biogas potential and therefore transportation to another site is rather economically feasible.

Anaerobic degradation of solid or pasty by-products focuses on meeting legislative restrictions for waste treatment, e.g. on the biological stabilization of organic waste or on generating a nearly inert waste fraction for further utilization or disposal. Sanitation of the material can also be included into the anaerobic digestion process if required.

On the other side transportation of very liquid by-products or wastewater other than piping is usually not cost efficient. Anaerobic treatment of wastewater is well known as a pre-treatment of organically high loaded wastewater. In case of systems with biomass retention the digesters are compact and are therefore easy to integrate on-site of the food and beverage production site. Anaerobic pre-treatment of wastewater converts most of the organic carbon into biogas, however, for discharge into water bodies further aerobic treatment is needed. Whereas anaerobic treatment is most efficient with high organic load, aerobic treatment of high load wastewater results in high effort and high demand on energy to reach discharging quality.

Feedstock originating from industrial processing is mainly characterized by constant macroscopic and microscopic characteristics; e.g. spent grains out of the brewing process are widely constant regarding their particle size and chemical composition. However, distinct seasonal changes in composition and process masses are common and need to be managed when planning an AD facility.

AD reduces the organic carbon load of the feedstock significantly, but not necessarily the volume or other compounds as nitrogen or minerals. Hence the masses of digestate to be managed is rather not influenced by AD (in particular of residues with high water content) the solution for the digestate is a crucial aspect for the design and economic feasibility especially of an industrial AD facility. The quality of the digestate depends on the feedstock used.

Legislative restrictions and local infrastructure will define the possibilities and the effort for the treatment or the direct utilization of digestate as a fertilizer. For AD facilities in rural areas the logistics behind the utilization as a fertilizer is easier to handle than for the ones in industrial sites with no arable land around. The storage of effluent till distribution, the transport and the demand of farmland area for spreading the fertilizer are critical aspects for the economic feasibility of an industrial AD installation. The larger the site gets, the more challenging the logistics become.

AD facilities for liquid substrates are continuously operated producing a constant biogas flow. The ideal state of a continuous process is the so called steady-state, where all process parameter are constant. Since the degradation follows a kinetic pattern and biological continuous processes require a distinct volume, a sudden stop of the supply of feedstock will not lead to a sudden stop of the biogas production. At industrial AD facilities the steady utilization of biogas should be designed thoroughly.

2.3. Technical aspects of industrial AD applications

AD solutions are highly specific with regard to the feedstock characteristics, additionally site-specific requirements demand for individual solutions. For AD systems there is no "one-size-fits-all" solution to treat all types of industrial waste/by-products and wastewater. AD systems for wastewater treatment are mainly characterized by high organic load and short hydraulic retention times. Short retention times are possible if biomass and hydraulic retention time are decoupled by retaining suspended flocs or pellets or biomass immobilizing on carrier material. Examples for such systems are Upflow Anaerobic Sludge Blanket (UASB) reactors, Expanded Granular Sludge Blanket (EGSB) reactors or fixed bed reactors. AD installations for solid feedstock or liquid feedstock with particles are comparable to the designs of agricultural biogas plants, using the technology of Continuously Stirred Tank Reactor, CSTR. Besides these general technical concepts there are a few individually designed applications for specific industrial processes.

The main driver behind variation in design and technology of the AD systems is the need to match the characteristics of the feedstock – the feedstock defines the design and technology of the installation. This is apparent when comparing wastewater with solid substrates - but the water content is not the only relevant criteria. Inhibitory substances, degradation rate, nutrient content need to be considered in plant design as well.

Besides the characteristics of the substrates which require a certain process design, the plant needs to be integrated in the infrastructure on-site, especially with the production process and with upstream and downstream processing. Changing the processing upstream can influence the feedstock as follows:

- Less or higher demand on freshwater reduces or increases the amount of wastewater and in succession reduces or increases the hydraulic load in the existing treatment facilities.
- Internal reuse of wastewater or by-products changes the hydraulic and/or load of the feedstock, substances in the process can accumulate and concentrations increase.
- Reducing or increasing the food and beverage production induces a corresponding impact on the by-products and wastewater - causing a mismatch in design parameter and operational conditions. Similar effects if seasonal changes in production are occurring.
- Deviation from design parameter regarding quality and quantity of the feedstock might ask for a modification and adaptation of the concept or the equipment of the treatment facilities.
- Upstream changes have not only on the AD an impact – also downstream of the AD process upstream changes might have a critical impact on the performance of treatment processes.

These aspects must be reflected by a thoroughly planning of an AD project.

2.4. Resource efficiency, environmental impact and energy demand

The food and beverage industry, like any other industry, is constantly investigating options to increase resource efficiency. The impact on the environment in general and the reduction of GHG emissions in particular is beyond the regulatory standards a relevant aspect for marketing and has growing impact on the decision of customers. The demand for energy is one of the major drivers for greenhouse gas emissions. Consequently, the first approach is focusing on the reduction of emissions from the energy supply.

The synergistic linkage between actions aiming on reducing the environmental impact and technologies aiming on resource and energy efficiency is obvious. Any actions undertaken under these premises are termed as production and process integrated environmental protection:

- Production integrated environmental protection is also referred to as cleaner production. It follows the principles of “avoidance before recycling” and “recycling before disposal”. In praxis it is aimed at that unavoidable residuals must, preferably, be reused internally or externally as a secondary feedstock.
- Process integrated environmental protection focusses on procedural improvements, like processes with less residues and takes priority over the production integrated measures. In praxis it is aimed at minimizing the demand on energy, consumption of resources and emissions in order to achieve overall low-emission processes and to optimise production yields.

Energy demand and cleantech for reduction of emissions and impact on the environment have often a synergistic linkage. To meet the production site´s demand of energy various energy sources and technologies are implemented, such as combined heat and power units, condensing boiler technology, heat recovery from compressors. To meet the production site´s restrictions in emissions cleantech is implemented, such as exhaust gas filter or exhaust gas catalysators. Sometimes both are using the same or similar technologies, aiming e.g. on lower emissions. Often actions in increasing the efficiency of energy supply have an impact on the emissions - less demand of heat, less CO_2 emission from the boiler. Increasing the resource efficiency of feedstock reduces the productional specific waste - less feedstock to be transported, stored, or processed reduces the energy demand, less waste and less emissions are the consequences.

Referring to on-site industrial AD applications and biogas out of production related feedstock the overall effects follow the same principle: implementing an AD facility and using biogas exerts a significant influence on the energy situation – e.g. less demand on fossil fuel – as well as on environmental impact – e.g. less GHG emissions.

3. AD of feedstock from the food and beverage industry

The technology and technique for AD plants are state of the art and field-tested all over the world. Local legislation and on-site characteristics are forming the individual framework of an AD installation affiliated to a food processing industrial site.

Technical and economical reliable AD installations ask for a consistent course of action, a holistic approach and a focused project management. The following chapters shall point to this importance and shall give a helping hand in implementing an AD project.

3.1. By-products, residues and wastes

The production and distribution of food and beverages does not only result in goods or products finally sold to the customers, but also in various fractions of by-products, residues, waste and wastewater. In Figure 2 the flow scheme depicts the principles of processing and of downstream utilization and treatment. Treatment is needed to stabilize or reduce fractions which have no other use, e.g., by aerobic treatment of wastewater or combustion of solid waste.

The criteria for process selection are mainly resource driven and/or energy related. Energetical utilisation can be realised by means of combustion (if the material has a very low water content) or by means of anaerobic digestion.

Resource utilization of organic residues from food processing as a secondary feedstock may be possible in biorefineries, as animal feed or in pharmaceutical production sites. Any utilization of secondary feedstock directs again a fraction into a sellable product and results into various fractions of by-products, and/or waste and wastewater. Then again, the decision of what to do with these residues has to be made. The longer the cascade, the more depleted the residues are and then a utilization gets more difficult. Since the anaerobic digestion process is quite unselective and undemanding in regards of substrate quality, it can be in most cases the final step in a cascade, utilizing the energy content of the remaining organics.

According to the basic flow scheme depicted in Figure 2 downstream processing and closing the loop are the key drivers in circular economy to increase resource efficiency and to reduce emissions. The main sources of residues, waste and wastewater occurring whilst production and distribution are as follows:

- Sub-standard products and rejects,
- Damaged products, defective packaging,
- Overstock, end of shelf life,
- Returns from wholesale, end of shelf life,
- Unavoidable residues whilst processing,
- Washing and cleaning of production facilities.

Any fraction of the raw material, which is not transferred into the product or cannot be utilized otherwise, generates various costs and emissions, e.g. for a higher demand of raw material, logistics and treatment of waste and wastewater.

According to the type, quality and quantity of residues or waste and wastewater the recycling to utilization as secondary feedstock respectively secondary source material is determined, e.g. as fodder for animal breeding, food- and non-food-production, fertilizers, fuel.

Major components in residues influencing the potential further utilization are minerals, proteins, fat, hemicellulose, cellulose, and sugars. Besides these main classifications there are many other components which might also influence the use of residues. Examples for residues containing mainly minerals as e.g. eggshells or horns might be suitable for fertilizer production. Recalcitrant organics as humic substances contribute to soil quality if applied on agricultural land.

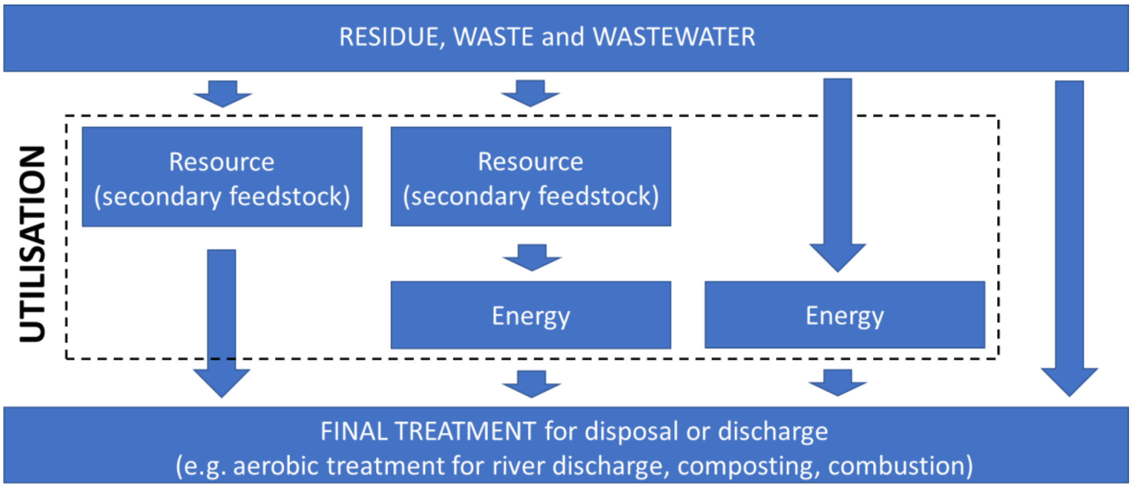

Figure 2 Flow-scheme of downstream processing of production related residues, waste and wastewater

Proteins are a major fraction in spent grains, surplus yeast, or whey, they are used as secondary feedstock for human nutrition or animal fodder. Slaughterhouse or rendering wastes contain mainly fat, being able to be used partly or in total for producing biogas in AD plants, as a secondary feedstock in biodiesel production, as a fuel in combined heat and power units or as lubricants for technical use. Mainly hemicellulose, cellulose and cellulosic compounds containing feedstock will be used as animal fodder, as basis for advanced fuel production, as fuel in biomass combustion or in human food production, e.g. spent grains, gluten, or rice husks.

Besides these main components residues can contain a wide range of compounds, not easily categorized into one of the main classes or mixtures, like sugars, alcohols, carboxylic or fatty acids, esters. Examples are wastewater from sugar production, sugar beet pulp, potato peels, processing/washing water from milk processing or from acetic acid production. The variety of compounds offers accordingly a wide range of utilization, as fuel, in human nutrition, for animal breeding or synthetic materials.

Since the anaerobic digestion process can convert almost all organic substrates, it is applicable to all residues containing the named major organic components and is always an option for secondary utilization. AD does not require the high level of feedstocks quality as e.g. specific fermentation processes, human nutrition or animal breeding does. This also means that several residue streams with different characteristics can be treated together and consequently only one processing is necessary. The amount of microbial degradable compounds as a carbon source for biogas production is the main critical criteria. Uncontrolled enzymatic and microbial degradation of by-products causing malodour, mildew, colour or blends are in most cases not harmful for further microbial degradation in AD plants. Other different utilization pathways of residues have various requirements regarding the quality of the feedstock, e.g. no mildew, no odour, no cleansing agents, no impurities from packaging.

Solid and pasty waste from the food and beverage industry is often collected and co-digested in centralized AD facilities together with other industrial or agro-industrial feedstock and waste, like kitchen waste, organic fraction of municipal solid waste or manure.

Co-digestion is commonly undertaken in a digester system comparable to agricultural biogas plants, a continuously stirred tank reactor (CSTR). The effluent, respectively, the remaining fractions of input material can be used as fertilizer. It can be applied on agricultural land after an aerobic post-treatment by means of composting or even directly without further treatment.

However, legislation is needed to allow and define the utilization of such residues or waste materials. If they can be used within high-end utilization in production of human nutrition, or as organic end-products (e.g. as fertilizer) in agriculture is dependent on legislation. If adequate legislative regulations are not existing, the material will not be reused or recycled, it will be attributed as waste to be treated and potentially disposed on landfills.

Aside from that, pasty or liquid by-products from the food and beverage industry are sometimes co-digested with sewage sludge on wastewater treatment plants. This type of co-digestion enhances the biogas yield of the sludge treatment and increases the substitution of fossil energy by regenerative energy when operating the aerobic wastewater treatment facilities.

When separating the residue or waste production at the industrial site and the treatment in an external AD facility the regenerative energy source biogas is not directly available for the industrial process onsite. Accordingly, the benefit of GHG reduction by using biogas directly onsite is not possible or requires the need for a gas grid and an appropriate administrative and legislative framework.

The implementation of an on-site AD facility allows a direct use of the gas, and the required gas composition is defined by the utilization and not the gas grid operator.

3.2. Wastewaters

Wastewater from the food and beverage industry is characterized by a varying but also high organic load, respectively a high Chemical Oxygen Demand (COD). The COD stands for the content of organics in the wastewater, the higher the COD the higher the gas potential. Table 1 depicts the average characteristics of wastewater from different sectors. Most parameters in Table 1 show a wide range, due to the specific, individual situation in each facility. The COD determined in wastewater from food processing industries is categorized as “easily degradable”, due to its mainly dissolved, organic compounds.

The most common wastewater treatment prior to discharge in a river system is based on aerobic microbial processes. Main advantages of aerobic processes are the thoroughly removal of carbon and the option for ammonia and phosphorus removal. AD processes remove only carbon. On the other side, reducing high loads of carbon in aerobic process requires a high input of energy for aeration purposes: the higher the COD in wastewater, the higher the demand of oxygen for the aerobic biocenosis, the higher the demand on energy for aeration, the higher the overall effort and costs for the wastewater treatment. Accordingly, aerobic systems are more suitable for the treatment of low strength wastewater or municipal wastewater.

Vice versa anaerobic systems are suitable for the treatment of high strength wastewater. Anaerobic biocenosis is not limited by oxygen availability and can therefore easily handle higher concentrations of carbon. Preferably COD concentrations beyond 4,000 mg O_2/L are interesting for anaerobic digestion (Chan et al., 2009). Accordingly, the demand on process energy for carbon reduction is lower than in aerobic systems and in addition biogas as energy source is produced.

Degradation rates in anaerobic systems are usually between 65 and 95% for organic matter which is less than the degradation achieved in aerobic systems, due to different pathways of microbial metabolism (Bischofsberger et al. 2005). For a treatment to reach discharge parameter for carbon, ammonia and phosphorus (and potentially other parameters) a downstream aerobic treatment is obligatory.

That is why in the food and beverage industry most AD facilities for wastewater treatment are implemented as a pre-treatment facility. Reducing the COD in the wastewater anaerobically reduces the downstream effort for the aerobic treatment – and reduces the costs for this aerobic post-treatment. Most industrial wastewater AD installations are paying off simply by the reduction of costs for aerobic post-treatment.

An AD pre-treatment of wastewater will influence its chemical composition significantly, in particular the content of organic carbon. Downstream processing might be influenced in its efficiency and effectiveness when receiving pre-treated wastewater. When discharged to a municipal treatment facility the share of the industrial wastewater in the overall flow of wastewater to be treated might impact the processing. Aside from the share of industrial wastewater further determining factors for estimating an impact are type and composition of all wastewaters shares as well as the design data of the municipal wastewater treatment plant, like size, process technology installed, operational parameters. An individually and on-site focused evaluation to determine the specific impact of pre-treatment actions on downstream processing is highly recommended. Such analysis shall accompany the feasibility phase of the project.

Table 1 Average characteristics of wastewater from food and beverage industry (Pesta, 2024)

Sector	Specific quantity [m^3/t product]	COD [kg O_2/m^3]	pH value
Sugar industry	15	7.5-10	6.8-7.5
Starch industry	1.5-2.3	5.7	5.9
Vegetable and fruit processing	10-100	8-50	7.8-7.9
Potato processing	0.9-18	6-46	6.2-12.3
Fat- and Oil-Processing	1-15	5.0-10.0	5-9
Meat Processing	5.5-20.4	3.0-60.0	7.15-8.4
Milk processing	0.5-4	0.01-0.5	1-13
Fish processing	7-45	3.5	6.7
Soda water	1.18-2.7	0.35-0.85	-
Refreshment drinks	1.4-2.8	0.85-1.6	-
Fruit juice production	1.8-2.8	3.0-6.0	3-4
Breweries	2.5-6	1.8-3.0	-
Wine	2.9-4.8	170	3.2
Distilleries	4-8.5	30-40	6.7-7.2
Yeast processing	10-40	5.0-25	4.8-6.5
Molasse distilleries	2-3	15-75	4-6

4. Composition and characteristics of feedstock

The origin and composition of feedstock define the technology of the AD plant and the dimensions of the process. The more is known about the physical, chemical, and microbial characteristics the more precise the design of the plant will be. Accordingly, the economic risk of the investment will be reduced.

The physical characteristics of the feedstock define the material handling and consequently the type of AD system, downstream also the type of post-treatment or digestate treatment. Physical characteristics combine for water content, particle size, content of impurities and inert material, resistance towards mechanical particle size reduction, viscosity. Physical characteristics have major impact on technologies for pumping, stirring, grinding, sieving, mashing, separating. Prior to the process unpacking and separating can be of relevance. In the post treatment the characteristics of the digestate influence the selection of technology for land application, separation, if applicable composting, drying, pelletizing.

The chemical characteristics determine the quantity and quality of the produced biogas as well as the process design in regards of retention time and the additional demand for nutrients, the handling of inhibitory substances or the tendency of foaming.

The microbial characteristics are closely linked to the physical and chemical aspects, as we are talking about microbial degradation: inhibitory compounds (disinfectants, cleansing agents, heavy metals, ammonia), degradation rate of the feedstock in general and if applicable fractions with varying rates, necessity of supplementation with trace elements or enzymes. Another aspect is the potential existence or formation of pathogens in the substrate.

The feedstock defines the AD system and accordingly the process design must consider/decide e.g. for:

- Necessity of sanitation by means of pasteurization or sterilization.
- Buffer capacity of the feedstock, resp. in the digestate,
- Odour control in the facility (e.g. by means of a biofilter).
- Mechanical pre-treatment: crushing, grinding, sorting, sieving, sink/swim separation, macerating.
- Design of process: separation of hydrolysis (two-phase-system), retention time, cascading or parallel operation of digesters, anti-foaming installations, additive supply, exhaust gas treatment.
- Biogas treatment: desulfurization, gas storage capacity, dewatering, gas transportation, CO_2 removal via upgrading.
- Biogas utilization: CHP, boiler, upgrading and grid injection, fueling station.
- Digestate treatment: sanitation, separation, drying, pelletizing, composting, storage, filling installations.

As an example, Figure 3 depicts a possible cascade of feedstock preparation techniques at a glance. Feedstock preparation takes place prior to the pre-storage or digestion and shall increase the feedstock´s digestibility e.g. by increasing the surface, by removing of impurities and by preparing a pumpable slurry. The cascade of preparation techniques shown in Figure 3 will be installed at centralized AD facilities processing various types of feedstocks with a wide range of characteristics and impurities – like separately collected municipal biowaste, market leftovers, kitchen waste or packed food and beverages.

Handling and preparation of by-products from food or beverage production on-site in decentralized AD facilities are likely to take place with less effort. E.g. only sieving or maceration might be necessary, to remove poorly degradable particles or solid impurities. In general, wastewater treatment plants are equipped with a screen, a grit chamber, a balancing tank and a calamity tank.

The individual configuration of feedstock´s preparation facilities will be a question of the on-site framework, type of feedstock and legislative restrictions as well.

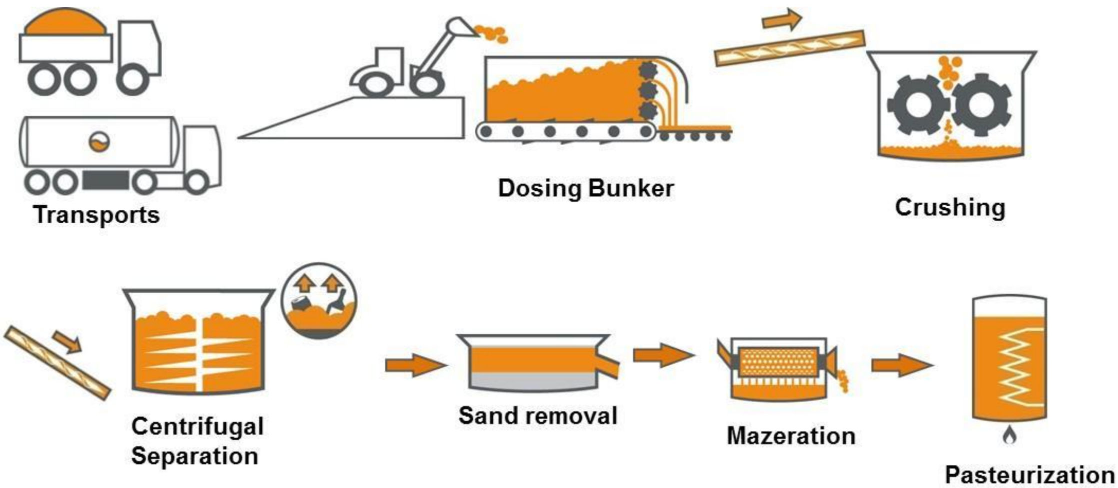

Figure 3 Selection of feedstock preparation techniques at a glance – cascade of treatment options (Pesta, 2024)

Though the available technology components for the pretreatment of feedstock is state of the art there will be no one-fits-all-solution for AD installations in the food and beverage industry. Different branches produce different types, quantities and qualities of by-products or residues. Examples are spent wash from distilleries, sugar beet pulp from sugar refineries, spent grains from breweries and potato peels from starch industry. But even within the single branches there will be different qualities and quantities of feedstock available, exemplarily this is due to:

- The size of the production facility, e.g. the bigger the more efficient will be the production.
- The year of manufacture of the installed technology, new production technologies change the residue composition.
- The effort already taken on optimization and maintenance of production facilities.
- The effort already taken on emission reduction, environmental protection, and resource efficiency.
- The quality of feedstock for food production.

Further considerations on parameters are shown in Table 4**Table 4**. Their impact on implementing an AD installation will be discussed in chapter 6. The variety of the parameters influencing the design, processing and operation of an AD plant and the individual constellation on every site result in a complex design problem which proves the importance of an individual, on-site-focused development approach for the design of each plant.

4.1. To gain overview: tables and calculators

The implementation and design of an AD facility into an industrial processing site requires careful preparation and care to avoid major pitfalls (see Chapters 6 and 7).

In the early feasibility stage of a project first estimates and calculations are done based on available information and figures, which are available with low effort and at low costs.

For a first rough estimation it is possible to use publicly accessible services, like online available tables with feedstock data and calculators. Based on this information the order of magnitude of biogas produced can be estimated and a first rough evaluation on the economical reliability of the AD plant can be executed.

Examples for various feedstocks from different branches and their methane yields are given in Table 2. Such figures can be found in several publications. As an example, the German institution “Bayrische Landesanstalt für Landwirtschaft (LfL)” offers online information on the biogas yield of a large number of feedstocks. (LfL, 2024)

Hence, figures in such data bases show a wide range if results are based on several samples and there is no information about the sampling process, sample handling, sample preparation or analysing method. In addition, specific processing or plant operation modes, seasonal feedstock changes or processing of feedstock can have a major impact on the gas yield.

Since the precise information on the substrate has such an importance on design and performance it is worth to base the detailed engineering on a precise analysis of the very substrate which shall be treated. The quality of the information is crucial for the reliability of design parameters (see Chapter 4.2).

Aside from single figures or tables there are also various biogas calculators available online. Though only a few provide information on industrial feedstock or wastewater. Consequently, online tables and calculators may be a welcome resource for first estimates. Basic information as the suitability of a feedstock for AD purposes, the biogas yield or the gross energy output are usually easily accessible.

Again, one needs to consider that there is no information on the sampling process, sample handling, sample preparation or analysing method. The pros and cons of these biogas calculators are the same as discussed before for the date from tables.

Online calculators - where to find them:

- The **FABbiogas-Calculator** focusses on industrial residues and wastewater. The output of the online tool shows the basic biogas production, the energetic potential of an AD plant and significant figures regarding the design of the plant and even characteristics of the effluent or digestate. (http://www.fabbiogas-calculator.eu/en/)
- The **Cost of Renewable Energy Spreadsheet Tool** (CREST) contains economic, cash-flow models designed to assess project economics, design cost-based incentives, and evaluate the impact of state and federal support structures on renewable energy. (https://www.nrel.gov/analysis/crest.html)
- The **European Biogas Association** offers a choice of online biogas calculators (no login needed). (https://www.europeanbiogas.eu/online-biogas-calculators-project-holders-policy-makers/)

Table 2 Characteristics of feedstock types and their methane yields (Behmel and Meyer-Pittroff (1998) - modified by Pesta)

Type of feedstock	Dry matter (DM) [%]	Organic Dry Matter (oDM) [% DM]	Total Nitrogen N_{tot} [% DM]	CH_4 yield [m^3/kg oDM]
Rotten potatoes	25	79	1.5	0.5-0.6
Clover	20	80	2.8	0.4-0.5
Apple slops	25	86	1.1	-
Spent grain	20-22	87-90	3.5-4	0.6-0.7
Vegetables	10-20	76	3-5	0.4
Bread (waste)	90	96-98	1.8-2	0.7-0.75
Cacao peels	95	91	2.5	-
Potato slops	12-15	90	5-13	0.55
Cereal slops	6-8	87-90	3-4	0.6
Molasses	80	95	1.5	0.3
Whey	95	-	1.5	0.5-0.6
Rape seed slops	92	97	1.4	0.58-0.62
Leftovers	9-18	90-95	0.8-3	0.5-0.6
Green waste	60-75	30-70	0.6-2.7	0.2-0.6
Meal (blood processing)	90	80	12	-
Flotating sludges (fat)	5-24	83-98	3-8	0.6-0.8
Faeces (intestinal)	12-15	80-84	2.5-2.7	0.2-0.3
Rumen (pressed)	20-45	90	1.5	0.6-0.7
Meal (animal waste)	8-25	90	2-7.5	0.5-0.8
Fat (separators)	35-70	96	0.5-3.6	0.7 (1.0)

4.2. To gain detailed insight: feedstock analysis

After a first estimation an in-depth planning is obligatory including detailed feedstock analysis. Aside from the chemical analysis of e.g. water content, ash, nutrients, nitrogen, sulphur or heavy metals also the determination of the biogas yield shall take place, at first with a batch test, for a more precise analysis a continuous test. Batch Test is described in Weinrich et al 2018. Continuous tests are much more cost intensive but gain more precise and detailed information on the process performance and biogas yields. It is of utmost importance to gain a representative sample, so it might be necessary to analyse the feedstock several times to identify seasonal or processing related changes.

Figure 4 depicts the Weihenstephaner Biogas Yield Test WBT(R), a laboratory setup for determining the biogas and methane yield according to the German VDI Guidelines 4630. VDI 4630 provides guideline procedures and specifications for the determination of the biogas potential of organic material. To receive reliable and comparable results the assigned laboratory for conducting biomethane potential tests should participate in round robin tests.

In case of unknown substrates (or substrates where no public data are available), specific or very complex feedstock it is recommended to increase the effort for characterisation. Complex feedstock e.g. might show a wide and varying range of easy/hard degradable compounds, a high content of inhibitory compounds, inert compounds, a high concentration of recalcitrant biomass. In such cases a continuously operated test system is recommended since it gives more precise information on the yield and the process characteristics than a batch test.

Feedstock characteristics also exert an influence on the quantity and quality of effluent respectively digestate - this is crucial for estimating the possibilities and effort for digestate utilization and treatment.

Figure 4 Determination of the biogas potential by Weihenstephaner Biogas Yield Test WBT(R) (Pesta, 2024)

The more effort provided during the feedstock analysis, the more likely the AD plant will operate with a high availability, will generate expected methane yields, and result in an overall economically feasible and profitable installation.

5. Treatment and utilization of digestate

AD of organic substances does not only produce biogas but also digestate, a slurry containing water, minerals and dissolved and solid organic residues. Digestate is a valuable fertilizer containing amongst others rather recalcitrant organics, nitrogen, potassium, phosphorus, sulphur and trace elements. Utilization of digestate from agricultural production sites as a fertilizer is state of the art and a common practice. However, in case of large industrial sites the land application would require large transportation capacities and agricultural area. Digestate distribution from large plants result in long distance hauling of digestate. Due to the high-water content of digestate long distance hauling becomes increasingly uneconomical.

Table 3 Different processes for digestate treatment (Fuchs and Drosg 2010)

Mechanical solid/liquid separation	Removal of solids from liquid phase	Treatment of solid phase	Treatment of liquid phase	Treatment for nitrogen removal
Screw press separator	Vibrating screen	Composting	Membrane processes	Ammonia stripping
Decanter centrifuge	Vibrating bow screen	Drying processes	Evaporation	Biological processes
Belt filter	Flocculation and precipitation	-	-	Ion exchange
Discontinuous centrifuge	Flotation	-	-	Struvite precipitation
-	Additional filter devices	-	-	Nitrogen removal with membrane contactors

Another aspect appears in case of biogas plants in regions where there is already a surplus of nitrogen in fertilizer management due to high density of animal husbandry. The application of nitrogen-rich digestates or manure is limited then, and it might not be possible to apply the digestate on agricultural land in the region within short transportation distances. In such cases facilities for digestate treatment have to be installed and operated, increasing the efficiency and reducing the cost of transportation: less water, higher concentration of nutrients.

Since these issues are even more pronounced with wastewater - the situation of AD plants for treating wastewater from the food and beverage industry are most often a different one. Wastewater is treated anaerobically to reduce the COD and therefore to reduce the loading and costs of the downstream aerobic treatment processes. The effluent of the AD plants goes directly into the sewer and the wastewater treatment plant, avoiding the land application.

AD plants at food and beverage production sites using feedstock with higher dry matter content than wastewater might face a lack of possibilities to use the digestate as a fertilizer directly, for the reasons mentioned above. Compared to the effluent from typical anaerobic wastewater treatment the dry matter content, particulates and the chemical oxygen demand in the digestate are usually too high for a downstream aerobic treatment. But, if there is no land application possible in the vicinity of the AD plant, the digestate needs to be further treated - to reduce its volume and to increase its quality for other purposes. Consequently, digestate treatment often represents the economic bottleneck of the entire biogas production at industrial installations. Digestate treatment technologies are costly but they concentrate the nutrients and reduce thereby transportation or other treatment cost. Some treatments produce value added by-products as compost, dried digestate pellets or struvite.

shows different processes of digestate treatment. They all are applied to concentrate nutrients and solids and/or to produce process water to be recycled in the process. It will be always a site-specific decision which processing or which combination of processes has to be installed. By-products or waste emerging from the digestate treatment must be considered in regards of resulting costs or revenues.

As example given Figure 5 shows a cascade of options for digestate or effluent treatment. The liquid phase after the decanter can be further treated by using membranes. Membrane plants are often combining ultrafiltration and finally reverse osmosis for processing the digestate. This cascade of treatment options results into high quality by-products and clear water out of reverse osmosis, but also asks for a high-level of investment and operational effort.

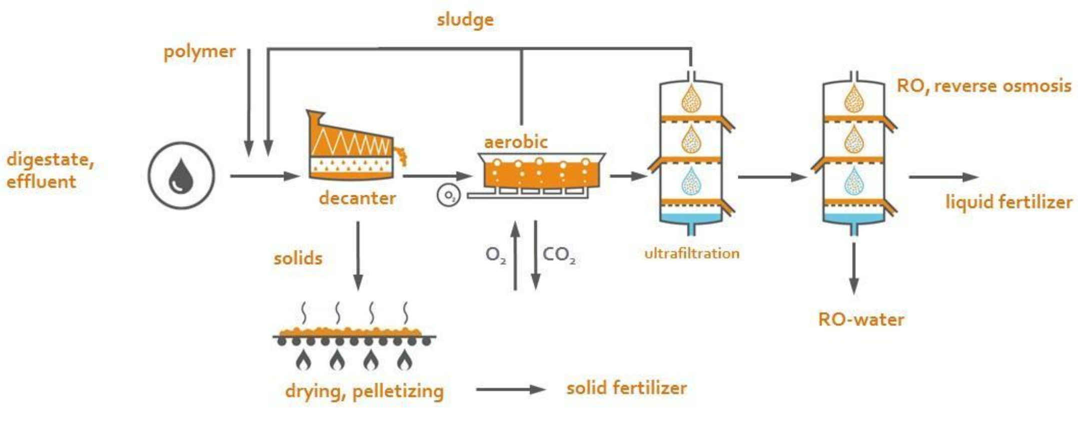

Figure 5 Example of a digestate treatment- cascade of treatment options (Pesta, 2024)

Fine particle separation by using flocculants must be carried out before, to prevent blocking of the membranes. Using the membrane technology high wear and tear costs and higher electricity costs occur in comparison to evaporation plants. In evaporation plants, a vacuum is applied so that water evaporates already at around 70°C. Nevertheless, the heat consumption of evaporation plants is very high and a volume reduction of 50% is often sufficient.

Direct application of digestate on arable land or even to transport the digestate to more distant areas might be economically more effective than investing in and operating a sophisticated treatment facility.

Technical reliability of digestate treatment options is most often to be solved but this results in additional costs, so economics are more difficult to solve. Especially operational costs (OPEX) are in the focus:

- OPEX of digestate treatment facilities are very high due to the demand of consumables for flocculation or filtration, membrane replacements, maintenance costs, the demand of electrical power for aeration or filtration, the demand of heat for dewatering, to name the most significant ones. These OPEX might exceeds e.g. the revenues of the product fertilizer.
- OPEX shall be estimated during the design and planning of the plant but is often underestimated. Poor design can lead to highly volatile OPEX and significant deviation from estimated figures. Other reasons for the variation can be volatile upstream processing or volatile feedstocks characteristics. Occasionally the assumptions on the digestate behaviour in the treatment process have been wrong. Most often the reasons for the misjudgement are too optimistic assumptions of performance of the equipment, service life and lifetime of equipment, resulting in the installation of too small capacities. This leads to low estimates of invest and OPEX in the design phase but increasing issues during operation.

The fundamental characteristic of OPEX is simple but crucial: once the plant has been installed and set into operation attempts on reducing OPEX are costly or even not possible (see Figure 6). The exchange of weak performing equipment with high OPEX causes additional investment costs for new equipment and infrastructure. Such additional expenses after the installation of the plant and commissioning are not considered in the project's overall investment costs CAPEX – and will exert a significant influence on return of invest.

Therefore, the project design has to follow the proceeding depicted in Table 5 with a high effort in the early evaluation phases. Effort in the early feasibility and preliminary planning stages increases the reliability of calculations, reduces the uncertainty of estimations and reduces the probability the effect of unwanted deviations between planning and operation.

6. Necessary considerations when starting a biogas project

The AD processing needs to be planned as a step within the overall mass flow and energy concept, with a focus on residue, waste and wastewater management concept. It needs to be fully integrated into the other process steps. Table 4 presents a non-exhaustive enumeration of aspects to be considered (see also Chapter 7). An AD facility is not only linked with the quality and quantity of the feedstock for producing biogas, but also with production processes, infrastructure, energy demand and supply, waste management and the company's perspectives and development in the future.

Table 4 Aspects to be considered when starting a biogas project

Aspect	Remark/description
Feedstock for biogas production	Water content and physical characteristics: liquid, pasty or solid Amount of feedstock available (quantity) Feedstock´s content of organic and inorganic fractions (quality) Feedstock´s content of nutrients and/or inhibitory substances Microbial degradability, potential biogas yield and degradation rate Availability and characteristics of feedstock during the whole year, time variation curve Status quo of revenues/costs from feedstock management Availability of additional feedstock for co-digestion Long term perspective according to overall processing development
Waste management	Status quo of waste and by-product treatment regarding infrastructure and processing Status quo of waste and by-product treatment regarding costs Possibilities/effect by increasing the resource efficiency: • reduction of the quantity of waste, • increase of the quality end-/by-products, • increase re-use of by-products internally, • impact on upstream and downstream processing.
Wastewater treatment	Status quo of wastewater treatment regarding infrastructure and processing, of costs for wastewater treatment Possibilities/Effect by increasing the resource efficiency: • to reduce the quantity of wastewater, • to increase the quality of wastewater, • to re-use wastewater or fractions internally, • impact on downstream processing.

Aspect	Remark/description
Infrastructure	Existing infrastructure: adaptability and possibility of expansion and rearrangement Area availability for installing additional facilities Necessary connected investments and replacements downstream and upstream of the AD plant Production fluctuations and resulting changes in the amount of available feedstock, demand on buffer or storage facilities Grid access power line, grid access gas line, options for fuel supply Grid access district heating, grid access sewage system
Energy management within the production processes	Demand of thermal energy; minimum/maximum, load duration curves: daily, weekly, monthly, annually Demand of electric energy; minimum/maximum, load duration curves: daily, weekly, monthly, annually Costs for energy supplementation: past, status quo and outlook Type and amount of energy sources to be substituted, fossil oil or gas State-of-the-art equipment or revamping/upgrading necessary Possibilities to increase the resource efficiency
Biogas utilization	Onsite biogas utilization for supply with process energy Biogas utilization by upgrading as fuel for vehicles as an option Biogas utilization by upgrading and feeding to the grid as an option Demand of facilities regarding treatment, storage or transport Costs for implementation and operation
Digestate, liquid effluent	Infrastructure and possibilities to treat the effluent from AD of wastewater Costs for further treatment or resulting wastewater fee Costs/revenues for further treatment, e.g. separation, drying, pelletizing Costs for further utilization of effluent, e.g. storage and transport Revenues and marketing options by liquid fertilizer production
Digestate, solid fraction	Infrastructure and possibilities to treat the effluent from AD by solid/liquid separation Costs for further treatment, e.g. separation, drying, pelletizing

Aspect	Remark/description
	Costs for further utilization of digested slurry, e.g. storage and transport Revenues and marketing options for solid organic fertilizer production
Legislative	Emission legislation Standards, e.g. hazardous waste treatment, effluent´s quality Building/construction regulations Verification management, e.g. hazardous waste Outlook on increasing restrictions, e.g. GHG related
Operation, human resources	Demand on additional staff Demand on skilled staff Staff has to be informed, engaged and trained Safety at work Socio-economic impact
Operation, technical resources	Infrastructure up- and downstream of the anaerobic digestion plant Connectivity to existing technical equipment Operational equipment, wear and tear parts, storage facilities Laboratory for monitoring purposes fitter´s shop for maintenance
Operation, financial resources	Overall investment costs for implementation of anaerobic digestion plant including connected investments up- and downstream Operational costs: maintenance, consumables, replacement investments, CO_2 pricing Return of invest, payback time Option to outsource operation and invest of biogas facility
Company	Effect of changes in production capacity Supply guarantee regarding energy Disposal guarantee regarding waste, by-products, wastewater setting up an overall concept for increased resource efficiency, resp. cleaner production mechanisms

Aspect	Remark/description
	Additional benefits and marketing effects as water- or CO_2-footprint Increasing local commitment by closing the loops, e.g. fertilizer production Marketing effects
Side effects	Losses or increase of revenues due to change of by-product utilization Reduction of costs due to change of by-product utilization Socio-economic impact due to • stabilizing or increasing the employment factor, • improvement of staff´s skills, • reduction of environmental impact, • improvement of environmental situation, • increasing resource efficiency.
GHG Emissions	GHG Balance and impact on Scope 1, 2 and 3 emissions Additional revenues by capturing of CO_2 as a by-product from biogas upgrading and utilization of CO_2, e.g. in green houses and food production

The consideration of the aspects described in Table 4 are crucial for implementing an economically reliable AD project. The AD project should start with detailed analysis of the status quo and develop from there alternative pathways for the treatment. The comparison of options allows the company to choose the most reliable one for implementation.

An AD plant might be the core of a holistic approach on improving the energy and resource efficiency of a food and beverage production site within a low-emission-concept. Even so-called zero-emission-concepts are thinkable, combining an industrial production site with an agricultural site.

7. Project phases of an AD project

Implementing and fitting an AD system into the overall concept of the production site is as crucial for the success of a project as the plain construction and operation of the AD plant itself. Implementation of an AD system into a production site of the food and beverage industry will always be a custom-made solution.

Table 5 depicts the approach for the development of an AD project in general but not concluding. In particular national regulations can be quite different when it comes to permission of construction and operation. The early phases define the costs of the project – investment as well as operation costs. In the early feasibility phase, enough effort should be put into creating the necessary basis for the decisions needed.

Table 5: Process phases and details in planning the installation of a biogas plant

Project phase		Necessary considerations
Feasibility Phase	Prefeasibility	Estimation of biomass quality and quantity, general design and capacities of components, site selection, energy quantities and utilization pathways based on literature values
	Decision	Decision if and how to proceed with the project
	Pre-engineering	Detailed analysis of biomass quantities, if necessary laboratory analysis and/or measurement campaign, design and capacities of components, site-specific expert statements and, energy utilization - contact to contracting parties
Project Prepara-tion	Permission of construction and operation	Application for permission of operation, negotiation with authorities, potential adjustment of design
	Site-engineering	Detailed layout of components, process and instrumentation diagram, control system design, cost estimation
	Preparation of Tender Documents	Detailed specification, performance specification, prequalification, component description, tender documents and publication and evaluation of tender; start to develop contract details of gas

Project phase		Necessary considerations
		utilization and digestate utilization
Project Implemen-tation	Decision	Decision on final package and procedures based on the offers, final go ahead
	Construction and supervision	Implementation phase and construction of plant, supervision of construction process
	Commissioning and Start up	Testing of all performance specification, test of safety systems, commissioning, training of staff and start up

Implementation of a biogas project is a long-term process. Depending on the situation on site and the needed permissions, the design, planning and installation of a biogas plant can last from several months up to several years. However, the operation of a biogas plant will take more than 20 years. It is evident, that any mistake made whilst designing the installation has long-term effects. Once the system has been built, modifications involve a great deal of effort and high costs, which have an impact on profitability. In the early project preparation phase, the cost can be calculated and a decision made on compensation. The more precise and "honest" the preparation and planning is, the more likely an economic benefit will be achieved during operation.

Figure 6 compares the correlation between the reduction of exerting influence on the decisions and the increase of costs related to ongoing adaptions:

- Feasibility Phase: no investments in hardware necessary; no component decision made yet; many options can be discussed; substrate characteristics should be evaluated and site-specific analysis done (logistics, construction area, permission etc); with low costs, a potential exit is possible prior to technical installations.

- Project Preparation Phase: expenses are rising e.g. for engineering or tender´s procedure; any adaption within this phase will already cause higher costs due to its influence on decisions already made before and to be considered in the necessary update of engineering; still an exit is possible prior to technical installations.

- Project Implementation Phase: system is fix and decision on investment is done; site preparation starts; installation is in progress; necessary adaptions during the construction due to weak planning will cause high costs e.g. for re-design, re-engineering, change of permission and alternative or additional equipment to be installed.

- Operation and Maintenance: once that AD plant has been set into operation costs for adaptions are most expensive; any shut down of the AD facility to install alternative or additional equipment results in external treatment costs; no biogas production causes costs for alternative fuels or loss in revenues; mistakes in the design of plant and its operation cause weak performance and lower treatment capacity; shorter intervals for maintenance cause higher costs for wear and tear parts; lower treatment performance may result in fines due to missing threshold values for emissions.

Investment costs (CAPEX) are only partly responsible for the economic success or failure of an AD plant. It is often neglected, that deviations of the estimated operational costs (OPEX) are most crucial in its influence on the economic performance and the calculated economic feasibility. In particular when looking a long time of operation periods operational cost add up to an increasingly important component of the economics of the plant.

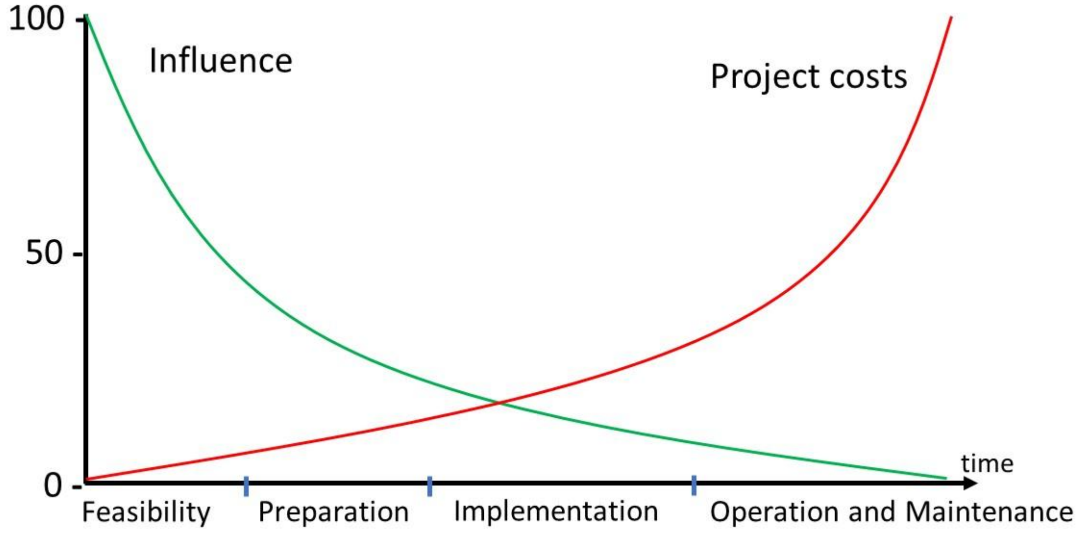

Figure 6 Comparison of influence on decisions and costs whilst project´s proceeding (Pesta, 2024)

8. Different examples of AD in the food and beverage industry

There are a lot of examples for the successful implementation and operation of AD facilities in the food and beverage industry all over the world. The examples in this chapter were chosen by the authors. The intention was to depict the variety of feedstock and installations and to present AD facilities which have in common a long-term operation, a reliable experience of the operator with accessible information. The authors selected examples of AD plants from different production facilities: meat, beer, sugar, liquor and potato products.

8.1. Meat industry

By-products of slaughterhouses mainly consist of wastewater, blood, rumen content, fats, and stomach content. Most of these by-products or waste materials need to be treated before they can be released to the environment for final disposal (Ortner et al., 2015).

Table 6 Gas potential, TS and classification of selected by-products from slaughterhouses (Ortner et al., 2014)

Waste fraction	TS (%)	Biomethane Potential (m^3_N CH_4/t VS)	Category
Blood	18-22	510-545	3
Stomach content	14-15	773-810	2
Grease separation	10-12	742-775	3
Rumen content	12-14	338-358	2
Wastewater	0.8-1.2	746-852	-

In Europe, the use of animal by-products is regulated by the Animal By-product Regulation 1069/2009/EC to avoid the outbreak and spread of diseases. The by-products are therefore to be split into three categories:

Category 1: meat and animal by-products with the highest risk from animals. These animals are killed or die due to disease, in particular BSE infested carcasses, or from contamination with chemicals or prohibited substances. Category 1 material must be incinerated and cannot be used for AD at all.

Category 2: meat and by-products presenting a risk of other diseases. It includes killed and fallen, i.e., not slaughtered, animals, animal by-products (e.g., milk), imported, and insufficiently controlled material, animal products containing by-products of medicines, and organs found to be infectious during the slaughtering process. Prior to AD processing these by-products must be treated with a steam pressure sterilization (grain size <50mm, temperature 133°C, 3 bar for 20 min.). Manure, rumen-, stomach- and intestinal contents which are also part of category 2 don´t need to undergo any pre-treatment (Pfundtner et al., 2007).

Category 3: waste and by-products from slaughterhouses, catering waste, food of animal origin no longer fit for human consumption, raw milk, fresh fish, or fresh fish by-products (EC, 2015). Category 3 by-products can be used in biogas plants after shredding (12 mm) and pasteurization (70°C for 60 min.) (Pfundtner et al., 2007).

Table 6 depicts the gas potential, total solids and category classification of different by-products from slaughterhouses. These values are typical for European processing standards and may vary internationally.

8.1.1. Slaughterhouse in St. Martin, Austria

The company Großfurtner in the village of St. Martin is the largest slaughterhouse in Austria, slaughtering 550,000 pigs and 50,000 cattle per year. In 2003 a biogas plant was directly integrated into the slaughterhouse (see Figure 7). While slaughterhouse waste has been co-fermented in many biogas plants, it is the first biogas plant worldwide to exclusively use slaughterhouse waste as feedstock. The feedstock consists of blood, rumen content, colon content and grease separation material. 10,000 tons of feedstock are used to produce 3.6 Mio. kWh electricity and 3.6 Mio. kWh heat per year. The company can now cover approximately 33% of their electricity demand and 75 % of their heat demand with renewable energies. The air conditioning and cooling system of the slaughterhouse additionally allows a waste heat recovery from the chillers. This waste heat is stored in a buffer system and used for the auxiliary supply with heat. A simplified process scheme of the anaerobic digestion unit in St. Martin is shown in Figure 8. The aim of the project was to improve the economic and ecological performance of this slaughterhouse. Two cost intensive areas in the company are the energy costs (natural gas, electricity) and the disposal costs (range between 5 – 50 €/t) for the slaughterhouse waste, both of which can be reduced with on-site AD. Mainly due to the high protein content in the feedstock mix, the ammonium content in the digesters is very high. A stable process can be ensured through various parameters such as digester temperature, organic loading rate and the use of trace elements. The digestate is spread on agricultural land as valuable fertilizer.

Figure 7 Biogas plant at the slaughterhouse in St. Martin, Upper Austria

Info Box:

Year of realisation:	2003
Investment costs:	€ 1.8 million (first stage in 2003)
Biogas production:	5,000 m^3/day; 67-69 Vol % CH4
Electric Power:	525 kWel
CSTR reactors:	1 x 600 m^3, 2 x 1,000 m^3
Feedstock/year:	2,000 m^3 blood, 1,000 t rumen content, 3,000 t colon content, 4,000 t grease separation material
Pre-treatment:	Continuous pasteurization
CO_2 reduction/year:	2,464 t
Plant operator:	Rudolf Großfurtner GmbH, Hofmark 1, A-4972 Utzenaich

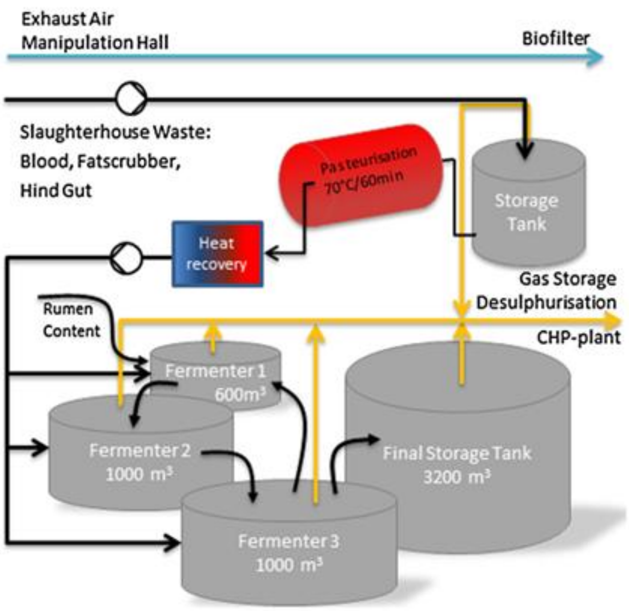

Figure 8 Simplified process scheme of the anaerobic digestion unit in St. Martin (Ortner et al. 2015)

8.1.2. Slaughterhouse in Medianeira, Brazil

Frimesa slaughterhouse is located in Medianeira, State of Paraná, Brazil. It is one of Frimesa's agro-industrial units, a group with a mix of more than 500 products from the processing of pork and dairy products. Frimesa is formed from five other cooperatives in the western region of Paraná: Copagril, LAR, C-Vale, Primato and Copacol. This unit, in particular, the Medianeira-PR Frigorific Unit (UFM), has a capacity to process 6,900 swine per day. It is composed of industrializes lines of frozen and chilled offal, fresh and seasoned pork cuts, pork carcass, savory snacks, lard, ham in piece and sliced versions, smoked, cooked and fresh sausages, bacon, ingredients for feijoada, sausages, mortadella, hamburgers, salami, cured cup, pepperoni, among others. In 2022, 2 million swine were slaughtered in this unit alone.

In 2011, the first anaerobic digester was installed in this unit, a covered lagoon model. The biogas was used for thermal energy, to singe the pigs, a process aimed at improving the visual appearance and microbiological quality of pig carcasses. Based on this experience and many lessons learned in relation to technology, construction and operation of biogas plants, the decision was made to change the technological route. In 2022, a new biogas plant was launched at the site, this time a CSTR model, with only the application of biogas to singe carcasses. In 2024, at another Frimesa unit, in Assis Chateaubriand city, a similar biogas plant was implemented for the same purpose.

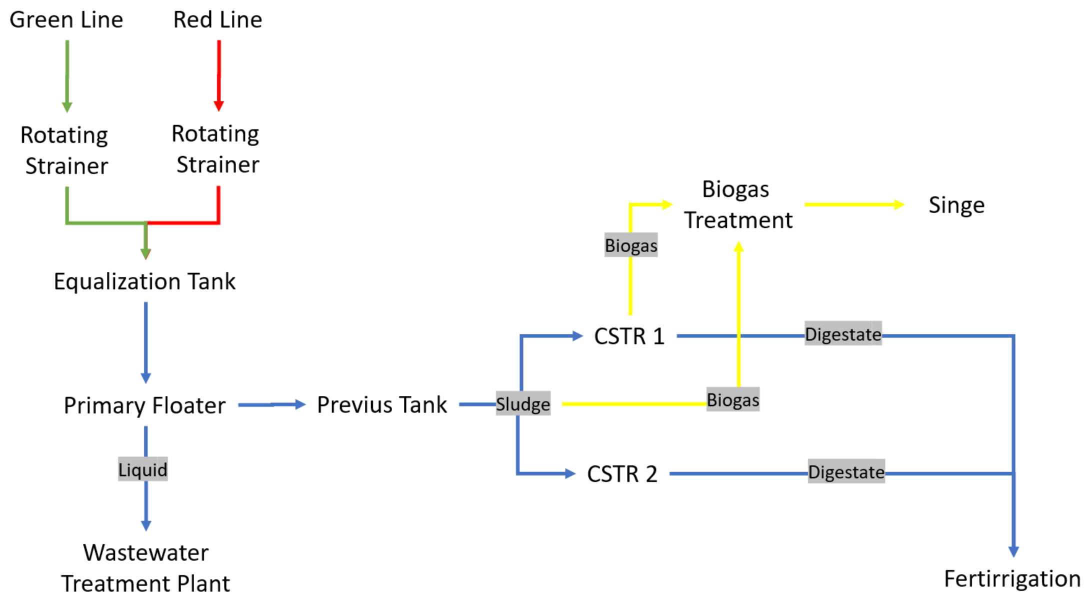

Figure 9 Processing lines of slaughtering by-products from the different processing lines (green, red) of Frimosa plant and the combined application of wastewater treatment and biogas recovery in anaerobic digesters (CSTR - continuously stirred tank reactors) including biogas utilisation flows

The effluents used in the biogas plant are originating from the industrial slaughtering process of Frimosa, details of the process flows can be seen in Figure 9. These effluents are classified in two ways, the red line, with protein and fat content (viscera, bones and blood) and the green line, with effluents from hydro-sanitary establishments, laundry, cafeteria, among others. The industrial effluents go through a sieving stage on a rotating sieve, and the material retained on the sieves is added to the CSTR reactors. The effluent that passes through the sieve is sent to an equalization process and a physical-chemical flotation device. The floated sludge is sent directly to a pre-tank. The pre-tank has 865 m^3, a biological desulfurization system and two agitators. The retention time at this stage is 3 days. There is no heating in this pre-tank. The main biogas step takes place in two CSTR reactors (3,700 m^3 each), adding up to a useful CSTR volume of 7,400 m^3 (for a picture of the plant see Figure 10). The digestate produced at the AD plant is used in fertirrigation process at forestry areas of the Agroindustry.

The mass input to the plant and the energy output are shown in

Table **7**.

Info Box:

Year of realisation:	2022
Investment costs:	€ 1.4 million (BRL 8.4 million)
Biogas production:	8.700 m^3/day
Thermal power:	12.9 million kWh/a
CSTR reactors:	1 x 865 m^3 (pre-mix) 2 x 3700 m^3 (main digesters)
Feedstock/year:	32,850 t/a primary floated sludge
Plant operator:	FRIMESA Cooperative, Medianeira, State of Paraná, Brazil

Table 7 Inputs and outputs of the biogas plant at Frimesa

Input		Output	
Primary floated sludge	32,850 t/a	Biogas produced	3.2 million m^3/a
		Thermal energy (singe process)	12.9 million kWh_{th}/a

Figure 10 Biogas plant at Frimesa Agroindustry in Medianeira, Paraná - Brazil (reproduced with the kind permission of Frimesa Cooperative)

8.2. Beer and beverage industry

Several organic by-products of breweries can be used for an anaerobic digestion process. Brewers' spent grain, cold and hot break, residual yeast, and wastewater also arise and need to be disposed of or treated (see Table 8). Brewers' spent grain exhibit by far the biggest organic amount and thus, the largest biogas potential. Tables 5 and 6 show the amounts and energy potential from different by-products from breweries.

Table 8 Energy potential from different by-products from breweries (Connaughton et al., 2006; Bochmann et al., 2015)

By-product	Amount [kg FM*hl^{-1}]	Biomethane potential [L*kg^{-1} FM]	Energy [kWh (MJ)]
Brewers' spent grain (BSG)	22	75	16.4 (59.2)
Wastewater	300	0.76	2.3 (8.2)

Brewer's spent grain are often used as animal feed, but they start degrading very fast and are stable only for a few days. Reduced amounts of cattle, changes in feeding practice, and desire for renewable energy have led to the rise of the idea of anaerobic digestion of this specific by-product (Bochmann et al., 2015). Especially the wastewater of breweries is perfectly suited for AD facilities. Not only the world's largest brewing companies are using AD systems on their production sites, it can also be economically viable for smaller breweries with a production capacity of less than 100,000 hl sales of beer per year.

Figure 11 shows the processing of brewing beer and its amounts of by-products and wastewater as an example. These by-products are suitable for AD purposes, average chemical oxygen demands (COD) are depicted in Table 9. The higher the COD the higher the biogas yield to be expected.

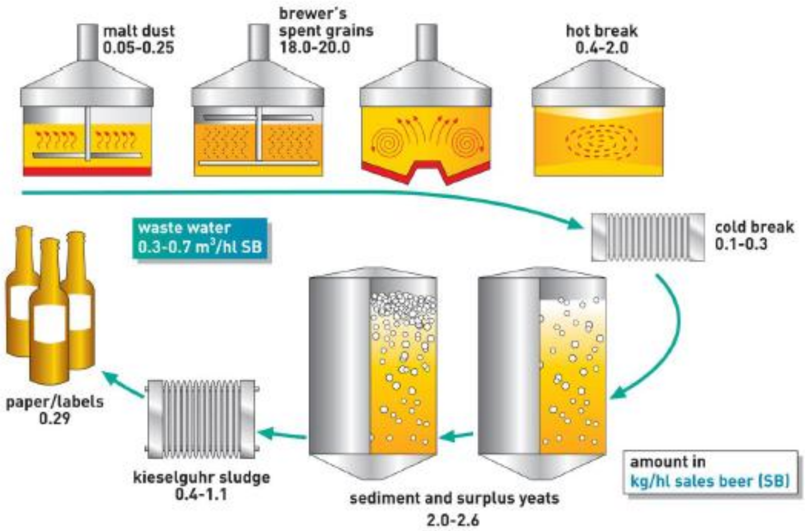

Figure 11 By-products and wastewater of the brewing process (Pesta, 2024)

Table 9 Average COD of brewery's by-products

By-product	Organic load
Hot break	100,000 mg COD / L
Cold break	130,000 mg COD / L
Fermenting room yeast (surplus yeast)	200,000 mg COD / L
Storage cellar yeast (sediments)	170,000 mg COD / L
Kieselguhr (as filter material)	15,000 mg COD / kg
Brewers' spent grain (BSG)	330,000 mg COD / kg

8.2.1. Brewery in Leoben, Austria

The Gösser Brewery is located in Leoben, Austria. It is part of the Heineken Group. This facility has a yearly production of approximately 100 Million litres of beer. Gösser decided to establish a decarbonised beer production facility as their contribution to the greening of the brewing industry. In 2015 an anaerobic digestion unit was set up at the site by the Austrian company BDI-BioEnergy International GmbH (Figure 12). Details on this plant can also be found in a case story publication (IEA Bioenergy Task 37, 2018).

Figure 12 Biogas plant at Gösser Brewery in Leoben, Austria (reproduced with the kind permission of BDI-BioEnergy International GmbH)

The biogas plant consists of a two-stage mesophilic anaerobic digestion system. The first stage is a biological acidification (hydrolysis) step. Polymers such as starch, cellulose, proteins, and fats are hydrolysed to sugars, amino acids and short chain fatty acids. These readily degradable compounds are then converted to acetic acid, propionic acid and butyric acid during acidogenesis. The pH of this reactor is acidic and typically below 6.5.

This first digester has a volume of 450 m³ and is fed with the brewer's spent grain. After the biological acidification step the volatile fatty acids, dominated by acetic acid, are pumped to the main digester with a volume of 2,560 m³. Both digesters are set up as continuously stirred tank reactor (CSTR) systems. Subsequent to the main digester there is a post digester with a volume of 3,680 m³ and finally a digestate storage with 8,280 m^3. Table 10 shows inputs and outputs of the biogas plant at the Gösser brewery.

The biogas plant uses two strategies for desulphurization of the biogas to avoid process inhibition and to guarantee a stable and fast degradation process.

1. Iron hydroxide is added to the main digesters to bind H_2S in the liquid during the anaerobic digestion process.
2. Microbiological desulphurisation: a small amount of air is injected in the headspace of the main and post digester. H_2S is oxidized by aerobic desulphurisation bacteria either to S or H_2SO_4, depending on the surplus of O_2 affected by this injection.

The biogas can be used after dewatering in the boiler of the brewery for the production of heat as saturated steam at about 140°C. Additionally, a CHP unit is installed to produce electricity and heat at a temperature of 90°C. The produced electricity is fed into the grid in accordance with the national feed-in rate of the Austrian Green Electricity Act (Ökostromgesetz).

Since the brewery is located in an area surrounded by residential area, there is no additional digestate treatment installed at the site to limit odour emissions. After storing the digestate in a covered post digester, the digestate is transported to the surrounding farmers and applied as fertiliser on arable land.

Additional to the anaerobic digestion of solid wastes from the brewing process, wastewater is treated anaerobically in a UASB reactor. The Gösser brewery covers 100 % of energy demand from renewable energy. Beside the anaerobic digestion units, heat from a nearby wood processing industry and a solar thermal system is used; 40 % of the heat demand is covered by a neighbouring wood processing company, 5–10 % from the anaerobic wastewater treatment plant and the residual 50 % from the biogas plant.

Table 10 Inputs and outputs of the biogas plant at Gösser brewery

Input		Output	
Brewers' spent grain	13,621 t/a	Biogas produced	2.3 million m^3/a
		Biogas to brewery (boiler)	3.3 million kWh_{th}/a
		Electricity (from CHP)	3.4 million kWh_{el}/a
		Heat (from CHP)	2.2 million kWh_{th}/a

Info Box:

Year of realisation:	2015
Investment costs:	€ 1.8 million
Biogas production:	6,900 m^3/day
Electric Power:	450 kWel
CSTR reactors:	1 x 450 m^3 (pre-acidification) 1 x 2,560 m^3 (main digester) 1 x 3,680 m^3 (post digester) 1 x 8,280 m^3 (digestate storage tank)
Feedstock/year:	13,700 t/a brewers' spent grain
CO_2 reduction/year:	3,036 t
Plant operator:	BDI Betriebs GmbH, Parkring 18, A-8074 Raaba-Grambach

8.3. Sugar industry

Depending on the feedstock for the sugar production, various types of wastewater and by-products originate from sugar beet or sugar cane processing (see Table 11 and Table 12):

- wastewater with low COD: washing and transporting
- wastewater with high COD: extracting and condensing
- sugar beet pulp, filter cake, bagasse
- molasses.

Internal reuse of wastewater reduces the demand of freshwater and therefore reduces the amount of wastewater down to 0.6 m^3 wastewater per t of sugar beet, with a COD of 0.5 to 3 kg O_2/m^3. Choosing a reliable AD system for wastewater treatment is dependent on the fact that sugar beet campaigns are timely limited to fall and winter. About half of the year the AD plant is shut down, due to the lack of feedstock. Nevertheless, AD facilities at sugar factories for treating wastewater are state of the art and well operated.

Table 11 List of crops for sugar production.

Crop	Product	By-product	References
Sugar cane	Sugar	Bagasse, molasse, filter cake	Zang et al., 2018
Sugar beet	Sugar	Sugar beet pulp, molasse	Brooks et al., 2008

Table 12 Typical main components of molasses from sugar cane, sugar beet and molasses from sugar beet after sugar extraction

	Unit [per FM]	Sugar cane (Bochmann et al., 2020)	Sugar beet (Schmid et al., 2019)	Desugarised sugar beet (Schmid et al., 2019)
Dry matter	%	73.5-87.5	82.0	70.7-71.6
Sucrose	%	15.7-46.9	50.5	13.2-17.6
Ash	%	-	10.9	20.4-25.5
Nitrogen	%	0.25-1.5	1.8	1.8-2.1
Protein	%	-	11.0	11.4-13.0
Phosphorus	%	0.3-0.7	0.02	<0.02
Sodium	$g*kg^{-1}$	-	13.4	25.2-26.2
Potassium	$g*kg^{-1}$	19-54	32.8	50.3-74.2
Calcium	$mg*kg^{-1}$	6-12	111	235-255

Besides the liquid and pasty molasses, the solid by-products are utilizable for AD treatment. Sugar beet pulp is the solid leftovers after sugar extraction. Sugar beet pulp can be ensilaged and consequently made available as a feedstock during almost the whole year. Processing sugar cane produces filter cake as a comparable by-product. It is not possible to treat sugar beet pulp or filter cake together with wastewater in an UASB or EGSB system, due to their macroscopic structure and high amount of particles.

8.3.1. Sugar factory in Kaposvár, Hungary

The factory in Kaposvár is the only sugar refinery in Hungary with a processing capacity of 7,000 t of sugar beet per day. The processing of sugar beet requires large amounts of heat and electricity. Traditionally, the factory used natural gas but the price of fossil fuels increased drastically and the use of fossil fuels was strongly limited by the carbon dioxide quota available to the factory. To increase the capacities, additional CO_2 quotas would have to be purchased or the required energy could be generated from a renewable resource, not subject to the quota regulation.

Figure 13 Biogas plant at the Kaposvár facility in Hungary (reproduced with the kind permission of AGRANA)

The sugar manufacturing process also generates by-products with a high organic matter content, which are suitable as feedstock for the production of biogas. The biggest fraction is pressed beet pulp with 1,800 – 2,000 t per day. Approximately 200 t of beet cleaning by-products, like pieces of sugar beet and other plant by-products. In addition, the complete project was realized through multiple-phase investments. Two biogas reactors with a volume of 13,500 m^3 each were built and started in 2007. In 2012, a main digester with a volume of 16,620 m^3 was added because of the positive experience, making the biogas plant of Kaposvár one of the largest biogas plants in Europe (see Figure 13). In addition to the three digesters, there is a post-digester with a volume of 3,000 m^3 where the residual dissolved organic matter of the digestate leaving the main digesters is decomposed, producing additional biogas. During the 120-day sugar beet processing period, 1,500 t of feedstock are fed to the digesters, producing a total of 180,000 m^3 biogas each day. The gas is then burnt in the boilers of the sugar factory, producing a total of 10 million m^3 natural gas equivalent sustainable energy. The plant is able to provide around 80% of the primary energy demand of the sugar factory with the biogas produced on-site during the sugar beet campaign. The digestate can be spread on agricultural land as valuable fertilizer.

With expansion of the facility a biomethane upgrading unit which separates CO_2 from the biogas by membrane technology (Figure 14) was installed. This produces biomethane with 98 % purity, which is fed into the natural gas grid. The upgrading plant is operated all year round and processes 1,200 m^3 of raw biogas per hour, generating app. 5.7 million m^3 of biomethane per year.

Info Box:

Year of realisation:	2007 (first stage), expansions in 2013 and 2015
Investment costs:	€ 6.8 million
Biogas production:	180,000 m^3/day in the 120-day sugar beet processing period
Gas boilers:	burning 10 million m^3 natural gas equivalent per year
Upgrading unit:	1,200 m^3 of biogas per hour, 5.7 million m^3 biomethane per year
CSTR reactors:	1 x 16,620 m^3, 2 x 13,500 m^3, 1 x post-digester of 3,000 m^3
Feedstock/year:	1,800 t/day pressed beet pulp, 200 t/day beet fragments, 350 t/day by-products from bioethanol, biodiesel and food industries
CO_2 reduction/year:	34,540 t

Figure 14 Membrane technology (reproduced with the kind permission of AGRANA)

8.4. Distilleries and liquor industry

Depending on the type of distillery and the processed materials, there are several by-products suitable for biogas production by anaerobic digestion, like vinasse, stillage and draff (see Table 13).

Vinasse

Vinasse is obtained after alcohol fermentation of molasses. It is a liquid fraction after the distillation process containing organic compounds like residual sugars and volatile fatty acids (Leite et al., 2015). Anaerobic digestion trials of vinasse were carried out at lab scale, technical scale and large scale in UASB, EGSB and CSTR reactors as mesophilic or thermophilic digestion. Biomethane potential tests showed a biogas amount between 221 and 270 L kg^{-1} COD (Leite et al., 2015). COD degradation in UASB and EGSB was reported in a range of 60 to 80 % (Leite et al., 2015; Lopez et al., 2018).

Stillage

Thin stillage is the liquid remaining after the distillation of pot ale (a residual liquid remaining after the initial distillation of fermented wort, also known as wash), thick stillage is the solid–liquid mixture remaining after the distillation maize mash in a continuous distillation column (O'Shea et al., 2020).

Draff

Draff consists of the residual solids following the brewing of malted and un-malted barley to produce wort (O'Shea et al., 2020).

Table 13 Organic by-products in distilleries applicable for biogas production by anaerobic digestion

	Unit	Draff O'Shea et al. 2020	Thin stillage O'Shea et al. 2020	Thick stillage O'Shea et al. 2020	Vinasse IFA-Tulln 2010
Total solids (TS)	% (FM)	27.6	3.9	8.8	47.9
Volatile solids (VS)	% (FM)	26.5	3.5	8.2	29.6
Methane Yield	LCH_4/kg (FM)	87.4	17.4	41.4	140

8.4.1. Distillery in St. Laurent de Cognac, France

The biogas plant in St. Laurent de Cognac was built in 1970 to valorise distillery waste from the Cognac production (Figure 15 and Figure 16). Approximately 300,000 t/a of vinasse is treated to produce 20,000 MWh worth of biogas. The vinasse is concentrated by mechanical vapor compression and tartaric acid is precipitated with calcium carbonate. The vinasse is then sent to the four infinitely stirred – down-flow recirculation – type digesters. Retention time is 3–4 weeks. The digestate (1,200- 1,500 t dry matter /a) is decanted, mixed with ground plant matter waste, and used as agricultural compost. The liquid fraction of the digestate is further treated and is discharged to the river. H_2S is eliminated in a soda washing tower and the gas is dehydrated by condensation on an exchanger. A mobile tank containing activated carbon removes pollutants. The gas is valorised via a 1.0 MW_{el} Jenbacher engine and a 0.6 MW_{el} Jenbacher engine. The electricity produced is sold and thermal energy is used to cover own demand.

Figure 15 Biogas plant in St. Laurent de Cognac, France (reproduced with the kind permission of REVICO)

Figure 16 Biogas plant in St. Laurent de Cognac, France (reproduced with the kind permission of REVICO)

Info Box:

Year of realisation:	1970
Investment costs:	€ 30.0 million
Biogas production:	13,000 m^3/day, waste received from November to June
Electric Power:	1 x 1.0 MWel + 1 x 0.6 MWel
CSTR reactor:	4 x 4,400 m^3, down-flow recirculation
Feedstock/year:	300,000 t/a cognac distillery by-products
CO_2 reduction/year:	5,863 t
Plant operator:	REVICO / REVICO Energies Vertes, 16100 Saint Laurent de Cognac

8.5. Potato processing industry

In the potato Industry there are several organic by-products suitable for AD, such as potato mash, potato pulp, potato peelings etc. Table 14 shows dry matter (DM), organic dry matter (oDM) and biogas yield of different organic by-products from the potato industry. The methane content of biogas produced out of these by-products varies from 56% to 60% (FABbiogas calculator).

Table 14 Organic by-products in the potato industry applicable for biogas production by anaerobic digestion (Deublein and Steinhauser, 2008).

Feedstock for biogas production	DM [%]	oDM in DM [%]	Biogas yield [m^3 kg^{-1} oDM]
Potato mash, potato pulp, potato peelings	6-18	85-96	0.3-0.9
Potato pulp dried, potato shred, potato flakes	88	94-96	0.6-0.7

8.5.1. Potato processing company in Frastanz, Austria

The 11er Nahrungsmittel GmbH operates a plant at the Frastanz site for the production of convenience products made from potatoes (French fries, potato hash brown, croquettes, …) and processes around 75,000 tons of raw potatoes every year. During the various processing steps, organic residues such as peelings, potato mash, sorting residues, removed starch, used frying oils and other production wastes are produced. A mixed sludge with a high energy content is prepared from these fractions which is used to produce biogas via anaerobic digestion.

Figure 17 Biogas plant treating potato processing by-products in Frastanz, Austria (reproduced with the kind permission of 11er Nahrungsmittel GmbH)

The plant (see Figure 17) comprises a pre-treatment plant, a fermentation plant, a gas cleaning and upgrading plant for the biogas to produce pure methane, a CNG fuel station and a sludge dewatering plant. In the pre-treatment plant, the solid, pasty and liquid residues are processed into a mixed sludge. This then forms the substrate for the biogas plant. Fermentation takes place at approximately 40°C. The thermal regulation of the fermentation temperature takes place with waste heat from heat recovery systems. The methane is separated from the carbon dioxide using a membrane and the purified gas is then compressed to approx. 8 bar. The upgraded biogas is partly used to fuel the trucks for the daily transportation of the raw potatoes. This project closes the energy cycle, as the biogenic residues from production provide the energy for the daily transportation of the potatoes. A surplus of the biogas is fed into the public gas grid.

Info Box:

Year of realisation:	2017
Investment costs:	€ 6.7 million
Biogas production:	2.9 million m^3/year
Upgrading unit:	1.5 million m^3/year
CSTR reactor:	3,900 m^3
Feedstock/year:	31,000 m^3/a mixed potato sludge
CO_2 reduction/year:	3,810 t/a
Plant operator:	11er Nahrungsmittel GmbH, 6820 Frastanz, Austria

9. Conclusions

Anaerobic Digestion (AD) is a state-of-the-art technology for treating wastewater, organic waste, industrial by-products or agricultural residues as a feedstock. Aside from the effects of stabilizing the feedstock by means of microbial degradation a regenerative energy source is produced, the biogas. Biogas is a mixture consisting mainly out of methane and carbon dioxide. Biogas is a carbon neutral energy source and offers a wide range of stationary and mobile applications. Various types of AD systems are in operation throughout the world, in different industry branches, like food and beverage but also in pulp and paper, chemicals production, and pharmaceutics.

The food and beverage industry offer a wide range of feedstocks for producing biogas and has a large demand on energy in the production processes, which can be (partly) covered by biogas. By-products, waste and wastewater out of the food and beverage production are perfectly suitable for biogas production, e.g. rich in organic compounds, without inhibitory or disturbing substances, mainly wet with a widely constant composition, available during the whole year. Production processes need constantly thermal and electric energy, both can be supplied by the utilization of biogas e.g. in boilers, CHPs or micro gas turbines.

The motivation for implementing an AD installation into an industrial production site varies individually, but there are some common drivers for starting a successful project. Due to ongoing changes or aggravations of legislative framework, conditions, climate change, social responses it is evident to start the rethinking of the environmental and energetical situation of the production site. Depending on the specific national regulations even financial support will be available e.g. for reducing the CO2 emissions, increasing the resource efficiency, or reducing the environmental impact.

Implementing technically, ecologically and economically reliable AD facilities in the food and beverage industry is not simply done by installing technical equipment available off the shelf. AD facilities are part of the overall material and energy streams and asks for integration and alignment with upstream and downstream processes. Upstream processes are focused on production and product integrated measures e.g. to reduce the amount of feedstock to be treated, to influence the quality of feedstock, to increase the resource efficiency, to reduce costs. This focus might not align in all cases with the operation of an AD facility.

Downstream most often the main focus is the reduction of costs for handling by-products and waste streams. The integration of an AD might change upstream considerations and changes masses and characteristics of mass flows downstream. These changes might lead to a significant change in the final treatment for the treatment of the plants by-product or waste strategies. Technologies for treating wastewater or by-products are state of the art and follow requirements of the physical, chemical and/or microbial processes – not only in separate processing steps but also in combination of these. Due to specific substrate characteristics and individual site conditions the planning process of the AD plant requires a detailed analysis of substrate and site conditions.

Experience show that a “standard” design not adjusted to the individual conditions onsite results often in weak performance of the plant, low efficiency in degradation, increased emissions, low processing stability and consequently in additional investments and high operational costs. To avoid such unwanted issues, it is highly recommended to take time and effort in the early phases of the project development planning phase, in particular during feasibility and preplanning phases. Main decisions in regards of technology and operation are made, which become later unavoidable costly if being wrong.

Therefore, several technical and organisational concept should be analysed and compared in detail. In the long term the operation costs of the plants become increasingly dominant for the overall costs of the process and are therefore decisive for economic success. Any decision for design and investment should therefore include a detailed assessment of these costs as well.

Due to these highly specific considerations in design and dimensions it is recommend to involve experienced planning engineers in the development of the plant, ideally ones, which have experience with the very substrate to be digested. In particular the design of feedstock´s preparation, digestion or effluent treatment requires practical experience since the characteristics of organic wastewater, waste and digestates are highly specific. In the best case the experts are independent from technology supplier to avoid standard solutions which might not fit the site-specific requirements.

List of abbreviations

AD	Anaerobic digestion
BMP	Biomethane potential
BOD	Biochemical oxygen demand
BSG	Brewers' spent grain
CAPEX	Capital expenditures
CHP	Compressed heat and power
CNP	Compressed natural gas
COD	Chemical oxygen demand
CSTR	Continuously stirred tank reactor
DM	Dry matter
EGSB	Expanded granular sludge bed (type of anaerobic reactor)
FM	Fresh matter
GHG	Greenhouse gas
GJ	Gigajoule
HRT	Hydraulic retention time
kWh	Kilowatt hour
Mbar	Millibar
ODM	Organic dry matter
OLR	Organic loading rate
OPEX	Operational Expenditures
TS	Total solids
UASB	Upflow anaerobic sludge blanket (type of anaerobic reactor)
VS	Volatile solids

References

Behmel, U., Meyer-Pittroff, R. (1998): The generation of biogas from biogenic wastes in agricultural biogas plants in combination with intelligent fertilizing management. Proceedings Biomass for Energy and Industrie – 10th European Conference and Exhibition. Würzburg 8 – 11 June 1998

Bischofsberger, W., Dichtl, N., Rosenwinkel, K. H., Seyfried, C. F. and Böhnke, B. Eds. (2005). Anaerobtechnik. Springer.

Bochmann, G., Drosg, B., and Fuchs, W. (2015). Anaerobic digestion of thermal pretreated brewers' spent grains. Environ. Prog. Sustain. Energy 34, 1092–1096 doi: 10.1002/ep.12110

Bochmann G, Pesta G, Rachbauer L, Gabauer W, (2020). Anaerobic Digestion of Pretreated Industrial Residues and Their Energetic Process Integration. Front Bioeng Biotechnol. 8, 487. doi: 10.3389/fbioe.2020.00487

Braun, R. 1982. Biogas - Methangärung Organischer Abfallstoffe: Grundlagen und Anwendungsbeispiele. 1st ed. Springer.

Brooks, L., Parravicini, V., Svardal, K., Kroiss, H., and Prendl, L. (2008). Biogas from sugar beet press pulp as substitute of fossil fuel in sugar beet factories. Water Sci. Technol. 58, 1497–1504. doi: 10.2166/wst.2008.516

Calli, B., and Yukselen, M. A. (2002). Anaerobic treatment by a hybrid reactor. Environ. Eng. Sci. 19, 143–150. doi: 10.1089/109287502760079160

Chatzipaschali, A. A., and Stamatis, A. G. (2012). Biotechnological utilization with a focus on anaerobic treatment of cheese whey: current status and prospects. Energies 5, 3492–3525. doi: 10.3390/en5093492

Chan J., Y., Chong M. F., Law, Ch. L., Hassell, D.G. (2009) A review on anaerobic–aerobic treatment of industrial and municipal wastewater. Chemical Engineering Journal 155 (1–2), 1-18. doi : 10.1016/j.cej.2009.06.041.

Connaughton, S., Collins, G., and Flaherty, V. (2006). Psychrophilic and mesophilic anaerobic digestion of brewery effluent: a comparative study. Water Res. 40, 2503–2510. doi: 10.1016/j.watres.2006. 04.044

Demirel, B., Yenigun, O., and Onay, T. T. (2005). Anaerobic treatment of dairy wastewaters: A review. Process Biochem. 40, 2583–2595. doi: 10.1016/j.procbio.2004.12.015

Deublein, D. and Steinhauser, A., (2008), Biogas from Waste and Renewable Resources – An Introduction, Wiley-VCH, Germany.

EC (2015). Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009, Vol. 58. Brussels.

FABbiogas Calculator: http://www.fabbiogas-calculator.eu/de/

FoodDrinkEurope (2021). Data & Trends 2021. https://www.fooddrinkeurope.eu/wp-content/uploads/2021/11/FoodDrinkEurope-Data-Trends-2021-digital.pdf

Fuchs W and Drosg B (2010) Technologiebewertung von Gärrestbehandlungs- und Verwertungskonzepten. Eigenverlag der Universität für Bodenkultur Wien, Wien, ISBN 978-3-900962-86-9.

IEA Bioenergy Task 37 (2018) A Case Story - Gösser Brewery the Role of Biogas in Greening the Brewing Industry. https://www.ieabioenergy.com/wp-content/uploads/2019/01/Goesser_case_study_LAY1.pdf

IFA Tulln (2010). Department of Agrobiotechnology, University of Natural Resources and Life Sciences, Vienna. Laboratory tests.

Khalid A, Arshad M, Anjum M, Mahmood T, Dawson L. (2011). The anaerobic digestion of solid organic waste. Waste Manag. 2011 Aug;31(8):1737-44. doi: 10.1016/j.wasman.2011.03.021.

Leite, A. F., Janke, L., Harms, H., Zang, J. W., Fonseca-Zang, W. A., Stinner, W., et al. (2015). Assessment of the variations in characteristics and methane potential of major waste products from the Brazilian bioethanol industry along an operating season. Energy Fuels 29, 4022–4029. doi: 10.1021/ef502807s

LfL - Bayrische Landesanstalt für Landwirtschaft: Biogasausbeuten verschiedener Substrate, https://www.lfl.bayern.de/iba/energie/049711/ [accessed 01.12.2024]

López, I., Borzacconi, L., and Passeggi, M. (2018). Anaerobic treatment of sugar cane vinasse: treatability and real-scale operation. J. Chem. Technol. Biotechnol. 93, 1320–1327. doi: 10.1002/jctb.5493

Nath, K., Das, D. (2004). Improvement of fermentative hydrogen production: various approaches. Appl. Microbiol. Biotechnol. 65, 520–529.

Ortner, M., Leitzinger, K., Skupien, S., Bochmann, G., and Fuchs, W. (2014). Efficient anaerobic mono-digestion of N-rich slaughterhouse waste: Influence of ammonia, temperature and trace elements. Bioresour. Technol. 174, 222–232. doi: 10.1016/j.biortech.2014.10.023

Ortner, M., Wöss, D., Schumergruber, A., Pröll, T., and Fuchs, W. (2015). Energy self-supply of large abattoir by sustainable waste utilization based on anaerobic mono-digestion. Appl. Energy 143, 460–471. doi: 10.1016/j.apenergy.2015.01.039

O'Shea, R., Lin, R., Wall, D.M., Browne, J.D., Murphy, J.D. (2020). Using biogas to re- duce natural gas consumption and greenhouse gas emissions at a large dis- tillery. Appl. Energy 279, 115812. doi: 10.1016/j.apenergy.2020.115812

Panesar, P. S., Kennedy, J. F., Gandhi, D. N., and Bunko, K. (2007). Bioutilisation of whey for lactic acid production. Food Chem. 105, 1–14. doi: 10.1016/j.foodchem.2007.03.035

Pesta, G., Faulstich, M., Meyer-Pittroff, R., and Bochmann, G. (2006). Der Einsatz von Rest- und Abfallstoffen aus der Brauerei als Sekundärrohstoffe," in Handbuch 39. Technologisches Seminar Weihenstephan (Freising), 1–9.

Pesta, G., Meyer-Pittroff, R., and Russ, W. (2007). "Utilization of Whey," in Utilization of By-Products and Treatment of Waste in the Food Industry, eds V. Oreopoulou and W. Russ (New York, NY: Springer), 193–207. doi: 10.1007/978-0-387-35766-9_10

Pesta, G. (2024) atres company information.

Pfundtner, E. (2007) Der sachgerechte Einsatz von Biogasgülle und Gärrückständen im Acker- und Grünland. AGES - Österreichische Agentur für Gesundheit und Ernährungssicherheit GmbH (Ed.)

Schmid, M. T., Song, H., Raschbauer, M., Emerstorfer, F., Omann, M., Stelzer, F., et al. (2019): Utilization of desugarized sugar beet molasses for the production of poly(3-hydroxybutyrate) by halophilic Bacillus megaterium uyuni S29. Process Biochem. 86, 9–15. doi: 10.1016/j.procbio.2019.08.001

VDI-Gesellschaft Energie und Umwelt (Hrsg.): VDI 4630 - Fermentation of organic materials - Characterization of the substrate, sampling, collection of material data, fermentation tests. 2016

Weinrich, S., Schäfer, F., Bochmann, G., Liebetrau, J., (2018). Value of batch tests for biogas potential analysis; method comparison and challenges of substrate and efficiency evaluation of biogas plants. Murphy, J.D. (Ed.) IEA Bioenergy Task 37, 2018: 10 ISBN: 978-1-910154-49-6 (eBook electronic edition), 978-1-910154-48-9 (printed paper edition)

Ward, A.J., Hobbs, P.J., Holliman, P.J., Jones, D.L. (2008). Optimization of the anaerobic digestion of agricultural resources. Bioresour. Technol. 99, 7928–7940.

Zang, J. W., Martins, K. F., and Da Fonseca-Zang, W. A. (2018). Life cycle inventory for biomethane as a diesel substitute for the Brazilian ethanol industry - case study. Energy Procedia 153, 444–449. doi: 10.1016/j.egypro.2018.10.048

Zhu, B., Gikas, P., Zhang, R., Lord, J., Jenkins, B., Li, X., (2009). Characteristics and biogas production potential of municipal solid wastes pretreated with a rotary drum reactor. Bioresour. Technol. 100, 1122–1129.

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