Farm-scale biomethane production plant for challenging raw materials.

Digestate processing report

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Contents

List of abbreviations

AD – anaerobic digestion.

ADFW – anaerobic digestate from food waste

CAPEX – capital expenditure

CHP – combined heat and power (cogeneration).

DG – digestate.

DM – dry matter.

DS – dry substance.

HTC – hydrothermal carbonization.

HTC-PC – hydrothermal carbonization with post-carbonization.

NPV – net present value.

OPEX – operating expenditure.

oDM – organic dry matter.

SBR – slope bottom reactor.

SHS – superheated steam.

TRL – technology readiness level.

WTE – waste-to-energy.

1 Introduction and method

A biogas plant operation is not limited to biogas production. The second and equally important product of the anaerobic digestion (AD) of the biomass is the anaerobic digestate. Digestate processing enables the production of valuable products, which in turn increases the operational profitability of biogas plants (Herbes et al., 2020; Plana & Noche, 2016; Tyagi et al., 2022; W. Wang et al., 2023). The various possible routes for digestate processing form at least two main directions, depending on the outcome: production of agricultural fertilizers or soil amendments, and energy recovery.

The agricultural direction relies on the digestate composition that can consist of so-called yield-forming elements such as nitrogen, potassium, phosphorus, as well as various microelements and organic matter (L. Bauer et al., 2021; Carraro et al., 2024; Drosg et al., 2015; Kovačić et al., 2022; Nowak & Czekała, 2024; Tyagi et al., 2022). Digestate compositions vary, depending on the feedstock compositions. Consequently, it is not possible to standardize them. For example, detailed information about different digestate compositions is presented in Appendix 1. Regarding energy recovery, there is an opinion that about half of the energy stored in biomass feedstock before AD remains in the output digestate (Kovačić et al., 2022). Dr. Pasi Makkonen (Karhubetoni Oy) notes that this depends mainly on the biogas yield and provides the example of carbon balance calculation (see Figure 1 below). Energy recovery from the digestate involves producing various types of fuel for further use in the generation of at least electrical and thermal energy (Kovačić et al., 2022; Logan & Visvanathan, 2019; Nowak & Czekała, 2024; Tyagi et al., 2022).

Coal content in oDM	50 %							
			Coal in			Coal out		
DM	27.0 %		2 250 ton/a		41 %	1 699 ton/a	Yield	75.5 %
AddOn carbon		Methane	53 in volume		8.45	6.34		
		CO2	47 in volume		20.77	5.66 g/mol		
Biogas density		1.30 kg/m³			29.22	12.00 g/mol		
				Carbon		41.07 % in weight		

Figure 1. Example of carbon balance calculation (Dr. Pasi Makkonen).

Digestate processing is also important from other perspectives. In addition to the economic perspective, digestate processing is feasible in terms of reducing costs for storage, transportation, and distribution of the digestate (Carraro et al., 2024; Kovačić et al., 2022; Tyagi et al., 2022). From an ecological perspective, digestate processing is needed since the digestate after AD is unstable, contains different volatile substances, and usually does not meet soil regulations (Kovačić et al., 2022; Tyagi et al., 2022). On a global scale, digestate treatment aims to complete the cycle of converting biomass into energy, nutrients, or other products effectively and without a negative environmental impact. Therefore, the importance of proper digestate processing is obvious.

The report is based on scientific publications obtained from the Tritonia Academic Library website and Google Scholar search engine. The following key phrases were used to search for publications: “digestate management”, “digestate separation”, “digestate drying”, “dry anaerobic digestion”, “high solid anaerobic digestion”, “digestate AND plastic”, “hydrothermal carbonization status”. Some publications were taken as primary sources from the bibliographies of the articles found. Information from project experts also provided an important theoretical and practical basis for the report.

The main ideas and solutions within the frame of the current project have been developed for the joint operation of the conventional continuous wet AD reactor(s) and novel batched reactor(s) with sloped bottom (hereinafter – slope bottom reactor or SBR). Therefore, at the first step, some articles and information from the project experts were studied to determine and classify possible conventional methods for digestate handling. At the second step, the information on digestate processing was analysed, expanded, and actualized to determine the possible routes for digestate processing based on the project conditions, which involve leaching/dry AD of plastic-contaminated biomass in the slope bottom reactor. These steps were iterative. Hence, Section 2 of the report reviews the main conventional routes for digestate treatment in general, and Section 3 describes the possible routes for the current project conditions. Section 4 contains a conclusion on optimal solutions for digestate processing for the current project. Information from equipment manufacturers' websites and company proposals was compiled in the appendices to the report and contains possible practical solutions for digestate processing.

2 Conventional routes of the digestate processing

In general, particularly for conventional wet AD, the digestate processing begins with the separation of the solid phase from the liquid phase (see Appendix 2). Further steps depend on which fraction is being processed and the objectives of the digestate processing. Based on some publications used in this report (Bauer et al., 2021; Catenacci et al., 2022; Fuchs & Drosg, 2013; Kovačić et al., 2022; Nowak & Czekała, 2024; W. Wang et al., 2023), a simplified diagram of the digestate processing is presented in Figure 2 below. The information on which Figure 2 is based can be found in Appendix 2.

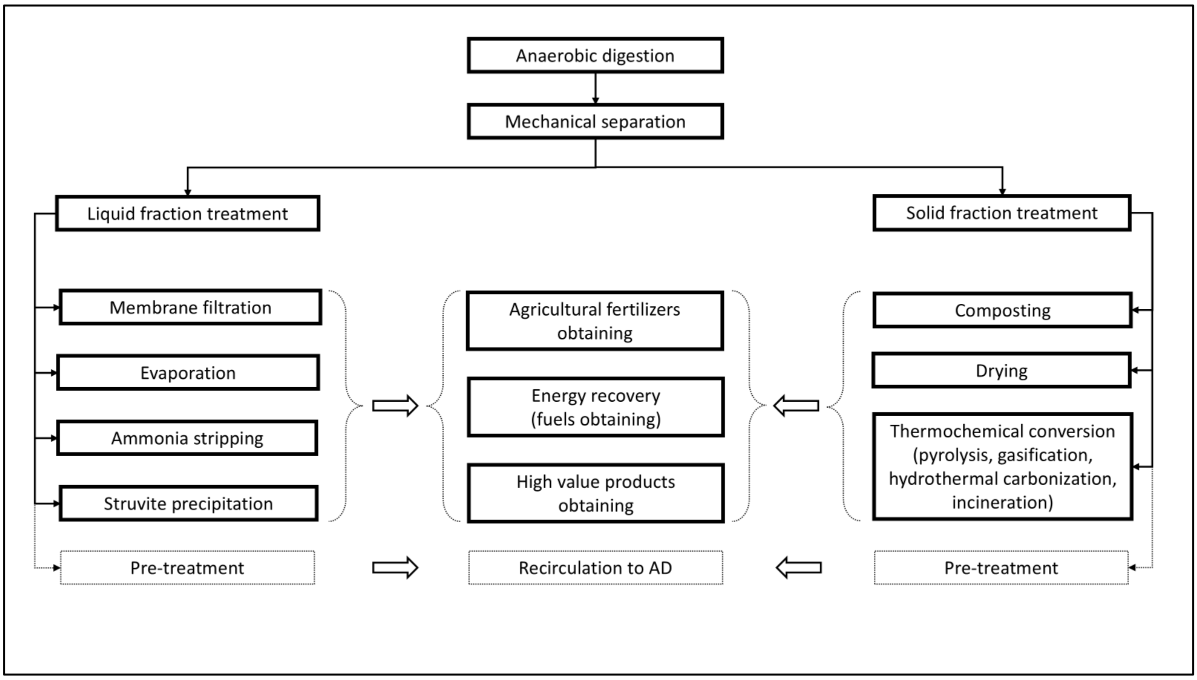

Figure 2. Possible digestate management processes.

2.1 Digestate mechanical separation

Traditionally, as mentioned above, the first step of the digestate treatment after wet AD is mechanical separation of the digestate into solid and liquid fractions (Bauer et al., 2021; Carraro et al., 2024; Kovačić et al., 2022; Nowak & Czekała, 2024; Tyagi et al., 2022). The process of mechanical separation of the digestate, which is referred to in the literature as partial treatment, is widely used in practice and aims to improve the possibility of further processing the digestate, focusing on resource recovery and nutrient concentration in the separated fractions. This process also helps reduce costs for digestate management. In particular, as shown in the above-mentioned publications, the separated solid fractions (dewatered digestate) can be stored, transported, and distributed more efficiently than unseparated digestate.

Regarding equipment for mechanical separation of the digestate, the two most applicable types of separators identified in scientific publications are: centrifuges (see Figures 3 and 4 below) and screw-press (see Figures 5 and 6 below) separators (Bauer et al., 2021; Carraro et al., 2024; Drosg et al., 2015; Nowak & Czekała, 2024). Each type comes with its specific purposes, advantages, and disadvantages. Centrifuges are better suited for digestate with low dry matter concentration and small solid particles, such as food waste digestate. Centrifuges are more effective at separating solid matter than screw-press separators. At the same time, according to the publications, the screw presses are more suitable for agricultural waste (with high fibre content) and are preferable from an economic point of view. In particular, screw presses consume approximately four to four and a half times less energy than centrifuges and require lower operating costs, since they have fewer moving and vibrating parts (Carraro et al., 2024; Nowak & Czekała, 2024). As we see in the publications above, screw presses' power consumption can vary from 0,4 to 1,2 $kWh \cdot m^{-3}$, centrifuges' consumption – from 2,2 to 5,1 $kWh \cdot m^{-3}$. Nevertheless, for cost and effectiveness optimisation, cascade separation (using serial separators), flocculating and precipitating agents, can be used to gain the required characteristics of the separated output fractions. In addition, Dr. Pasi Makkonen notes that characteristics of solids, such as wear-inducing components like abrasive sand, may also play a role in selecting the process.

The separated solid and liquid fractions of the digestate have different content of elements and, accordingly, need different purposes for further processing and applications (L. Bauer et al., 2021; Carraro et al., 2024; Kovačić et al., 2022; Nowak & Czekała, 2024; Tambone et al., 2010; Tyagi et al., 2022). Detailed information about the distribution of mass and nutrients after solid–liquid separation is presented in Appendix 3. According to the above-mentioned publications, solid fractions contain more phosphorus and insoluble and organic matter, such as lignin, cellulose, and organic N, than liquid fractions. Therefore, they are regarded as soil amendments more frequently than the liquid ones. Liquid fractions contain more nitrogen and potassium than solid fractions, making them suitable for use as fertilizers. The approximate total solids content of the separated solid fractions is in the range of 20 to 40%. Market potential of liquid fractions is limited compared to solid fractions, which have a higher fertilizer and humus value (Herbes et al., 2020). Regarding economics, the authors observe that separation alone does not reduce the total volume of the digestate but does lead to the expansion of infrastructure for the liquid and solid fractions separately. Therefore, the authors recommend considering digestate separation processes in combination with the following stages of digestate processing.

Figure 3. “Decanter centrifuge” (Drosg et al., 2015)

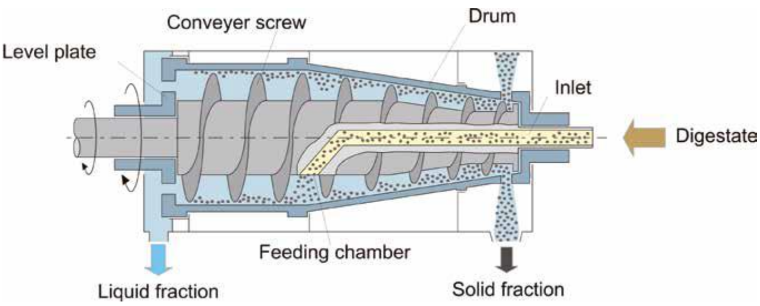

Figure 4. “Detailed set-up of a decanter centrifuge (Source: Fuchs and Drosg, 2010)” (Drosg et al., 2015)


Figure 5. “Screw press separator (Source: Fuchs and Drosg, 2010)” (Drosg et al., 2015)

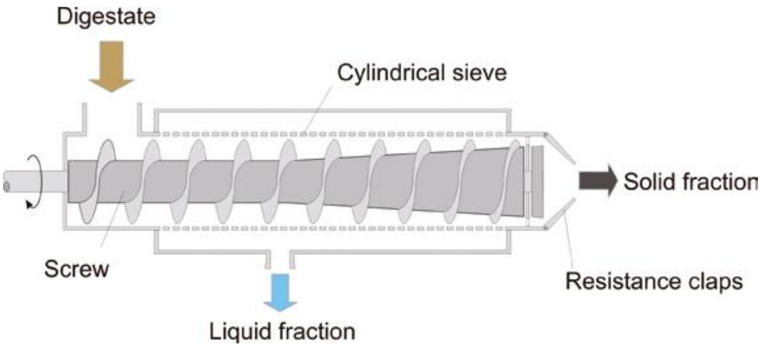

Figure 6: “Detailed set-up of a screw press separator (Source: Fuchs and Drosg, 2010)” (Drosg et al., 2015)

2.2 Liquid fractions post-treatment

Although there is a perception that processing liquid fractions of the digestate is not widespread (Tyagi et al., 2022), some approaches to their processing have been studied in numerous publications. Additionally, some methods can be categorized as novel and promising with high potential for development. Nevertheless, the primary purposes of processing liquid fractions currently are associated with nutrient recovery and technological water production. In addition, liquid fractions treatment is also needed from an ecological point of view to avoid problems, such as nitrogen leaching and further nearby water pollution, as well as emission and air pollution (Kovačić et al., 2022; Logan & Visvanathan, 2019; Nowak & Czekała, 2024; Sheets et al., 2015; Tyagi et al., 2022).

In terms of technology, various practical methods for processing liquid fractions include membrane technology, evaporation, stripping, reuse of the liquid fraction in AD processes to increase biomethane yield, and liquid fraction use in composting processes for moisturizing (Bauer et al., 2021; Drosg et al., 2015; Kovačić et al., 2022; Logan & Visvanathan, 2019; Nowak & Czekała, 2024). New and promising approaches include technologies such as osmosis, electrodialysis, enhanced precipitation using (bio)electrochemical processes, and microalgae cultivation for the further production of high-value products and bioenergy (Bauer et al., 2021; Chong et al., 2022; Pulgarin et al., 2021; Tyagi et al., 2022). The choice of technology for liquid fraction processing may depend on several factors and aspects, such as composition of the liquid fraction after mechanical separation, availability of heat sources, economic feasibility, environmental requirements, and others (Kovačić et al., 2022; Logan & Visvanathan, 2019; Nowak & Czekała, 2024). In addition, besides these factors and the primary purposes of the above-mentioned technologies, their practical application also faces several conditions, barriers, and limitations. The main limiting factors mentioned in the publications above are the following.

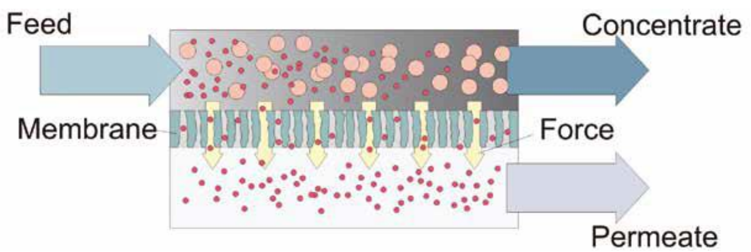

Figure 7: "Principle of membrane separation (Source: Fuchs and Drosg, 2010)" (Drosg et al., 2015)

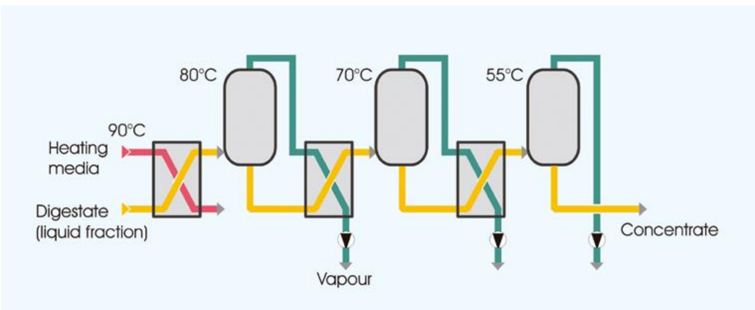

Figure 8: "Multistage evaporation system (Source: Fuchs and Drosg, 2010)" (Drosg et al., 2015)

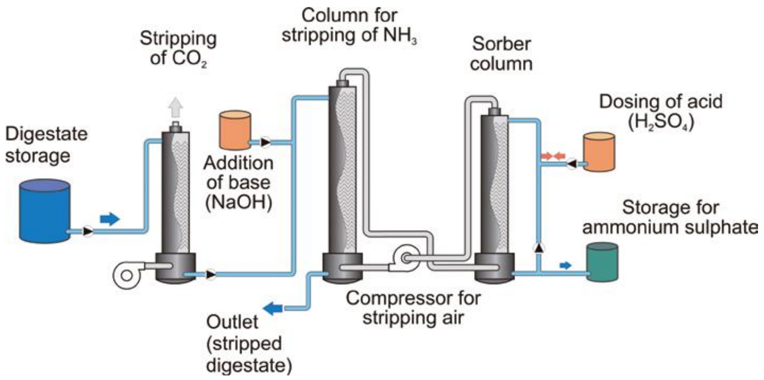

Figure 9: "Ammonia air stripping including CO_2 removal and ammonia recovery by sulphuric acid scrubbers (Source: Fuchs and Drosg, 2010)" (Drosg et al., 2015)

Membrane technologies (see Figure 7 above) for processing liquid fractions of the digestate are associated with relatively high capital costs, as well as high operating costs due to membrane fouling (Kovačić et al., 2022; Nowak & Czekała, 2024; W. Wang et al., 2023). The operation of evaporators (see Figure 8 above), which concentrate nutrients, depends on the availability of heat sources (e.g. CHP[1] of biogas plant or district heating) and the possibility of preliminary purification of liquid fractions of the digestate from large mechanical particles and fibres to avoid damage to heat exchangers, as well as the use of chemicals (Kovačić et al., 2022; Logan & Visvanathan, 2019; Nowak & Czekała, 2024). Stripping (see Figure 9 above), which aims to produce nitrogen fertilizers, is an energy-intensive process that may require more efficient solid-liquid separation of the digestate and relatively high costs for maintenance and cleaning (Logan & Visvanathan, 2019; W. Wang et al., 2023). Regarding liquid fraction reuse in AD processes, despite the potential of this reuse for increasing biogas yield, it is crucial to control the concentration of ammonium nitrogen in terms of avoidance of AD process inhibition (Li, Liu, et al., 2018; Nowak & Czekała, 2024; Sheets et al., 2015; Wu et al., 2018). In addition, regarding aerobic biomass degradation, Drosg et al. (2015) mention that before moistening the compost with liquid fractions of the digestate, it is necessary to reduce the concentration of ammonia in the liquid to minimize emissions. However, Dr. Pasi Makkonen, providing an example of N balance calculation (see Appendix 4), notes that controlling ammonium nitrogen concentration is not just a simple process.

[1] CHP - Combined Heat and Power (cogeneration).

2.3 Solid fraction post-treatment

2.3.1 Composting

Digestate composting is a widely known and technologically developed process of aerobic biodegradation of organic matter. In terms of the digestate processing, firstly, composting aims to stabilise the separated solid fractions of the digestate, which usually are characterized by residual volatility, microbial activity, and odour emission (Drosg et al., 2015; Kovačić et al., 2022; Logan & Visvanathan, 2019; Tyagi et al., 2022). Secondly, as we can see in the above-mentioned publications, digestate composting aims to produce qualified soil improvers (biofertilizers) with slow release of nutrients.

Technologically, there are two approaches to digestate composting (see Figure 10 below) - in open systems (open air), which are best known and the most inexpensive, and in closed systems (reactor), which allow to control composting processes and also decrease emissions (toxic NH_3, N_2O with high global-warming potential) that represents one of the disadvantages of the digestate composting (Kovačić et al., 2022). The composting process consists of two stages: fermentation (self-heating, activity of mesophilic and thermophilic bacteria) and maturation (actinomycete and fungal activity, lignocellulose degradation, and humification) (Kovačić et al., 2022; Tyagi et al., 2022).

Figure 10: "Composting facilities in an open (left) or closed (right) environment (© Erwin Binner, Institute of Waste Management, University of Natural Resources and Life Sciences, Vienna" (Drosg et al., 2015)

From an economic perspective, digestate composting costs can vary from EUR 45 to EUR 160 per tonne, depending on the country, plant capacity, market access, and approach to digestate composting (Kovačić et al., 2022). According to the publications mentioned in this section, composting duration may take a few weeks to several months, depending on parameters such as moisture and oxygen content of the composted material, C/N ratio, air porosity, temperature profile, and aeration rate. Increasing the latter, on the one hand, can improve the activity of aerobic microorganisms and therefore accelerate the composting process. On the other hand, it can lead to air pollution, water and heat losses, which are crucial for the activity of aerobic microorganisms. Thus, optimisation of the aeration rate, for example, by adding bulking materials with high porosity to the composting material, or by shifting a pile, or by using fans, is an important area in terms of composting performance (Kovačić et al., 2022).

2.3.2 Digestate drying

Physically, the primary purposes of drying the digestate solid fraction are associated with its total mass reduction and stabilization (Kovačić et al., 2022; Logan & Visvanathan, 2019; Salamat et al., 2022; Tyagi et al., 2022). Ultimately, as we can see in the publications mentioned above, this helps decrease emissions, concentrate nutrients, achieve hygienization of the digestate, and store and transport digestate efficiently The authors also note the applications, such as obtaining fertilizers, pelletizing to increase marketability, and use in special cultivation systems. Regarding possible target drying parameters, the authors observe that reducing the costs for digestate storage and transportation is achieved by increasing the dry matter content as much as 90%.

There are several drying techniques applied to digestate drying (see Figures 11, 12, and 13 below, as well as Appendix 6), which are associated with convective, conductive, radiative (solar), hybrid (for example, fluidized-bed dryers), and superheated steam drying systems (Salamat et al., 2022). The comparison of these techniques is in Appendix 5. Currently, such conventional equipment as belt dryers, drum dryers, and solar dryers prevails in European farms (Barampouti et al., 2020; Drosg et al., 2015). Among these conventional drying systems, belt dryers are used more commonly (Salamat et al., 2022).

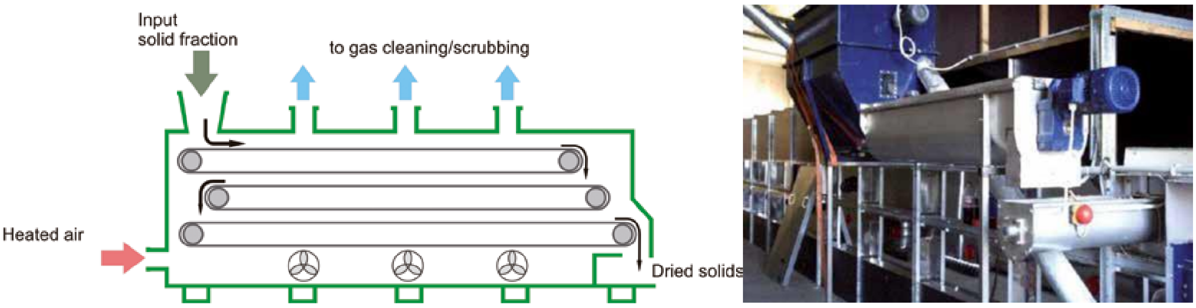

Figure 11: "Scheme of a belt dryer (Source: Fuchs and Drosg, 2010)" (Drosg et al., 2015)

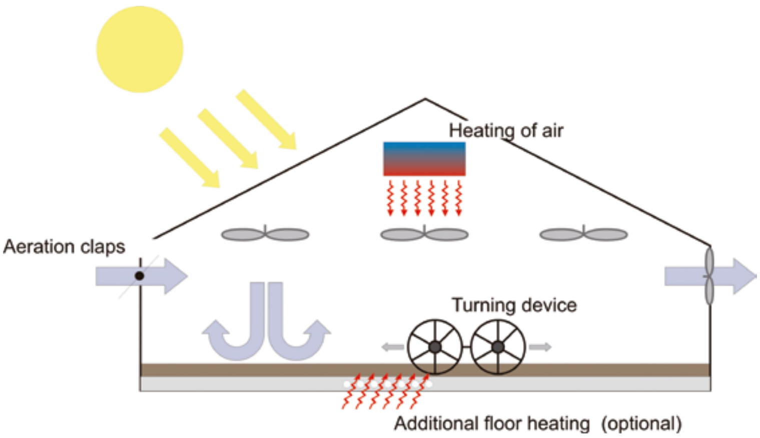

Figure 12: "Solar drying of digestate (Source: Fuchs and Drosg, 2010)" (Drosg et al., 2015)

Figure 13. Different types of dryers for sludges (Dr. Pasi Makkonen).

As we see in the publications above (Kovačić et al., 2022; Logan & Visvanathan, 2019; Salamat et al., 2022; Tyagi et al., 2022), in addition to moisture evaporation, the process of digestate drying is accompanied by emissions, losses of useful elements, and a decrease of the calorific value of the digestate. Ammonia emissions are undesirable due to both air pollution and loss of digestate fertilizer value. Carbon dioxide and volatile hydrocarbons emission, in addition to their negative impact on the environment, reduces the carbon content and calorific value of the digestate. Thus, in combination with dryers, the digestate drying process requires the use of exhaust gas cleaning systems such as scrubbers or washers.

The process of thermal drying of the digestate is an energy-intensive process. According to the comparison mentioned above (see Appendix 5), conventional digestate dryers consume approximately 700 to 1400 kWh to evaporate 1 ton of water from the digestate. Compared to solid-liquid separation (see Subsection 2.1), energy consumption for thermal drying of the digestate can be 100 to 1000 times higher (Salamat et al., 2022). Compared to transportation costs, "according to a European study (Turley et al., 2016), up to a transport distance of 100 km, transportation is more cost-efficient than thermal drying" (Salamat et al., 2022, p. 6).

Sludge drying as a unit operation is, in principle, a simple process, which contains three (or four) main phases (see Figure 14 below), and can be done whether as a batch operation or as a continuous run. Water present in organic material may be of the following types (Dr. Pasi Makkonen):

a. Water between pores (unbound) that is subordinate to the gravity force and can be easily removed by gravity settling (thickening). This water is removed before thermal drying.

b. Free capillary water, held in by adhesion and cohesion forces, that is readily removed by mechanical dewatering without using chemicals; for example, in centrifuges where centrifugal force (inversely directed) opposes capillary force and helps to get rid of capillary water. Most of this water is removed before thermal drying.

c. Physically half-bound water that is bound inside flakes of the organic material.

d. Bound water:

i. biologically - in intracellular form, it is a part of the cells of living organisms present, bound by molecular forces to the constant phase of organic material,

ii. chemically - in intercellular form, it is a part of the crystal lattice of molecules of the constant phase of sludge,

iii. physically – in colloids, bound by the surface tension present on the border of phases.

1. Removal of free water
2. Removal of interstitial water
3. Removal of surface water
4. (Removal of bound water.)

Usually phases 1 – 3 are needed to create solids with sufficiently low water content.

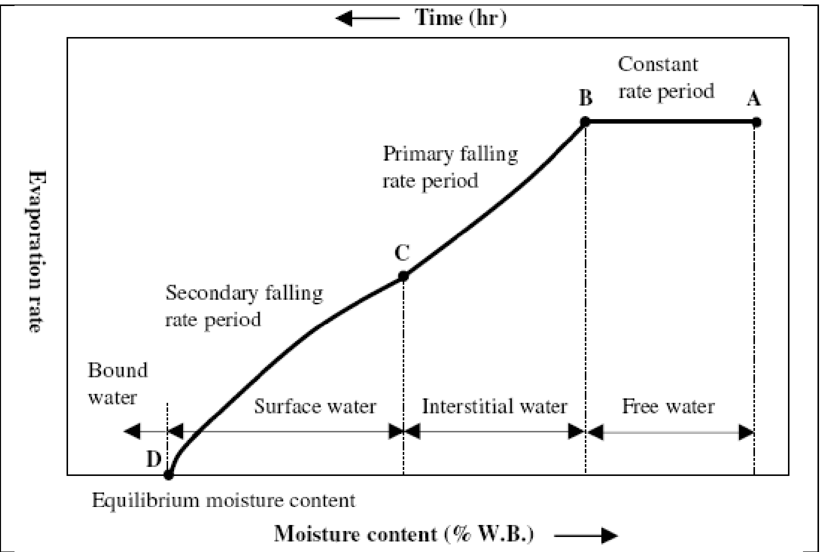

Figure 14. Sludge drying as a unit operation (Dr. Pasi Makkonen).

The individual phases of the drying process can be listed as follows (Dr. Pasi Makkonen):

a. Warming up of the system, especially heating of the metal structure, may take a long time. Here, the main parameters are the structure weight and batch size.

b. Evaporation of free water.

c. Primary evaporation, the interstitial water, almost linear drying curve.

d. Secondary evaporation, the surface water, non-linear drying curve.

e. Disinfection period.

f. Cooling.

Dr. Pasi Makkonen also says that the drying process can be continued until there is only bound water left in the organic material, but often a slightly lower degree of drying is considered sufficient. Removal of the bound water is very difficult, and cannot be done if there is vapor in the environment, as there will be an equilibrium between the vapor in the external gas, and the organic material water content.

Various approaches to digestate drying are discussed in the literature in terms of energy efficiency (Barampouti et al., 2020; Drosg et al., 2015; Kovačić et al., 2022; Logan & Visvanathan, 2019; Salamat et al., 2022; Tyagi et al., 2022). The first and obvious way is the use of CHP excess heat for digestate drying in the case of heat and power production at biogas plants. The second way is associated with solar drying systems, which are characterized, among other drying systems, by significantly lower energy consumption. Solar drying systems can be integrated into the energy systems of biogas plants and used in greenhouses. In addition, regarding AD of biomass with a high solid content (high-solid AD), as in the current project, solar drying is one of the most suitable drying techniques (Fagbohungbe et al., 2015). However, solar drying systems require large land areas and relatively long drying durations, and depend on climate conditions. The next energy-efficient approach is superheated steam drying, which demonstrates a relatively high share of thermal energy recovered and low energy consumption, low emissions and air pollution, and matches sterilization requirements (Salamat et al., 2022). These advantages make superheated steam dryers more and more popular. Regarding digestate drying, information on possible technical solutions is provided in Appendix 6.

2.3.3 Energy recovery. Thermochemical conversion of the digestate.

Due to the significant carbon content of the digestate solid fractions, energy recovery is an obvious pathway for digestate processing. Besides relatively mature Waste-to-Energy technology associated with waste incineration, depending on the technological parameters and conditions, there are different promising approaches to thermochemical conversion of the digestate solid fractions into biochar, bio-oil, syngas, as well as soil amendments and activated C material (Catenacci et al., 2022; Kovačić et al., 2022; Logan & Visvanathan, 2019; Tyagi et al., 2022). Among these methods, the authors mention gasification, pyrolysis, and hydrothermal carbonization. However, carbon content is not the only factor for these approaches. Moisture content, ash content, and other factors also impact the energy value of the digestate (Nowak & Czekała, 2024). Due to the technological parameters and processing conditions of the challenging raw material in the current project[2], the thermochemical conversion of the digestate is discussed in more detail in Section 3.

[2] Digestate output from the SBR(s) is equal 450 tonnes per year (1,2 tonnes per day) with 80% of dry solids. Digestate output from wet AD reactor(s) is equal 1577 tonnes per year (4,8 tonnes per day) with 25% of dry solids. The overall digestate output is equal 2027 tonnes per year (6,0 tonnes per day) with 37% of dry solids.

3 Digestate processing for the current project conditions

3.1 Selection of possible processes for digestate treatment

According to the project's technological parameters and conditions of biomass leaching/dry AD in SBR, and because of feedstock contaminations, not all conventional processes and purposes of the digestate processing mentioned in Section 2 are suited. Firstly, the solid content of the raw material for dry AD is from 20 to 40% (Angelonidi & Smith, 2015; Logan & Visvanathan, 2019; Rocamora et al., 2020). Moreover, according to the current project documentation, the solid content of the output material after leaching/dry AD in SBR is approximately equal to 80%. Thus, the solid–liquid separation process is not required for the output material of SBR, since the output solid fraction of mechanical separation has an approximate value of solids content from 20 to 40% (see Subsection 2.1).

Secondly, the utilisation of plastic-contaminated digestate as agricultural fertilizer is problematic from an ecological perspective. The problem of plastic degradation concerns both conventional plastics and bioplastics, as plastic degradation only occurs under certain conditions, which may not correspond to AD conditions (Mioduska et al., 2023). In a broader sense, environmental aspects in terms of the digestate utilisation are expectedly to be regulated in the future in detail by setting stricter requirements for the content of undesirable inclusions in the digestate (Logan & Visvanathan, 2019; Mioduska et al., 2023; Tyagi et al., 2022; W. Wang et al., 2023). In addition, Herbes et al. (2020) raise the issue and provide examples of possible nutrient surpluses in soils in various regions. This issue can lead to an additional financial burden for biogas plant operators. Thus, the direct agricultural application of the challenging digestate is not considered an option in the current project (at first glance and in the short term).

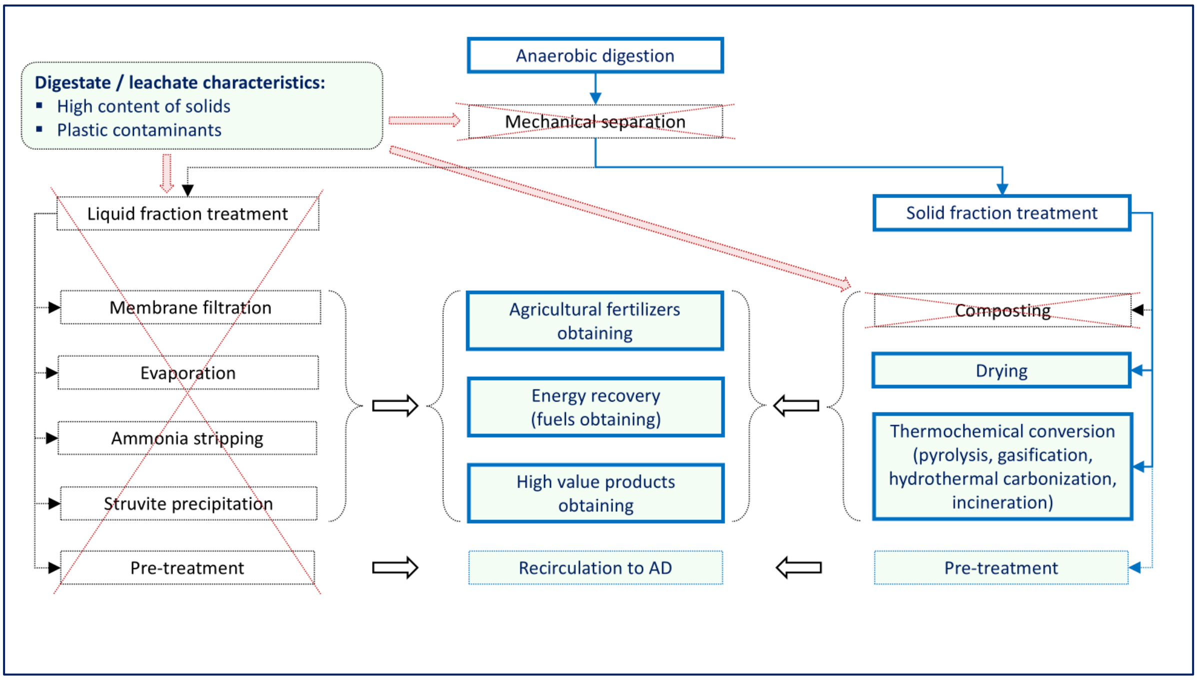

Figure 15. Possible processes for digestate treatment within the frame of the current project.

The possible direction of the digestate processing within the frame of the current project is associated with energy recovery. The selected processes for digestate treatment are summarized in Figure 15 above. In addition to the digestate drying processes described in Subsection 2.3.2, the following information has been formed for digestate processing after leaching/dry AD of the plastic-contaminated biomass.

3.2 Thermochemical conversion of the digestate after leaching and dry anaerobic digestion

The literature contains many detailed considerations of the thermochemical conversion of biomass and its parameters. For example, Kovačić et al. (2022, p. 18) provide the following definitions of gasification, hydrothermal carbonization, and pyrolysis of organic matter (OM):

> Gasification is the partial oxidation of OM that occurs in a temperature range from 800 to 1200 °C (Giuliano et al., 2020). The main product of the process is syngas, while other products are solid carbonaceous biochar and bio-oil (a mixture of different polycyclic aromatic hydrocarbons). Several authors have shown that

gasification of the dried solid fraction of the DG[3] could be a promising way to produce a gaseous product that can be used as fuel in an internal combustion engine, while the by-products (biochar, bio-oil, and ash) can be further converted into value-added products and used for different purposes (Chen et al., 2017; Giuliano et al., 2020).

Hydrothermal carbonization (HTC) is a process that converts OM into high C content under varying temperatures (190–250 °C) and pressure (2 to 10 MPa) for several hours. Through relevant studies conducted over the last decade, HTC has emerged as a promising technology due to its many advantages such as the conversion of biomass into numerous products, e.g., solid fuel, bio-oil, soil amendment, activated C material that can be used as an adsorbent, C catalyst (Nizamuddin et al., 2017). The HTC process may be classified as either a direct or catalytic HTC process. In the direct HTC process, only water and feed are heated in a reactor at different temperature ranges, while the catalytic HTC process uses a catalyst (Funke & Ziegler, 2010).

Pyrolysis is a process that converts high solids content substrates into value-added products such as biochar, bio-oil, and syngas by heating in the absence or low concentration of oxygen (Rezaee et al., 2020). It is usually conducted in an inert gas environment at atmospheric or slightly high pressure, although vacuum conditions or pressurized hydrogen (H) are sometimes employed (Balagurumurthy & Bhaskar, 2014).

An illustration of the possible thermochemical conversion processes of ADFW into valuable products is shown in Figure 16 below. The integration of AD and thermochemical conversion of the digestate is mentioned in the literature as a broadly studied and promising field (Peng et al., 2020; W. Wang et al., 2023). Thermal conversion of the digestate from high-solid AD is considered a suitable approach (Peng et al., 2020).

Regarding the integration of high-solid AD and gasification, Peng et al. (2020) mention the main products, such as syngas and biochar, as well as an example of syngas yield of 1,55 Nm^3/kg with a calorific value of 5,3 MJ/Nm^3. Zhang et al. (2022) investigated a hybrid biological and thermal system for converting plastic-containing food waste into energy. The authors assessed the energy balance of the system and observed that the system can process plastic-containing food waste and recover renewable biofuels and bioresources (i.e., biogas, syngas, and biochar) on an industrial scale. The system's scheme is in Figure 17 below. At the same time, Mei et al. (2024) note that the technological process of gasification is intricate, as it requires precise regulation of

[3] DG - digestate

conditions[4] and may have relatively high capital investment and operating costs, which consequently make this technology unsuitable for small-scale production. Regarding the air gasification process of the digestate at 800 °C, Z. Wang et al. (2024) note the relatively low calorific value of syngas, with a maximum value of only 6,35 MJ/m3, which limits its application. Nevertheless, the authors list several possible optimization solutions to mitigate these obstacles (for example, co-combustion, co-gasification, etc.).

Dr. Pasi Makkonen, comparing gasification and combustion technologies, considers two cases: small-scale power production and medium-scale WTE[5] (see Table 1 below). We can see that the gasification process is more efficient for power generation compared to

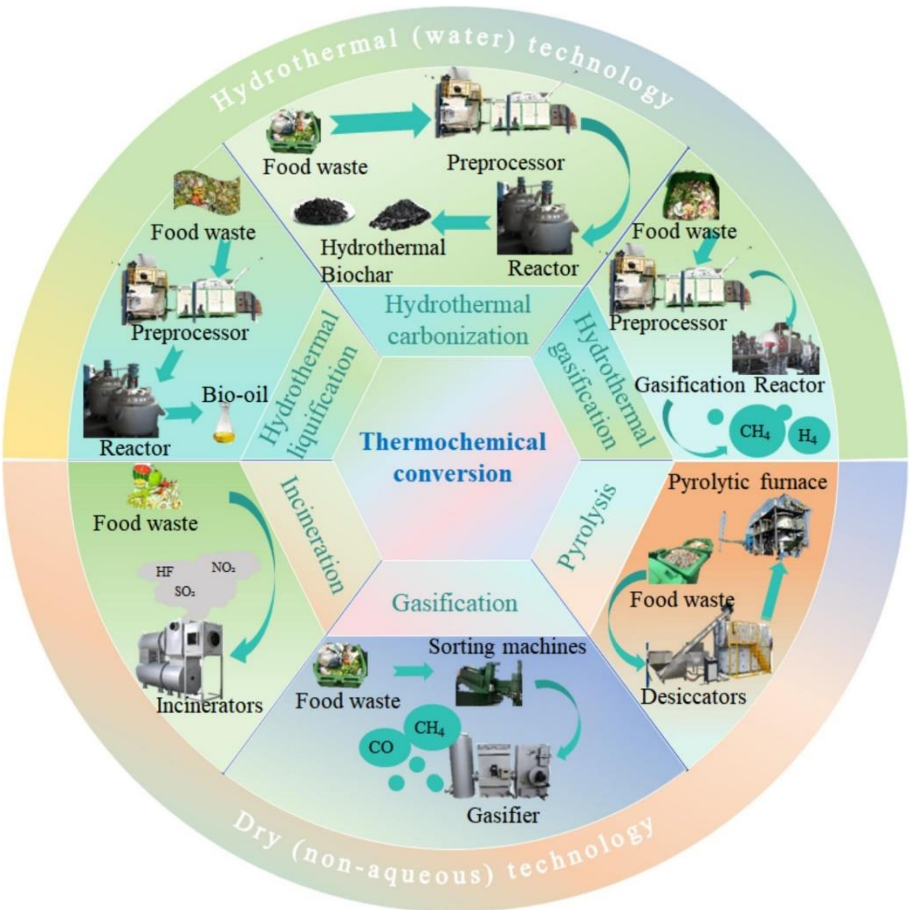

Figure 16. Thermochemical conversion technology of ADFW (Mei et al., 2024).

[4] For example, the process temperature can be limited by the ash melting point of the raw material, the value of which can be 800 °C, which in turn limits the calorific value of syngas and the efficiency of the process (Pecchi & Baratieri, 2019).

[5] WTE – Waste-to-Energy

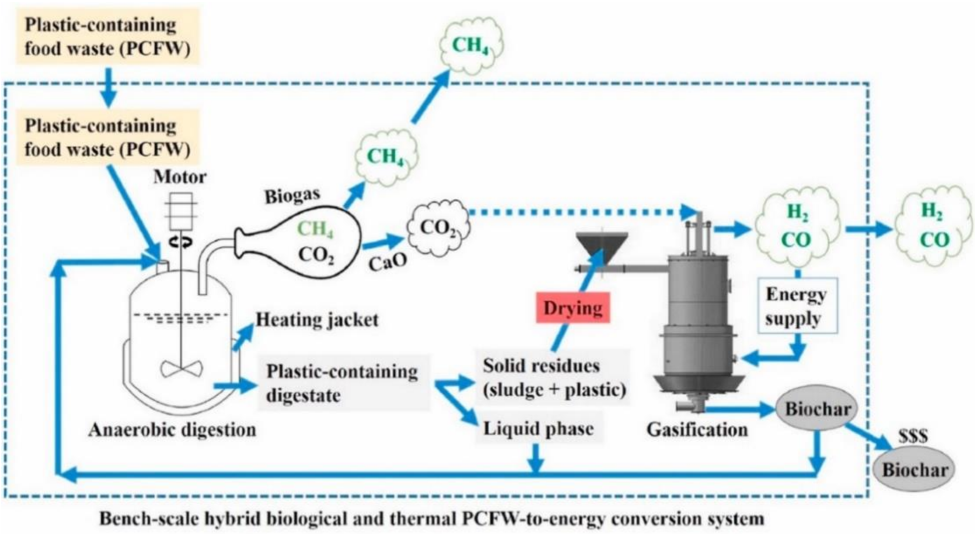

Figure 17. The hybrid biological and thermal conversion system (Zhang et al., 2022)

combustion, while the latter is more efficient for heat production. In terms of investment, combustion technology requires 1,9 times more investment than gasification for small-scale power generation and 2,2 times more for medium-scale WTE.

In case of the combination of high-solid AD with pyrolysis of the digestate, Peng et al. (2020) provide examples of a 42% increase in electricity production at a biogas CHP plant, as well as bio-oil production with a calorific value of 7,78 MJ/kg (52,2% of the total mass) or with a higher calorific value of 28,48 MJ/kg (59,38% of the total mass) in the case of microwave liquefaction. In addition, the authors consider reusing pyrolysis products in the AD process to increase biogas yield. At the same time, as Mei et al. (2024) note, even though pyrolysis emits fewer pollutants, this process is less efficient and requires temperature control compared to incineration. In addition, regarding the digestate pyrolysis, Z. Wang et al. (2024) refer to numerous publications on the potential applications of pyrolysis products such as pyro-oil, pyro-gas, and pyro-coal. However, according to the authors, the complexity of pyro-oil composition, the lower calorific value of pyro-gas compared to natural gas, and the need to improve the economic efficiency of pyro-char production are factors limiting the widespread use of the above-mentioned pyrolysis products.

Table 1. Technology comparison

GASIFICATION	COMBUSTION
CASE 1: SMALL SCALE POWER PRODUCTION	

• Biomass or residue → gas production→ gas cleaning → gas use in a gas engine → heat recovery
• Efficiencies:
  • Power up to 35 %
  • Heat up to 55 %
• **Investment for 1 MW_e:**
  • Drum gasifier 3 MW_{fuel}, 400 k€
  • Gas cleaning, 100 k€
  • Gas engine, 500 k€
  • Boiler, 300 k€
  • **TOTAL: 1 300 k€**
	• Biomass or residue → combustion → steam generation in a boiler → steam turbine + flue gas cleaning
	• Efficiencies:
	  • Power up to 25 %
	  • Heat up to 65 %
	• **Investment for 1 MW_e:**
	  • Grate combustor 4 MW_{fuel}, 500 k€
	  • Boiler, 900 k€
	  • Steam turbine, 800 k€
	  • Gas cleaning, 300 k€
	  • **TOTAL: 2 500 k€**

CASE 2: MEDIUM SCALE WTE	

• Waste → gas production→ gas cleaning → gas use in a gas engine → heat recovery
• Efficiencies:
  • Power up to 40 %
  • Heat up to 45 %
• **Investment for 10 MW_e:**
  • 6 * Drum gasifier 5 MW_{fuel}, 6 M€
  • Gas cleaning, 2,5 M€
  • 5 * 2 MW gas engine, 8 M€
  • Boiler, 4.5 M€
  • **TOTAL: 21 M€**
	• Waste → combustion → steam generation in a boiler → steam turbine → flue gas cleaning
	• Efficiencies:
	  • Power up to 20 %
	  • Heat up to 65 %
	• **Investment for 10 MW_e:**
	  • Grate combustor 50 MW_{fuel}, 12 M€
	  • Boiler, 10 M€
	  • Steam turbine, 6 M€
	  • Gas cleaning, 18 M€
	  • **TOTAL: 46 M€**

NO LIMIT IN POWER PLANT SIZE: AMOUNT OF MODULES CAN BE INCREASED!	

In terms of processing of the plastic-contaminated raw material, Al-Rumaihi et al. (2022) conclude that, although the separate pyrolysis of the biomass or plastic waste has reached a relatively high technology readiness level (for example, applied demonstration regarding pyrolysis oil production), the co-pyrolysis of plastic and biomass has not yet reached the same level (see Figure 18 below). Nevertheless, Hilber et al. (2024) argue that thermochemical conversion can eliminate plastic from the raw material. Numerically, the authors show that “600°C × 12 min is sufficient, whereas 450°C × 12 min may not for the elimination of plastic” (Hilber et al., 2024, p. 11) and “Despite the need for further research, our study showed that the pyrolysis of plastic-contaminated biomass can be an important pathway for carbon and nutrient recycling. It avoids their total loss in waste incineration and expands the range of possible biomass to produce biochar-based C sinks" (2024, p. 11). Mei et al. (2024) suppose that catalytic pyrolysis/gasification of plastic-containing anaerobic digestate with red mud and copper slag as catalysts is a promising technology. The principles of this solution are in Figure 19 below.

The following type of thermochemical conversion of biomass – HTC – is of particular interest due to its specific characteristics. Selvaraj et al. (2022), providing an extensive list of studies on HTC of biomass, note that carbon-rich hydrochar and organic-rich liquor[6] are the main products of HTC of wet biomass. In particular, the authors note that HTC converts the biomass with a dry solid between 15% and 25%[7]. It means that, unlike pyrolysis and gasification, HTC does not require drying of biomass and, in combination with lower temperature of the process, provides more energy-efficient conversion of the digestate (Catenacci et al., 2022; Farru et al., 2024; Gamaralalage et al., 2025; Romano et al., 2023; W. Wang et al., 2023). The authors note that, depending on the feedstock composition, a hydrochar can be utilized in different ways, such as a renewable fuel[8], soil amendment, carbon sequestration, enhancing AD performance, and carbon-based material production. In addition, Gamaralalage et al. (2025) argue that, unlike incineration, HTC of plastic-contaminated digestate releases both biogenic and fossil carbon into the final hydrochar product. Mei et al. (2024) also highlight the advantages of no drying, relatively mild process conditions, low emissions and pollution, high value-added products, and higher energy potential recovered compared to incineration, landfilling, composting, or anaerobic digestion. At the same time, as the authors note, HTC is characterized by high equipment costs and a high threshold for product sales.

Regarding the practical application of HTC, despite a significant number of HTC-related scientific publications and patents, as well as many pilot plants and some full-scale plants, this technology is currently undergoing a phase of evolution (Romano et al., 2023). Even though HTC stands out among other thermochemical methods in that it does

[6] Also known as aqueous HTC liquid
[7] According to other sources of information, dry solid content value might be from 10% to 25% (Catenacci et al., 2022), or from 20% to 50% (see Appendix 7). The required dry matter content is probably achievable for the current project, as it involves the joint operation of the traditional wet AD reactor and SBR.
[8] For example, hydrochar is characterized by a relatively high calorific value ranging from 15 to 20 MJ/kg (Catenacci et al., 2022), or ranging from 14,37 to 33,21 MJ/kg (Marzban et al., 2022).

not require digestate drying, the pace of this technology transition from laboratory research to commercial use is slow (Farru et al., 2024). The authors highlight transition barriers, such as regulatory constraints, market acceptance, insufficiency of investments, competitiveness of hydrochar, and substantial energy consumption. At the same time, among the 24 companies surveyed that use HTC in their operations, more than 80% employ this technology in waste management of several biomasses and residuals, 54% in biocoal production, 58% in nutrient recovery, and 33% in advanced materials. Thus, as the authors mention, HTC's potential is clear for several sectors. In addition, in terms of energy efficiency and maximum possible amount of energy and bioproducts recovery, AD integration with HTC is highlighted among other thermochemical conversion technologies (Farru et al., 2024; Romano et al., 2023; W. Wang et al., 2023). Regarding the national market, for example, it is interesting to note that, considering HTC applications in various countries, Romano et al. (2023, p. 5) cite the example of Finland:

> In January 2020, a plant in Heinola, Finland, capable of processing 20,000 tons/year of biological sludge, also went into operation. C-Green's patented solution for efficient chemical heat generation eliminates the need for costly external heat generation. It is so efficient that, once started up, it requires no external heat.

Considering energy recovery from the anaerobic digestate, Catenacci et al. (2022) provide possible solutions for AD integration with pyrolysis and HTC, highlighting the difference between these processes and utilisation of the outcome products (see Figure 20 below). Despite technological capabilities, practical applications of gasification/pyrolysis/HTC of the digestate are still limited (W. Wang et al., 2023; Z. Wang et al., 2024). Catenacci et al. (2022) also mention critical aspects, such as economic issues, scale-up difficulties, raw substrate characteristics and variability, ash content in char, limited standards, high temperatures, and intense digestate drying requirements (for pyrolysis and gasification), complicated recovery of liquid fractions, etc. According to Kovačić et al. (2022), one of the main limiting factors for digestate thermochemical conversion is its moisture content, which should be less than 30%[9].

[9] This factor is probably related to gasification and pyrolysis of the digestate.

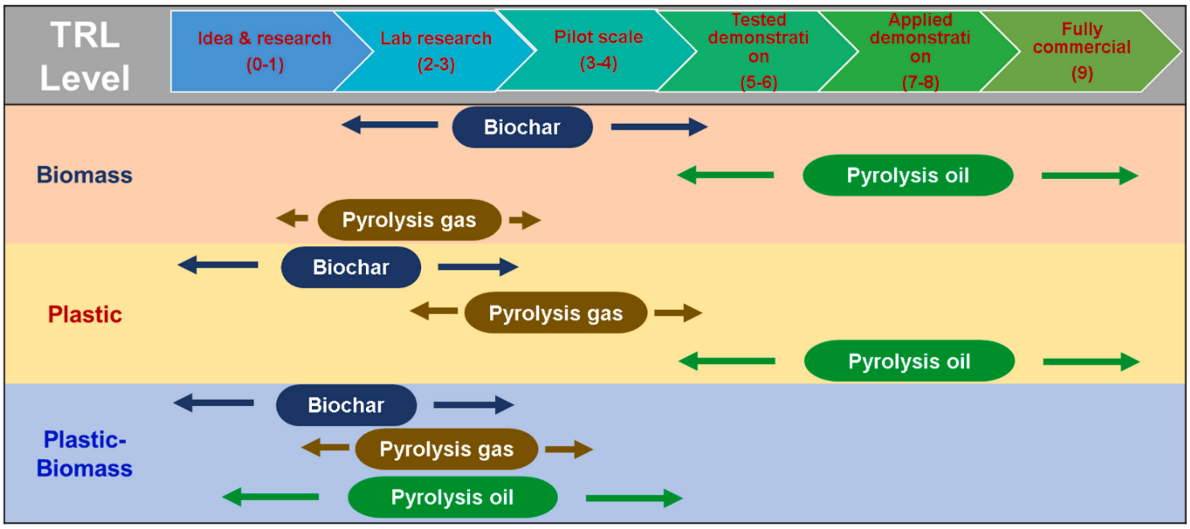

Figure 18. TRL[10] level of biomass, plastic and (biomass-plastic) for bio-oil, biochar (Al-Rumaihi et al., 2022).

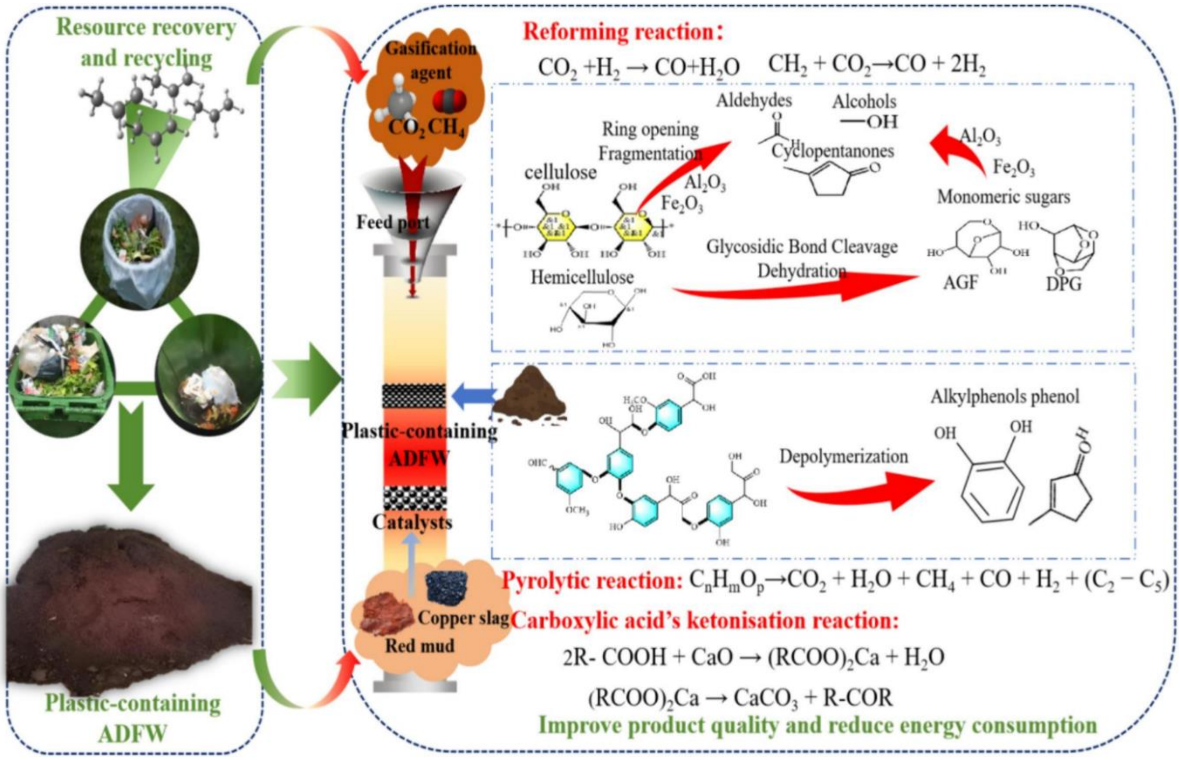

Figure 19. Catalytic pyrolysis/gasification of plastic-containing ADFW[11] using red mud/copper slag under CO_2/CH_4 atmosphere (Mei et al., 2024, p. 10).

[10] TRL - Technology Readiness Level

[11] Anaerobic Digestate from Food Waste

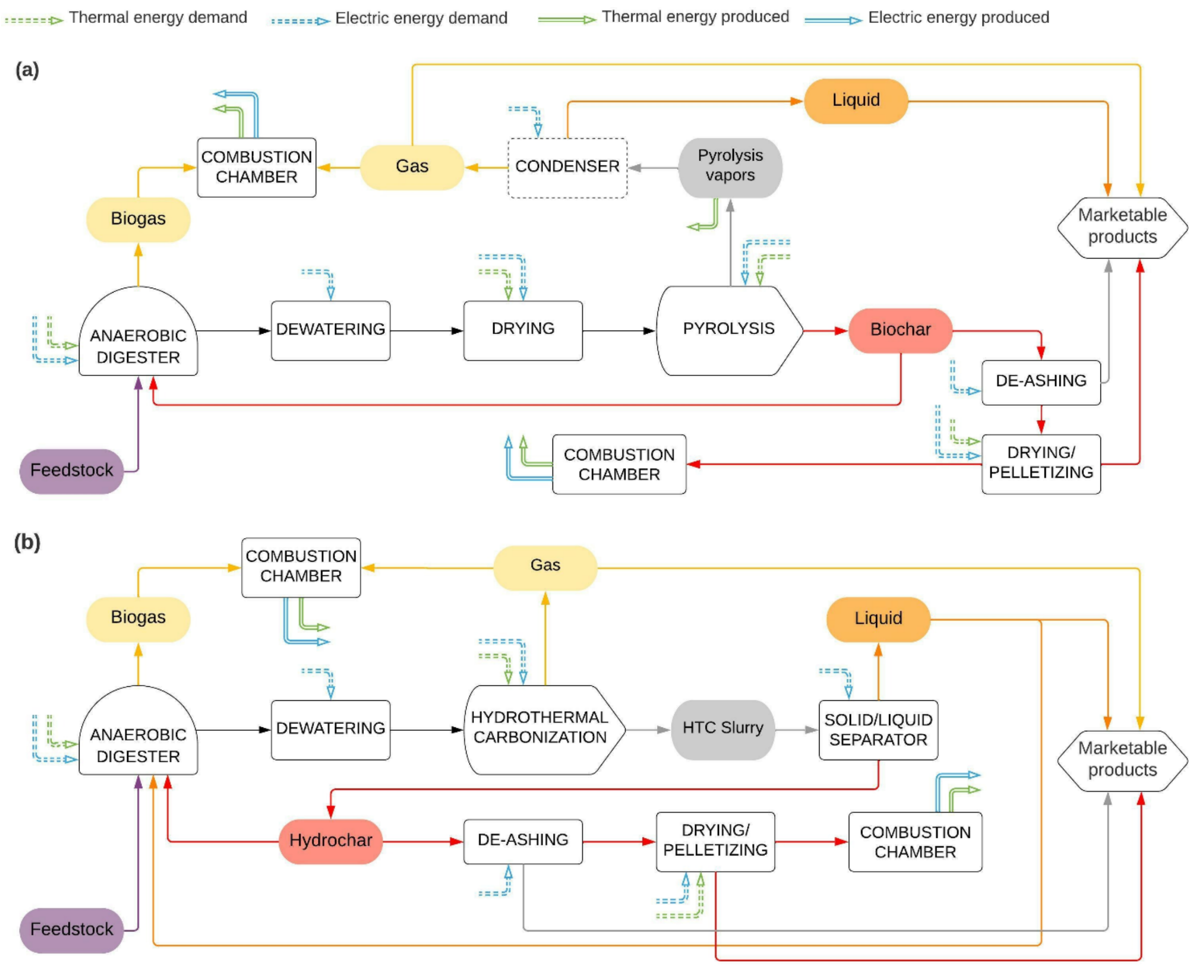

Figure 20. Integration of AD with (a) pyrolysis, (b) HTC: strategies for energy recovery (Catenacci et al., 2022).

The next possible pathway of energy recovery from the digestate solid fractions mentioned in the publications is combustion[12], as well as co-combustion (Logan & Visvanathan, 2019; Nowak & Czekała, 2024; Tyagi et al., 2022). Z. Wang et al. (2024) provide examples of studies on solid digestate as a feedstock for combustion and mention that the calorific value of solid digestate is comparable to that of wood. Nowak & Czekała (2024) show that it is possible to produce pellets with a calorific value of 18,2 MJ/kg from digestate solid fractions with a moisture content of 14,3%, which is even higher than the calorific value of wood pellets (16 MJ/kg on average). Dziedzic et al. (2021) conclude that digestate from agricultural biogas plants studied can be a combustion fuel. The moisture content of the digestate samples ranged from 11,9 to 12,2%, and the

[12] Using the publications reviewed, the terms “combustion” and “incineration” are used interchangeably in this report.

calorific value ranged from 15,34 MJ/kg to 18,41 MJ/kg. The authors also note that this fuel is preferable to biogas plant feedstock. Xiao et al. (2022) show that, under eco-industrial park conditions with existing technological facilities, where digestate transportation costs are negligible, digestate incineration after dry AD demonstrated more favourable ecological and economic indicators than landfill and composting, mainly due to the highest revenue from electricity generation. Gamaralalage et al. (2025) also note that incineration of food waste[13] digestate is preferred to landfill because of its lower cost. Z. Wang et al. (2024) argue that combustion of solid digestate is an economically feasible solution and, compared to other thermochemical conversion processes, this process involves simpler equipment with lower investment costs and mature technology.

However, Mei et al. (2024), considering and comparing technologies for the thermochemical conversion of anaerobic digestate from food waste, argue that incineration is characterized, on the one hand, by relatively high processing capacity and, on the other hand, by high production costs, the complexity of ash disposal, and emissions. There are opinions that the energy properties of the digestate solid fractions are lower compared to other biofuels; for example, they contain more ash compounds, which negatively impact the combustion process (Jurgutis et al., 2021; Kratzeisen et al., 2010). When selecting technical solutions for digestate combustion, the relatively high ash content of the digestate should be taken into consideration (Dziedzic et al., 2021). From an economic point of view, in addition to digestate calorific value, which should be higher than 17 – 18 MJ/kg, there are also several conditions to use digestate for combustion (Nowak & Czekała, 2024; Tyagi et al., 2022):

- Dry matter content should be higher than 75%.
- Digestate production should be more than 10 t/d.
- The cost of conventional methods of digestate disposal should be higher than 50 €/t.
- The technology should match the regulatory requirements regarding emissions.

[13] Food waste often contains plastic packaging.

Given the problems of slag formation, deposits, and corrosion during digestate combustion, Z. Wang et al. (2024) mention co-combustion with other types of fuel as a solution to these problems, which also leads to a reduction in emissions. Compared to combustion of the digestate as a sole feedstock, Tyagi et al. (2022) also mention the following advantages of co-combustion of the digestate solid fractions at Waste-to-Energy plants. Since such power plants have a relatively high fuel flexibility and the most advanced cleaning systems for exhaust gases, co-combustion reduces the environmental impact. The authors also mention that economically retrofitting existing equipment is preferable to constructing a new processing facility. Nevertheless, the moisture content of the digestate remains a critical parameter for its optimal combustion (Z. Wang et al., 2024). As the authors mention, the value of this parameter should be less than 10%.

Information on possible technical solutions for thermochemical conversion and incineration of the digestate is in Appendix 7, and in Appendix 8 in terms of the digestate transportation to third parties for further processing (see Subsection 3.4 below).

3.3 Economic feasibility of the digestate processing

From an economic perspective, there are three key parameters, which affect economic feasibility of the digestate processing: “the size of the plant, the allocation of heat produced by the plant, and the share of digestate transport and storage costs the plant operator has to bear” (Herbes et al., 2020, pp. 2, 6, 10). Investigating the entire value chain of the digestate processing (see Figure 21 below), the authors note the following:

> The third factor decisive to the investment valuation is the share of costs for storage, transport and distribution of digestate that has to be borne by the biogas plant. This share obviously depends on the plant’s bargaining power vis-à-vis the customer. In nutrient-rich regions and/or in regions with many biogas plants, farming customers have substantial bargaining power and can ask fees for taking digestate off the plant. In other regions, biogas plants may be able to negotiate a price for their digestate. (Herbes et al., 2020, p. 6)

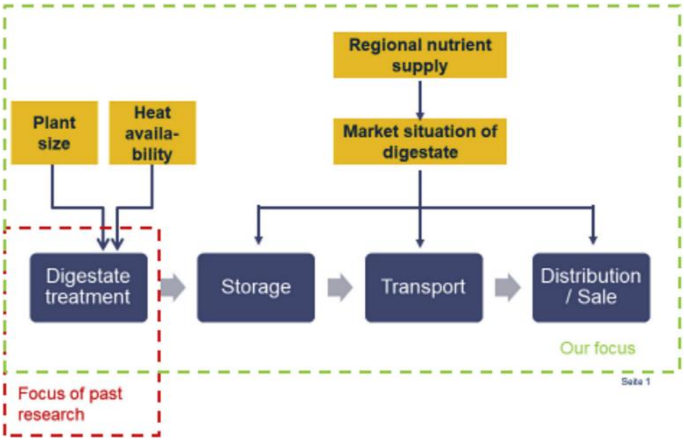

Figure 21. Research scope compared to past studies (Herbes et al., 2020).

Considering, for example, that digestate sold to farms generates a revenue based on the price of the nitrogen (€843/kg) and phosphorous (€875/kg), regarding the biogas plant with substrate input 13,383 t per year equipped by CHP[14] and used the off-heat in digestate processing, and plant operator bears the transport cost (a fixed transport distance of 300 km by truck), the authors show that "an investment into any of the processing technologies yields a positive NPV[15], i.e. all technologies are advantageous compared to not investing and using the raw digestate" (Herbes et al., 2020, p. 7). According to Table 8 of the publication, a belt dryer, employed in combination with a screw press, generates NPV €218,750 to €319,200, depending on the share of costs for digestate storage, transport, and application. At the same time, the authors note that some treatments, such as biochar production, are omitted due to their commercial impracticability.

Gamaralalage et al. (2025) considered the life cycle of biochar production from food-waste digestate at 70% moisture content employing HTC with post-carbonization[16] (HTC-PC) at a capacity of 20 kilotons per annum. There are two scenarios (cases) considered: the base case, where HTC-PC and AD facilities are co-located[17], eliminating the need for digestate transport, and the digestate transport case, where HTC-PC facilities are

[14] CHP with installed electrical capacity 500kW (electrical efficiency 38%) and installed thermal capacity 524kW (thermal efficiency 40%).
[15] NPV - Net Present Value.
[16] Post-carbonization is used to produce stable biochar from hydrochar.
[17] On-site biochar production

centralized and transportation is carried out by 25 t-capacity lorries over a distance of 37km. The authors mention annualised CAPEX, fixed OPEX, and, depending on the market situation, a gate fee for digestate processing as the main essential factors (parameters) to the economic viability of this technology. In addition to these factors, the authors emphasize that transportation cost significantly affects biochar production costs. For example, for the scenarios considered in the publication, biochar production cost more than doubled due to the digestate transportation (see Figure 22 below). Assuming the gate fee of £65 per tonne of the digestate[18], biochar production cost was £88 per tonne in the base case (or £759 without the gate fee), and £183,9 per tonne in the digestate transport case (or £858 without the gate fee). The break-even gate fees were £74 per tonne of the digestate in the base case and £84 per tonne of the digestate in the digestate transport case. Both values are lower than the fee of £93 per tonne associated with incineration (see Figure 23 below). The authors conclude that biochar production from food waste digestate can be a cost-effective method, which is competitive with other carbon dioxide removal technologies, especially in the case of co-location of the biochar production with AD facilities.

Besides the above-mentioned factors, Romano et al. (2023) highlight that plant capacity strongly influences the economic feasibility of hydrochar production. For example, in the case of using HTC for olive tree pruning, the break-even selling price of the hydrochar should be higher than 590 EUR/ton for a plant capacity of 2500 tons of raw material annually and 390 EUR/ton for a plant capacity of 9900 tons of the feedstock annually. The latter value, as the authors note, is comparable to current prices for traditional coal. The authors point out that other factors, such as valorisation and utilization of all by-products of the process, as well as possible integration of HTC processes with AD, should be considered.

Considering the different economic estimates in the publications mentioned in this subsection, since the current project is associated with small-scale production, centralised digestate processing, in particular centralised thermochemical conversion of the digestate, is one of the economically feasible options. Therefore, the next

[18] The average value is between £37 for in-vessel composting and £93 for incineration.

subsection is related to the topic of digestate transportation to third parties for further processing (centralised digestate processing).

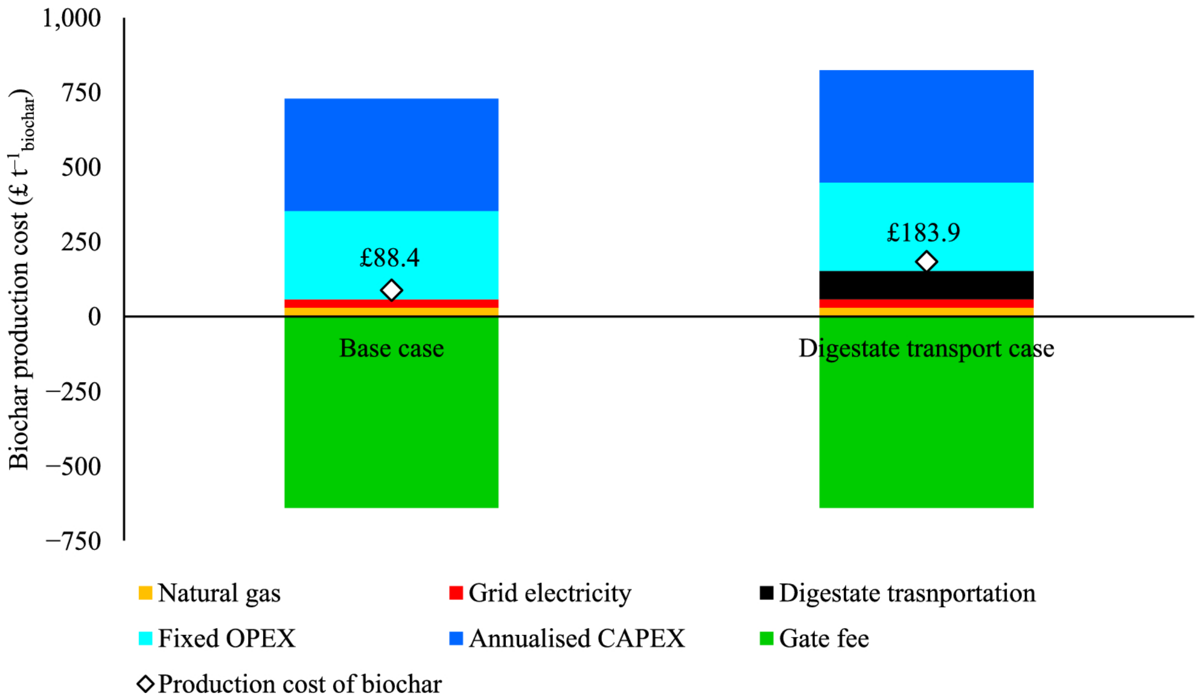

Figure 22. Production cost of 1 tonne of biochar (Gamaralalage et al., 2025)

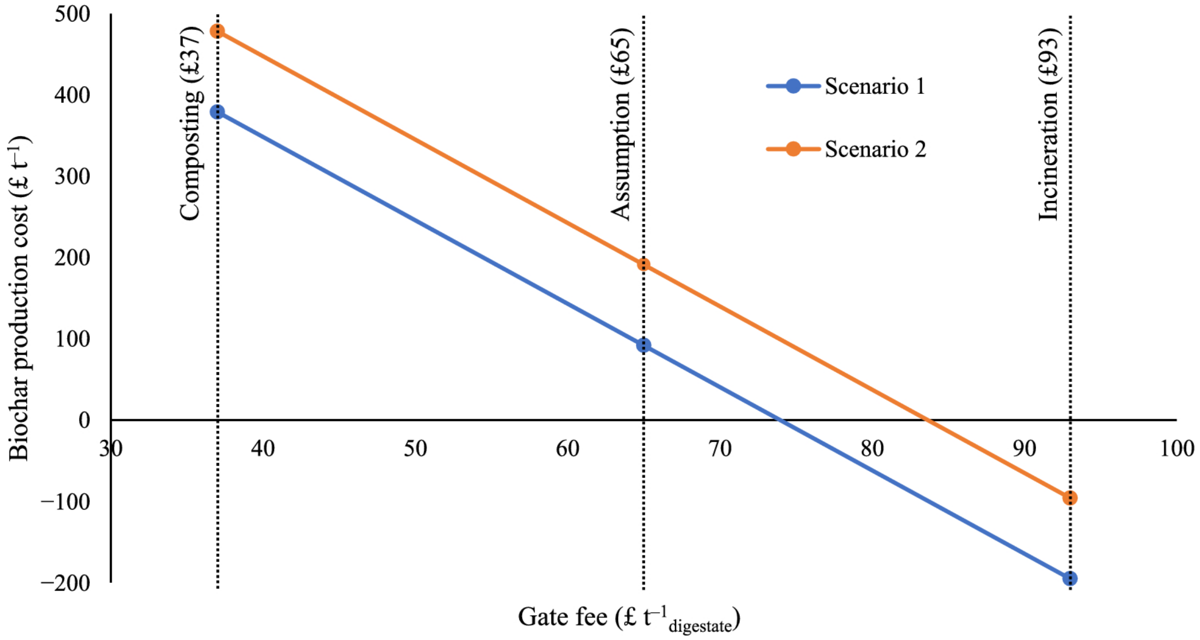

Figure 23. Gate fee effect on biochar production cost (Gamaralalage et al., 2025). Scenario 1 is the base case, Scenario 2 is the digestate transport case.

3.4 Digestate transportation. Final diagram of the digestate processing

Assuming that the digestate meets the requirements for raw materials for thermochemical conversion or fuel requirements, its transportation makes sense at a certain distance between biogas plants and the digestate processing facility, even based on the costs of the digestate drying (see Subsection 2.3.2). Considering the effect of transport distance on the total operational cost of selected digestate management at large-scale biogas plants (30 000 – 100 000 ton of feedstock annually), Feiz et al. (2022) note, for example, that for Sweden, full processing of the digestate from manure by using centrifuges and ammonia stripping makes sense after 70 km.

As the next example, Figure 24 below presents estimates of the costs of transporting biogas digestate for large biogas plants (Drosg et al., 2015). These costs are compared with digestate treatment processes (see Figure 25 below) such as solid-liquid separation, evaporation, and membrane filtration, which are, obviously, applied to the digestate from conventional wet AD (Drosg et al., 2015). The authors note that land application of the digestate is usually more attractive from an economic perspective, but as the distance between biogas plants and the digestate application places increases, digestate processing becomes more cost-effective. The authors believe that the economic feasibility of digestate processing should be determined on a case-by-case basis, considering synergistic effects such as freshwater replacement and the use of excess heat.

The above-mentioned cost estimates and comparisons mainly concern conventional wet AD. Based on current project parameters, using logistics calculator provided by Dr Pasi Makkonen and considering the following parameters and conditions – 40-m^3 trucks are used, loading/unloading time is 0,5h, average speed is 65km/h, salary is 30 €/h, average consumption is 0,5 l/km, investment in trucks is 250 k€ and in containers is 35 k€, maintenance is 2,5% of the total investment, interest rate is 6%, as well as other operating cost – we can obtain the values of normed digestate transportation cost, for example, for two cases – (1) transportation of the digestate from SBR only (450 ton/a) and (2) joint transportation of the digestate from both SBR and wet AD reactor(s) (2027 ton/a) – which are shown in Figure 26 below where we can see the scale effect. It makes sense to consider digestate transportation costs in comparison with drying and/or thermochemical conversion of the digestate at biogas plants after leaching/dry AD in SBR, as well as after conventional wet AD, taking into account the requirements for raw materials for thermochemical conversion or fuel requirements for incineration. The possible solutions for digestate transportation to third parties and information about required fuel (waste) parameters are in Appendix 8.

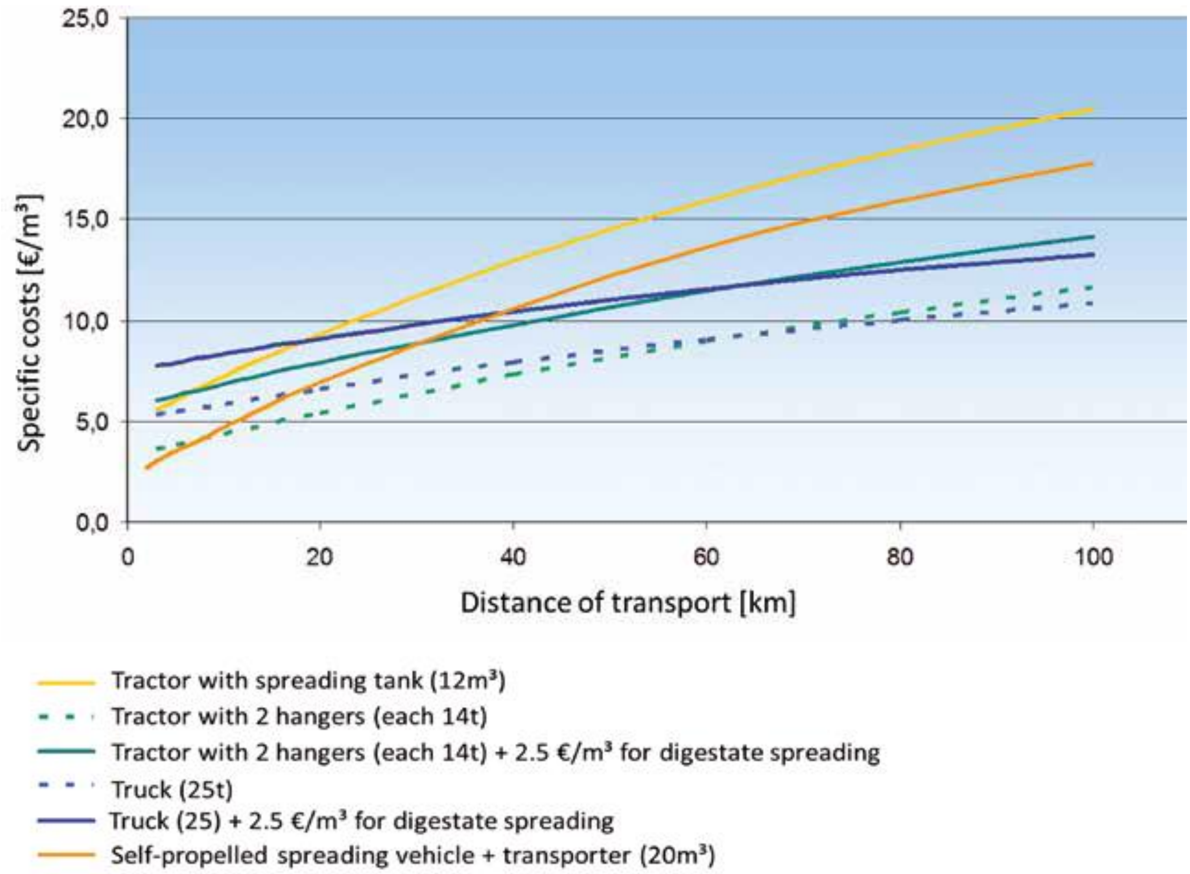

Figure 24. "Costs of digestate land application depending on distance of transport (Josef Bärnthaler et al., 2008). The stippled curves show only transportation costs, without costs for application" (Drosg et al., 2015)

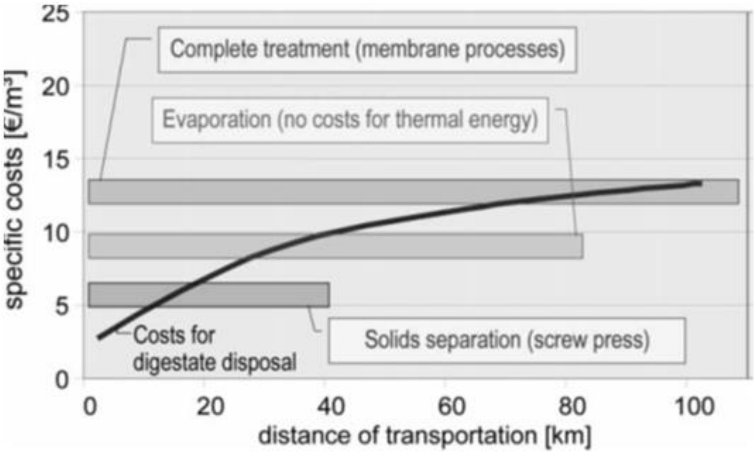

Figure 25. "Comparison of cost ranges for specific treatment options versus costs for digestate disposal (Fuchs & Drosg, 2013)" (Drosg et al., 2015).

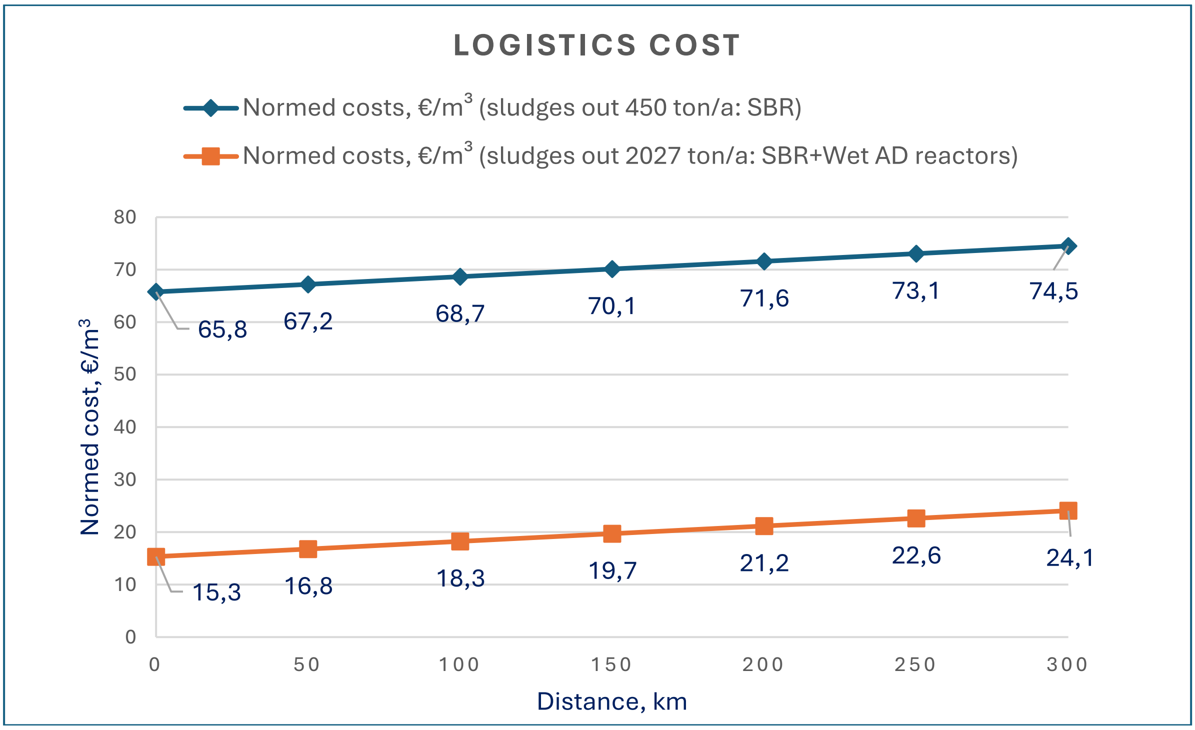

Figure 26. Logistics cost.

Based on the above-mentioned economic considerations (see also Subsections 3.3), digestate transportation to third parties for further processing (for example, for thermochemical conversion or incineration at Waste-to-Energy plants) has been added to the set of possible processing routes (see Figure 27 below). Since the project involves the joint operation of the conventional wet AD reactor(s) and slope bottom reactor(s), the diagram shows both groups of the digestate treatment processes: after wet AD (depicted by black coloured dotted lines) and after leaching/dry AD in SBR (depicted by blue coloured solid and dashed lines). In addition, the links for integration between Wet AD and HTC, for both centralized and on-site options, have been added (see footnote 7 in Subsection 3.2 and the corresponding text). The blue solid lines indicate possible options to bypass (except) the digestate drying process in case of sufficiently low moisture content and/or more advantageous transportation to third parties for further digestate conversion.

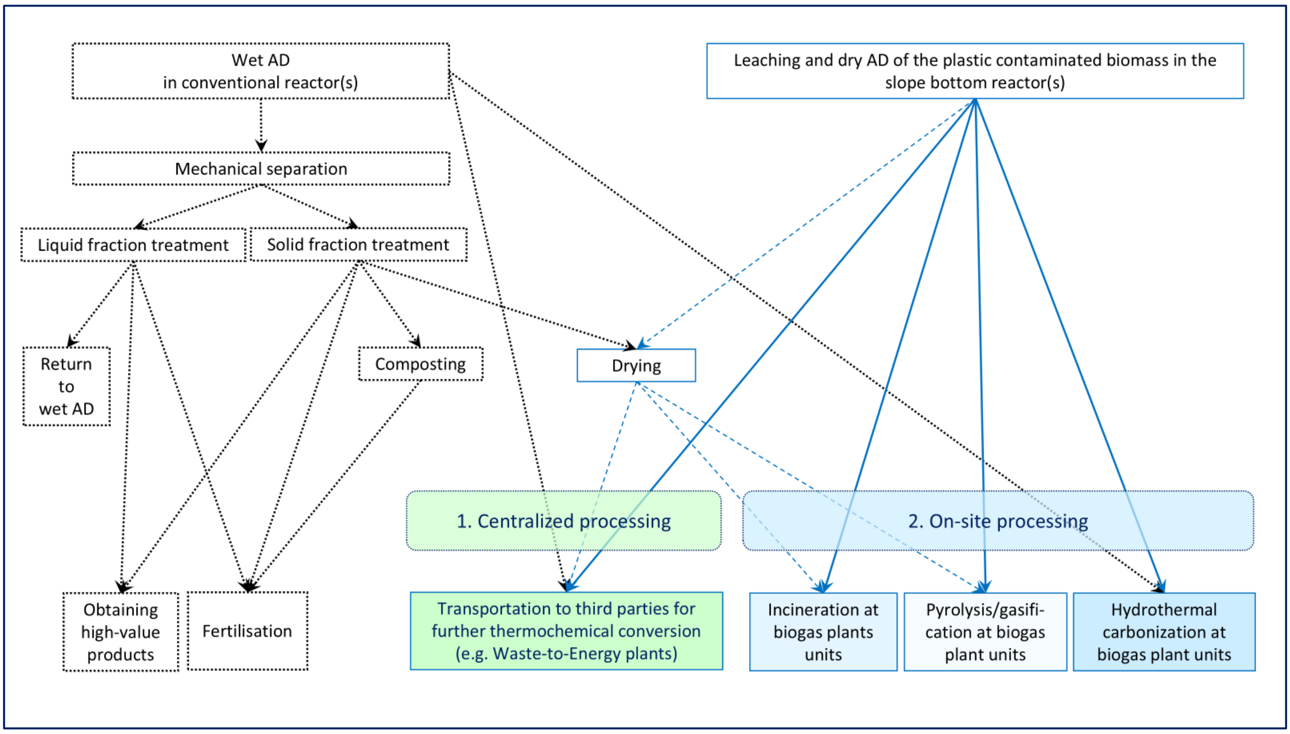

Figure 27. Possible routes for digestate processing within the frame of the current project (final diagram).

4 Conclusion

Based on the publications mentioned in Sections 2 and 3, possible routes for digestate processing for the current project are theoretically selected (see Figures 15 and 27 above). In general, for our case, thermochemical conversion of the digestate (incineration, gasification, pyrolysis, and hydrothermal carbonization) is preferable both for processing digestate with high solid content and converting plastic contamination into valuable products. Moreover, digestate incineration, for example, is preferable economically and environmentally to digestate landfilling or composting. There are two options for processing high-solid and plastic-contaminated digestate: transportation to third parties for further thermochemical conversion (centralized processing) and thermochemical conversion at biogas plant units (on-site processing).

Among the processes of thermochemical conversion mentioned above, waste incineration is currently characterized by a relatively high level of maturity, since the Waste-to-Energy plants operate in the real sector of the economy (see Appendix 8). The most important critical factors for digestate incineration are the energy properties of the digestate, such as calorific value, moisture content, and ash content, as well as the transport distance between biogas plants and Waste-to-Energy plants. Due to the low energy properties of the biomass gasification products, this process is currently suitable for industrial scale (not suited for small-scale production) and could be considered in terms of co-gasification with other substances. The low calorific value of biomass pyrolysis products, the complexity of their composition, and the immaturity of co-pyrolysis of biomass in combination with plastic inclusions also make this technology a future or large-scale solution. Regarding energy efficiency, hydrothermal carbonization of the digestate offers advantages, such as no need for preliminary drying of the digestate, lower process temperatures compared to pyrolysis/gasification and incineration, and lower CO_2 emission compared to digestate incineration. Practically, the most frequent use of biomass hydrothermal carbonization is the Waste-to-Energy process.

In summary, one of the significant problems is the relatively limited practical application of the thermochemical conversion processes for digestate treatment due to the immaturity of the technology, to a greater or lesser extent depending on the type of technology. This situation necessitates achieving economies of scale in large-scale production. The several proposals from manufacturers of thermochemical equipment, which are mainly suited for relatively large-scale production, also indirectly confirm this situation. Since the current project is associated with small-scale production, the most likely option appears to be centralized thermochemical treatment or incineration of the digestate, depending on the biogas plant size and the distance of the digestate transportation, which can be determined on a case-by-case basis.

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Appendices

Appendix 1. Nutrient content of the digestate.

Table 1. Origin and composition of anaerobic effluents (Bauer et al., 2021)

Origin	Raw Material	pH [-]	TS [a] [%]	VS [b] [%]	NH_4-N [c] [g kg^{-1}]	TKN [d] [g kg^{-1}]	P [e] [g kg^{-1}]	References
Agricultural residues/ renewable materials	n.d. [f]	7.5–8.4	6.41–24	4.42–18.5	0.03–4.1	0.09–5.04	0.46–5.76	(Barampouti et al., 2020) *
	Co-digestion manure + crops and/or industrial waste	5.6–8.3	1.5–24	0.93–18.5	0.01–1.63	0.02–12.1	0.002–2.4	(Barampouti et al., 2020) *
	Corn silage, manure, agricultural residues	7.7–8.1	6.1–8.3	4.4–6.3	4.9–6.1	7.6–9.6	n.d. [f]	(Drosg et al., 2015)
	Crop digestion with manure	7.7–8.0	6.5–8.6	4.8–6.4	2.3–4.2	4.3–6.1	n.d. [f]	(Drosg et al., 2015)
	Crop digestion	7.4–7.9	6.2–8.6	4.8–6.2	1.5–2.5	3.6–5.2	n.d. [f]	(Drosg et al., 2015)
	Crop digestion	7.2–7.9	7.8–9.0	5.7–6.7	1.3–3.6	4.6–6.3	n.d. [f]	(Drosg et al., 2015)
	Corn and grass silage	7.6–8.0	6.6–9.3	4.8–6.9	1.3–2.4	3.6–4.9	n.d. [f]	(Drosg et al., 2015)
	Manure	7.3–8.6	2.2–9.2	1.49–6.9	0.06–0.93	0.01–0.57	0.007–0.2	(Barampouti et al., 2020) *
Industrial residues	Brewers' spent grains	7.3–7.5	5.3–5.8	4.7–5.3	1.9–2.3	2.3–3.1	n.d. [f]	(Drosg et al., 2015)
	Slaughterhouse waste	7.9–8.3	2.2–4.9	1.6–3.9	5.3–7.7	6.4–8.1	n.d. [f]	(Drosg et al., 2015)
	Thin stillage—bioethanol by-product	7.7–8.1	1.7–2.8	0.9–1.6	2.2–2.8	3.0–4.3	n.d. [f]	(Drosg et al., 2015)
Food waste/residues	n.d. [f]	7.9–8.3	1.4–7.88	0.56–5.78	0.01–0.67	0.01–098	0.002–0.1	(Barampouti et al., 2020) *
	Bio waste	7.6–8.1	2.5–4.7	1.4–2.7	1.5–5.6	3.0–6.8	n.d. [f]	(Drosg et al., 2015)

	Bio and food waste, blood	8.0–8.3	3.9–4.1	2.4–2.8	5.1–7.2	6.4–8.1	n.d. [f]	(Drosg et al., 2015)
	Bio and food waste	7.3–7.9	1.6–3.3	1.0–1.7	0.6–1.5	1.4–2.3	n.d. [f]	(Drosg et al., 2015)
	Bio and food waste, blood, food industry residues	7.8–8.2	5.6–8.1	3.0–4.5	3.1–4.1	4.2–6.7	n.d. [f]	(Drosg et al., 2015)
	Manure, slaughterhouse, bio, food, and kitchen waste	8.0–8.3	5.7–7.2	4.1–5.6	6.8–8.6	8.4–10.8	n.d. [f]	(Drosg et al., 2015)
	Kitchen food waste	8.0	5.9	n.d. [f]	4.02	n.d. [f]	0.67	(Fernandes et al., 2020)

[a] TS—total solids, [b] VS—volatile solids, [c] NH_4-N—ammonia nitrogen, [d] TKN—total Kjeldahl nitrogen, [e] P—phosphorous, [f] n.d.—not defined/determined, * values converted into fresh matter.

Table 2. Main digestate characteristics obtained after AD of different feedstocks (Kovačić et al., 2022).

Parameter	**Unit**	**Values**	**References**
EC	μS cm^{-1}	100–642	(Elalami et al., 2020), (Beggio et al., 2019)
pH	-	5.6–8.6	(Li, Luo, et al., 2018),(Elalami et al., 2020), (Beggio et al., 2019), (Alburquerque, de la Fuente, Campoy, et al., 2012), (Alburquerque, de la Fuente, Ferrer-Costa, et al., 2012), (Walsh et al., 2012)
DM	%	0.7–90	(Li, Luo, et al., 2018),(Elalami et al., 2020), (Beggio et al., 2019), (Alburquerque, de la Fuente, Campoy, et al., 2012), (Alburquerque, de la Fuente, Ferrer-Costa, et al., 2012), (Walsh et al., 2012)
OM	% DM	15.6–98.0	(Elalami et al., 2020), (Beggio et al., 2019)
Total C	% DM	10.4–58.7	(Li, Luo, et al., 2018),(Elalami et al., 2020), (Beggio et al., 2019), (Alburquerque, de la Fuente, Campoy, et al., 2012), (Walsh et al., 2012), (Głowacka et al., 2020)
Total N	% DM	0.2–20.5	(Li, Luo, et al., 2018),(Elalami et al., 2020), (Beggio et al., 2019), (Alburquerque, de la Fuente, Campoy, et al., 2012), (Alburquerque, de la Fuente, Ferrer-Costa, et al., 2012), (Walsh et al., 2012), (Głowacka et al., 2020)
NH_4^+-N	g kg^{-1} DM	2.1–17.9	(Elalami et al., 2020), (Beggio et al., 2019), (Makádi et al., 2012)

Ca	g kg^{-1} DM	0.6–98.5	(Elalami et al., 2020), (Alburquerque, de la Fuente, Campoy, et al., 2012), (Alburquerque, de la Fuente, Ferrer-Costa, et al., 2012), (Walsh et al., 2012), (Głowacka et al., 2020)
K	g kg^{-1} DM	0.9–110.5	(Elalami et al., 2020), (Beggio et al., 2019), (Alburquerque, de la Fuente, Campoy, et al., 2012), (Alburquerque, de la Fuente, Ferrer-Costa, et al., 2012), (Walsh et al., 2012), (Głowacka et al., 2020)
Mg	g kg^{-1} DM	0.1–14.1	(Elalami et al., 2020), (Alburquerque, de la Fuente, Campoy, et al., 2012), (Alburquerque, de la Fuente, Ferrer-Costa, et al., 2012), (Głowacka et al., 2020)
P	g kg^{-1} DM	0.1–54.0	(Elalami et al., 2020), (Alburquerque, de la Fuente, Campoy, et al., 2012), (Alburquerque, de la Fuente, Ferrer-Costa, et al., 2012), (Walsh et al., 2012)

Appendix 2. Possible digestate management processes.

There are several classifications of the processes of the digestate treatment. For example, some classifications of the processes are presented in Figures 1 – 7 below.

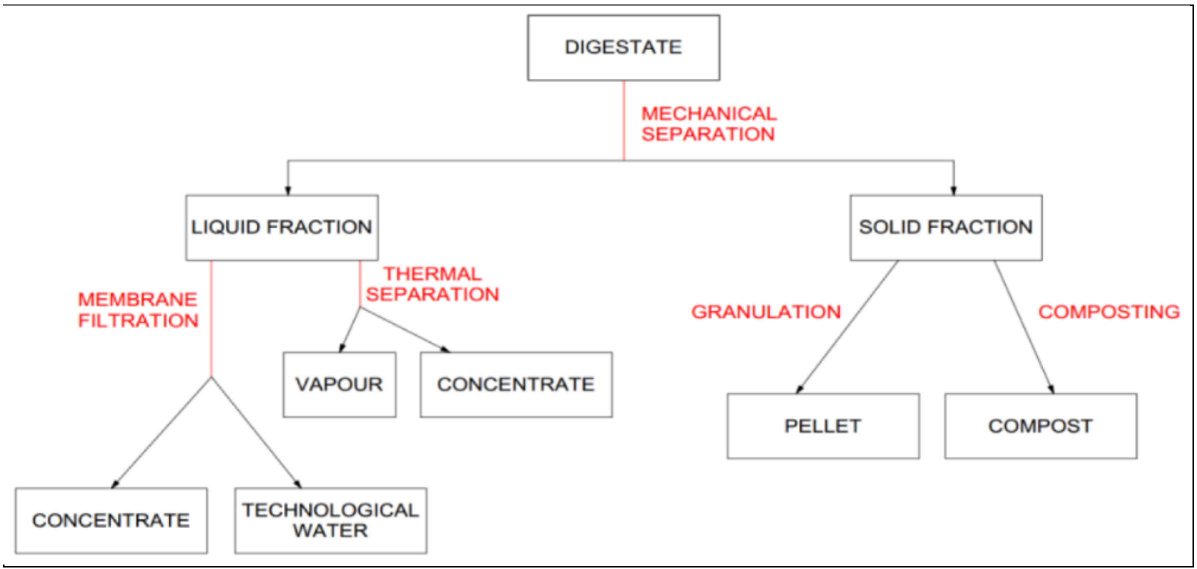


Figure 1. Possibilities of processing the digestate (Nowak & Czekała, 2024)

Nowak and Czekała (2024, p. 6) note that

> "The processing of digestate can be divided into two types, according to (Lyons et al., 2021). The first case of processing is called partial in the literature and is based on methods such as mechanical separation, among others. The second creates the possibility of complete processing of the digestate, which includes separation into solids, minerals, and water. The unlimited possibility of processing the pulp is associated with combining several technologies, requiring a higher energy input than partial separation".

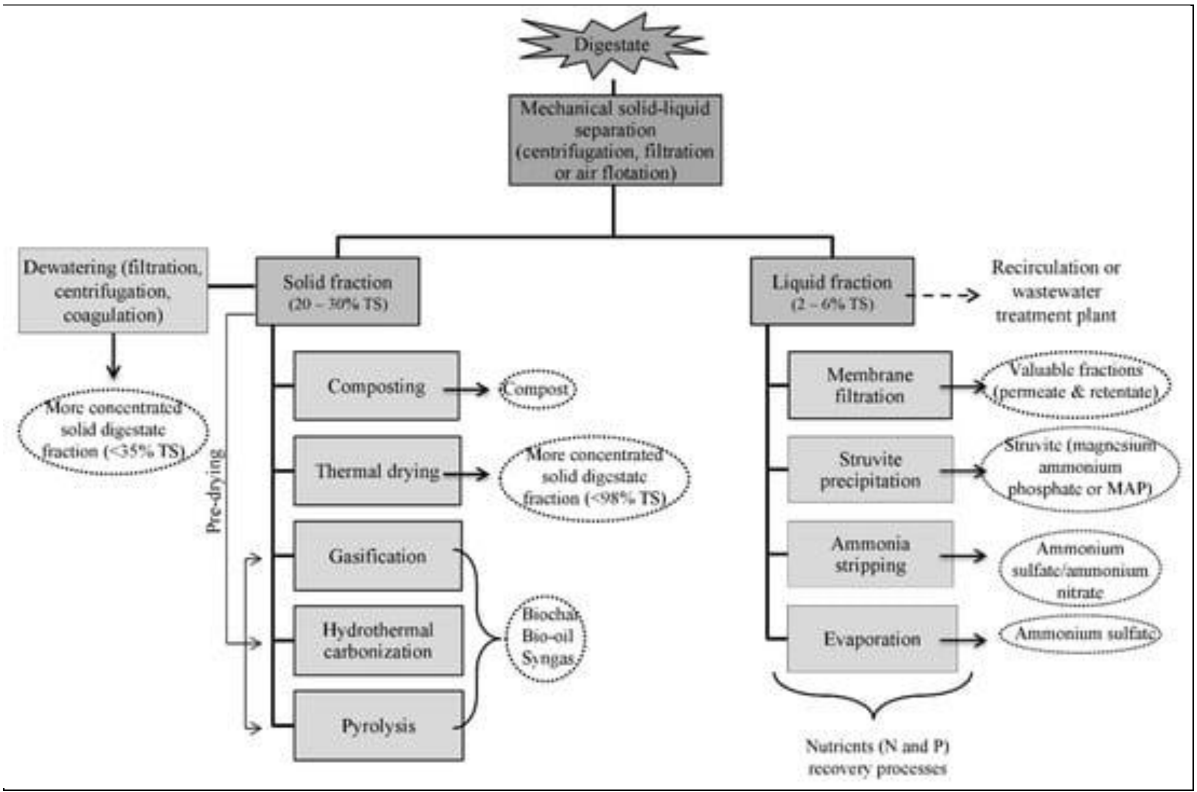


Figure 2. Most commonly applied digestate valorization processes (Kovačić et al., 2022, p. 13)

Kovačić et al. (2022, p. 13) also note that

> ”In general, DG treatment processes can be classified into two different approaches: (a) Partial treatment—this aims to reduce the volume or separate it into solid and liquid fractions that can be more easily handled or stored. It is usually the first step in the DG treatment and is less energy demanding and cheaper if compared to (b) complete purification—where the valuable ingredients are separated and concentrated while the remaining liquid fraction is purified, allowing reuse in the AD process or direct discharge to a water body (Fuchs & Drosg, 2013; Plana & Noche, 2016)”.

The authors suppose that

> “Except for specific cases, such as some advanced technologies and membrane filtration technologies, all processes described below have already been applied at a large scale (Monfet et al., 2018). Most of the DG treatment technologies that are currently available on the market work on volume reduction and concentration of nutrients (*AgriKomp*, n.d.)”.

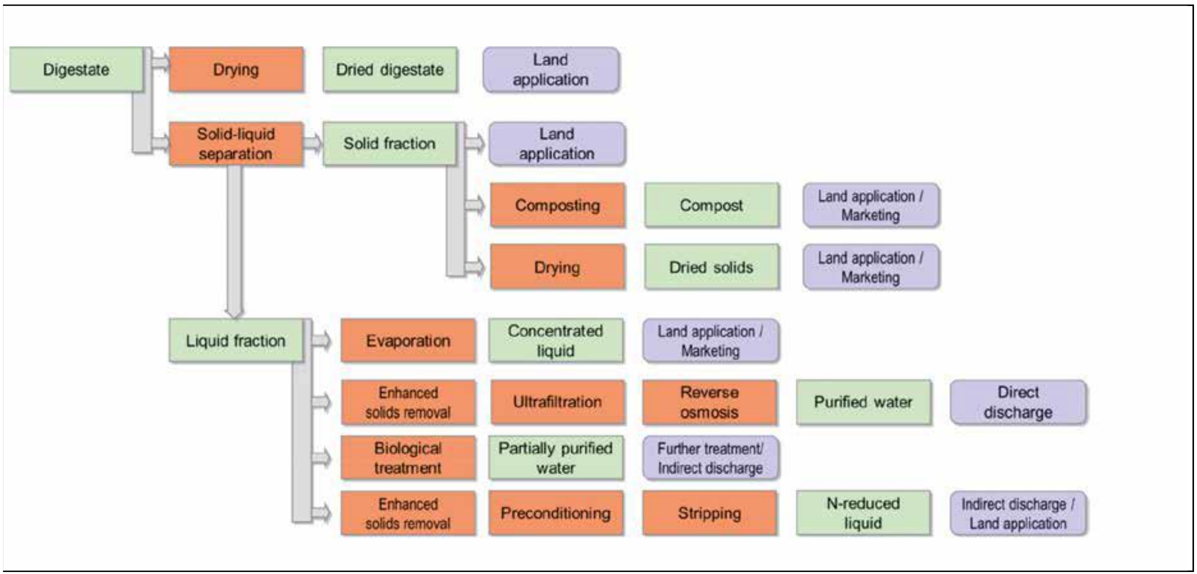


Figure 3. Overview of viable options for digestate processing (Fuchs & Drosg, 2013)

Fuchs and Drosg (2013, p. 9) note that

> "Digestate processing can be partial, primarily for the purpose of volume reduction, or it can be complete, refining digestate to for example pure water, a solid biofertiliser fraction, and fertiliser concentrates" and "While partial processing uses relatively simple and cheap technologies, for complete processing different methods and technologies are currently available, with various degrees of technical maturity, higher energy input, and higher investment and operating costs".

Regarding the first stage of the digestate treatment, Kovačić et al. (2022, p. 13) mention that "Separation of the DG into a solid and a liquid fraction is a simple and low cost-effective technology (Tambone et al., 2017), which is usually carried out before any further post-treatment of the DG (Zeng et al., 2016)".

As we can see in the figures above, based on scientific publications, usually after AD, the first step of digestate processing is solid-liquid separation (Carraro et al., 2024; Kovačić et al., 2022; Nowak & Czekała, 2024; Tyagi et al., 2022) and (or) digestate drying (Fuchs & Drosg, 2013). The next steps of the digestate processing involve different technologies both for the solid fractions and the liquid ones.

The next route of liquid fraction processing is associated with microalgae cultivation. L. Bauer et al. (2021, p. 1) mention that "Microalgae grown on digestate can be used to produce various products (e.g., bioenergy, animal feed, bioplastics, and biofertilizers)". From an energy recovery perspective, the authors note that (Bauer et al., 2021, p. 2):

> "Recently, new energy-concepts using microalgae have been introduced. After extraction of lipids from microalgal biomass to produce biodiesel, the residual biomass can be fermented in two steps to produce hydrogen and methane, so-called bio-hythane (Ghimire et al., 2017). Moreover, the application of microalgae in microbial fuel cells, producing electricity, is being explored (Saratale et al., 2017)".

The graphical abstraction and possible processing routes are shown in Figure 4 and 5 respectively.

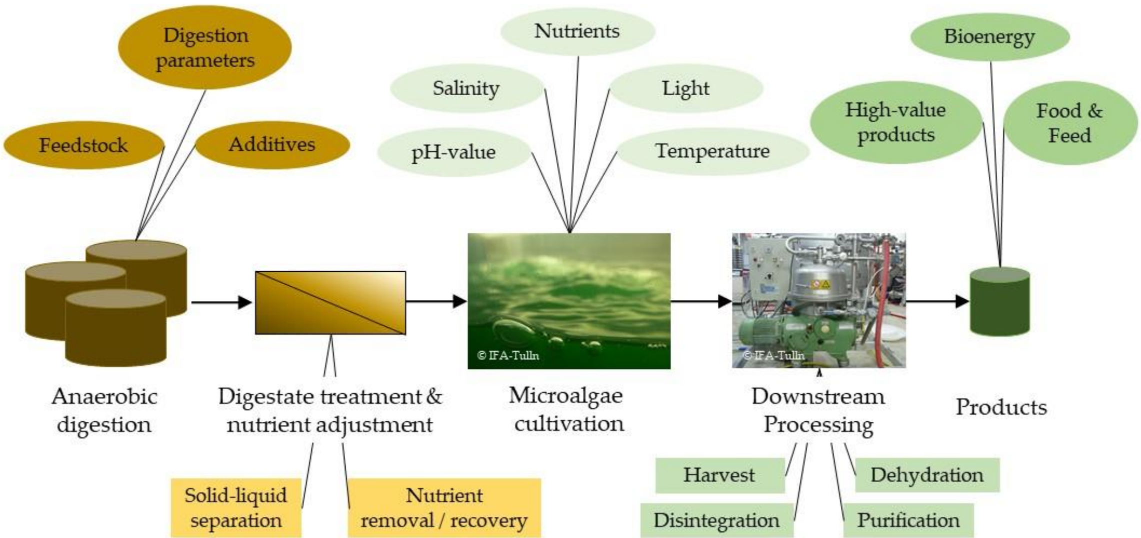


Figure 4. Graphical abstraction from MDPI web site (Bauer et al., 2021)

Logan and Visvanathan mention biological treatment of the liquid fraction (2019, p. 34):

> Biological oxidation reduces concentration of BOD[19] and ammonia, before final discharge of digestate. Typically, the digestate is aerated in the presence of bacteria which oxidize the BOD and ammonia. The treatment of liquors in this manner is well proven but can have high operating costs. The process produces a biological sludge as a by-product which can be returned as a feedstock to the digester. Examples of these processes include membrane bioreactors, sequencing batch reactors, moving bed bioreactors, and the SHARON (Single reactor system for High activity Ammonium Removal Over Nitrite) process (Frischmann, 2012).

[19] Biological oxygen demand

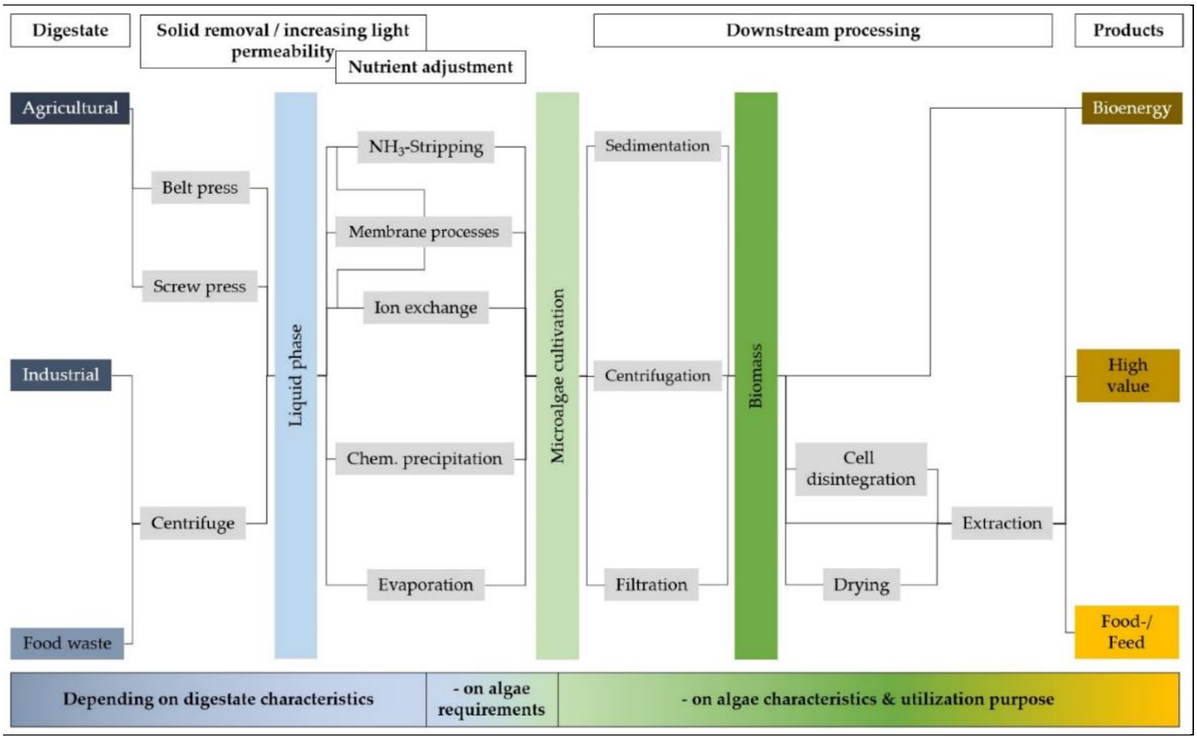


Figure 5. Overview of possible process steps for obtaining microalgae products by using digestate as nutrient source. Solids separation during digestate processing and microalgae harvesting can be enhanced by using precipitating or flocculating agents (Bauer et al., 2021, p. 5).

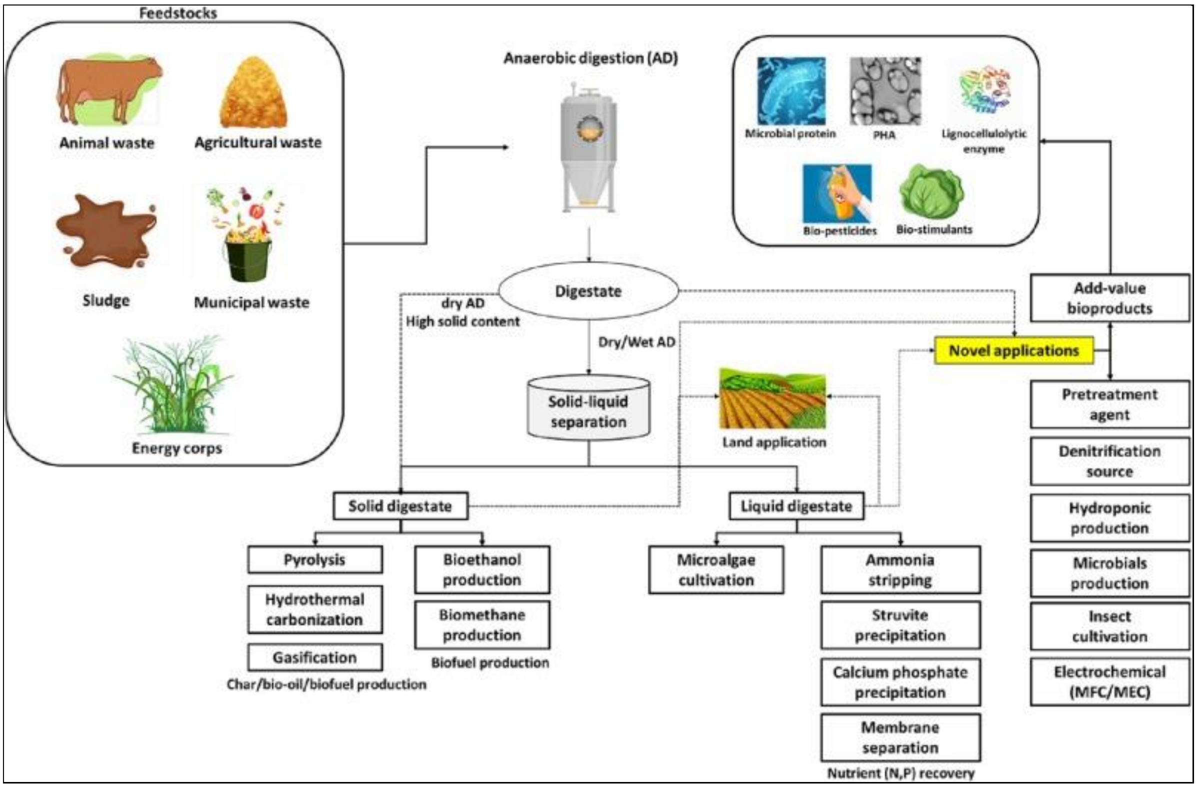


Figure 6. The outline of the techniques for digestate valorization (W. Wang et al., 2023).

Figure 6 above “outlines the digestate valorization routes other than the land application” (W. Wang et al., 2023, p. 2).

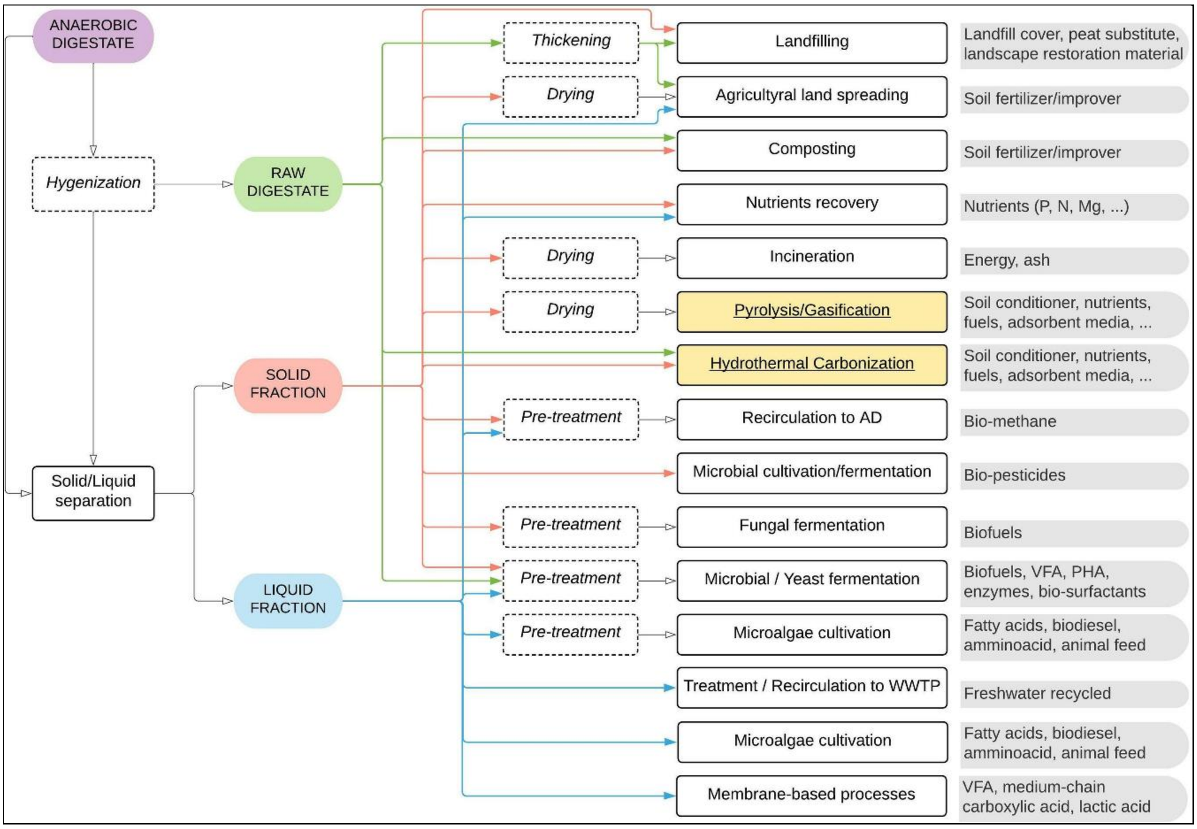


Figure 7. “Anaerobic digestate management: conventional solutions and emerging technologies. Black bordered boxes depict processes (thermochemical conversion processes in yellow), while dotted lines indicate optional processes; grey boxes show end-products”. (Catenacci et al., 2022, p. 4)

Appendix 3. Distribution of mass and nutrients after solid-liquid separation.

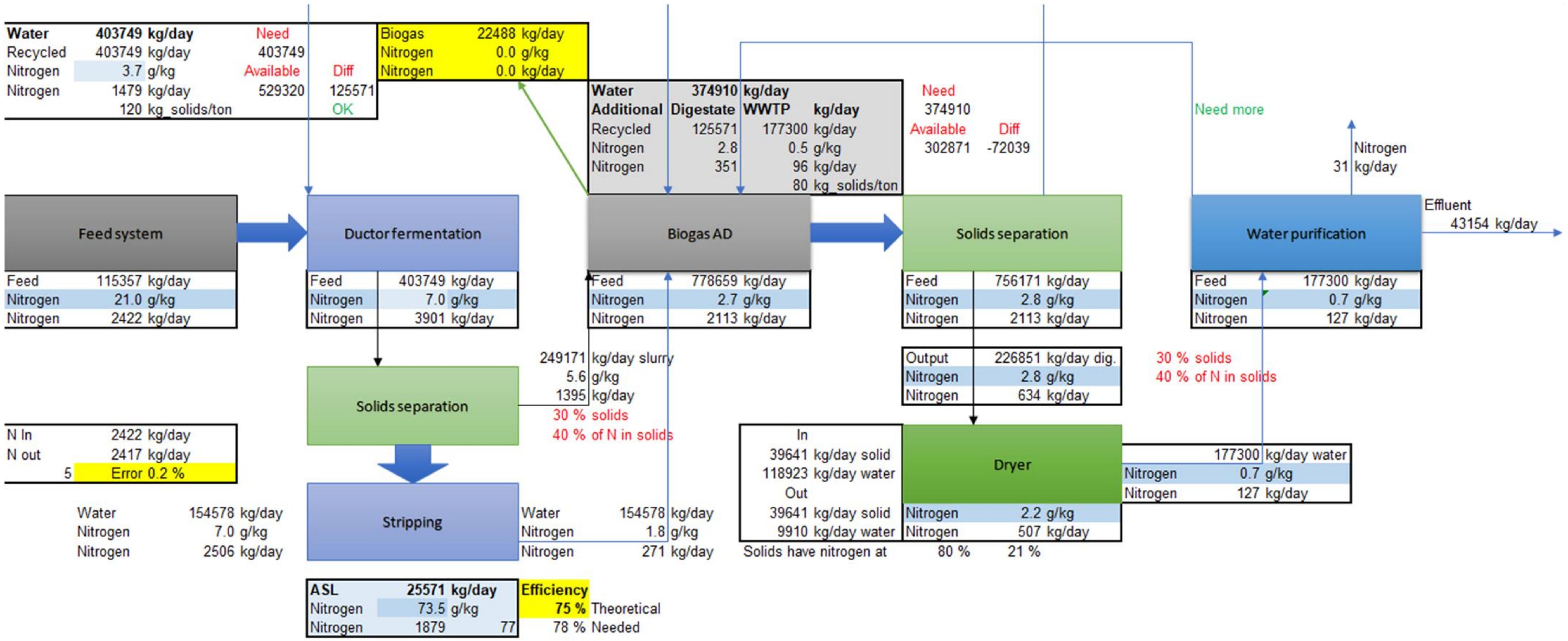
Table 1. Distribution of mass and nutrients after solid–liquid separation (Al Seadi et al., 2013; Bauer et al., 2021; Drosg et al., 2015)

	Unit	Liquid	Solids
Mass	[%]	80–90	10–20
TS [a]	[%]	40–50	50–60
VS [b]	[%]	35–45	55–65
Ash	[%]	50–60	40–50
TN [c]	[%]	65–75	25–35
NH_4-N [d]	[%]	70–80	20–30
P [e]	[%]	35–45	55–65
K [f]	[%]	70–80	20–30
C [g]	[%]	30–40	60–70

[a] TS—total solids, [b] VS—volatile solids, [c] TN—total nitrogen, [d] NH_4-N—total ammonia nitrogen, [e] P—phosphorous, [f] K—potassium, [g] C—carbon.

Appendix 4. Example of nitrogen balance calculation.

The calculation is provided by Dr. Pasi Makkonen (Karhubetoni Oy).



Ductor decanters

From	62293 kg/day solids	To	62293 kg/day solids
12 %	341456 kg/day water	25 %	186878 kg/day water
d.s.		d.s.	**249171 kg/day sludge**

Digestate dewatering

From	39641 kg/day solids	To	39641 kg/day solids
6.6%	559257 kg/day water	25 %	118923 kg/day water
d.s.		d.s.	**158564 kg/day sludge**

Thermal drying

From	39641 kg/day solids	To	39641 kg/day solids
25 %	118923 kg/day water	70 %	16989 kg/day water
d.s.		d.s.	**56630 kg/day sludge**

Appendix 5. Comparison of digestate drying techniques.

Table 1. "Comparison of digestate drying techniques (Bennamoun et al., 2013)" (Salamat et al., 2022)

Drying technique	Advantages	Disadvantages	Specific energy consumption (kW h t^{-1} water removal)	Specific drying rate (kg m^{-2} h^{-1})
Convective drying	Design allowing easy process control Dried product used in agriculture	Relatively long drying time Bad odors Gaseous emissions	Belt dryer: 700–1140 Drum dryer: 900–1100 Flash dryer: 1200–1400	Belt dryer: 5–30 Drum dryer: 3–8 Flash dryer: 0.2–1
Conductive drying	No pollution of the heat carrying medium Steam and odor confinement VOC concentration is low Reduction of fire and explosion risks Dried product used in industrial applications	Relatively long drying time Sticky phase alters dryer performance	Disc dryer: 855–955 Paddle dryer: 800–885 Thin film dryer: 800–900	Disc dryer: 7–12 Paddle dryer: 15–20 Thin film dryer: 25–35
Solar drying	Use of free solar energy Pathogen free sludge Dried product used in agriculture During the same operation, important quantities are dried	Depends on climatic conditions Relatively long drying time High surfaces are needed	30–200 (in some cases until 1000)	–
Fry drying	Short drying time Possibility to employ used oil Dried sludge used for incineration Odor confinement No gaseous emissions Reduction of fire and explosion risks	High temperatures are needed	888	–
Superheated steam drying	No dust No volatile emission Pathogen free sludge Short drying time Low energy consumption	High temperatures are needed	–	–

Appendix 6. Digestate drying solutions.

This appendix contains technical proposals for digestate drying. First, Dr. Pasi Makkonen (Bikasu Oy) describes the superheated steam drying solution. Then, information retrieved from manufacturers' websites is presented.

I. Bikasu Oy. Drying by superheated steam[20]:

1. INTRODUCTION

Sludge drying is an essential process considering the end-use of the fiber product. The challenge is in transport and storage, as without proper drying, there is a large quantity of water to be transported with the solid material. There are two main parts in the drying:

1. Mechanical water separation.
2. Drying.

The mechanical water separation is performed by a device which uses a physical principle (molecule size difference, density difference) to remove as much water from the material as possible. Usually the product arrives at about 10 % solids content, and leaves the mechanical water separation at around 30 % solids content.

The best way to remove the water remaining after the mechanical separation is to use *thermal drying*, where the water is evaporated by a heat source, which can be flue gas, hot air, steam or a combination of these. Thermal drying can be *direct* where the heat media is in contact with the sludge, or *indirect* where a surface is heated, and this surface is in contact with the sludge, thus releasing the energy needed for evaporation.

2. THERMAL DRYING WITH SUPERHEATED STEAM

Direct drying with flue gas or air is well known, but the use of *superheated steam* is less common. Superheated steam is formed when water is heated above the steam saturation point, for instance at 100 kPa(abs) steam is saturated at 100 °C, and any temperature higher than this causes the steam to become superheated. Due to this, additional energy can be stored in the steam, and this energy can then be used for water evaporation. Saturated steam at 100 kPa(abs) and 100 °C has an enthalpy of 2676 kJ/kg, and at 150 °C the enthalpy is 2776 kJ/kg. This means that one kilogram

[20] Written by Dr. Pasi Makkonen, Bikasu Oy 08.02.2016

of such steam can evaporate 44 grams of water at 100 kPa(abs) and 100 °C. How to utilize this in drying? At the late 2000's, Mr. Heimo Välimäki came up with an interesting idea and design:

- What if external energy is used for making superheated steam, and this steam is then recirculated in a mixing chamber by using a special fan?
- What if this steam is formed by using the water which enters with the sludge?

Figure 1 shows the design and main parts of the SHS[21] dryer by Mr. Välimäki.

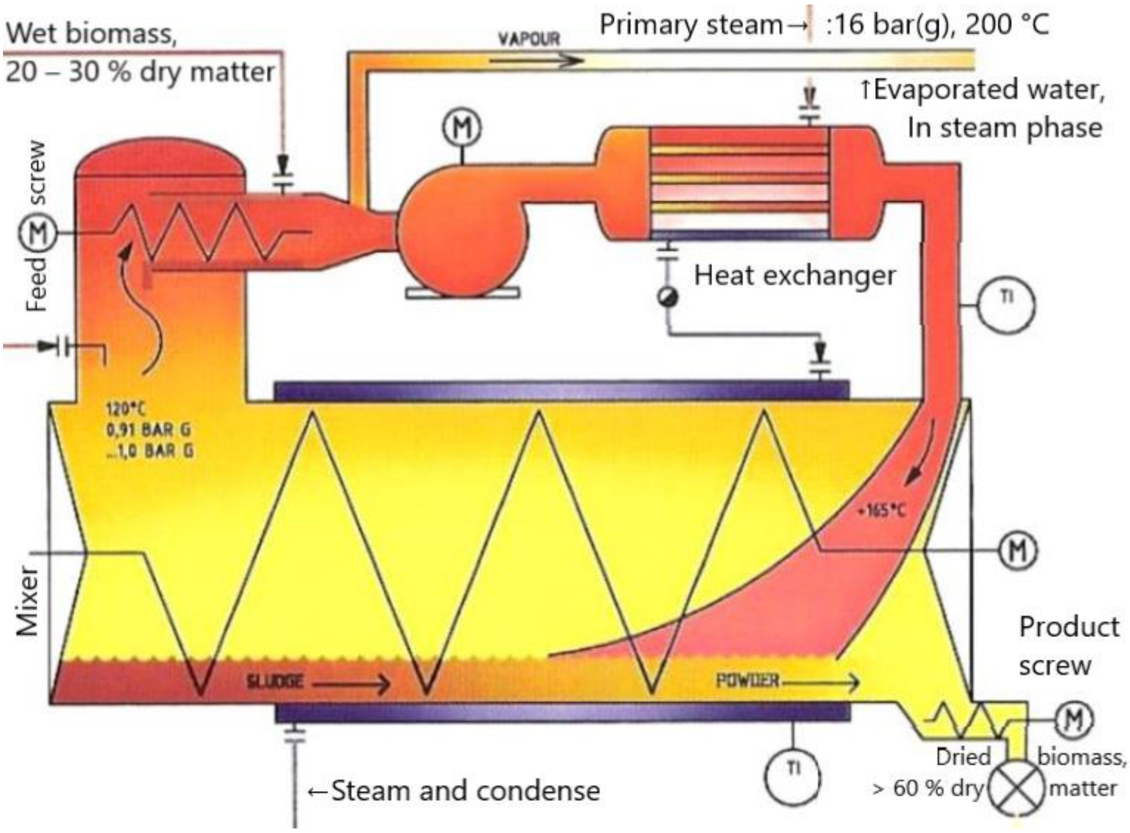


Figure 1. Illustration of a thermal dryer using superheated steam for sludge drying (the image has been adapted from the original file).

The external energy can be steam, hot air, flue gas or even electricity: the main point is that the drying chamber contains only sludge, water and steam: no risk of fire. In addition to this, superheated steam is a good leaching agent, and it also penetrates the structure of the sludge. By agitating the sludge during the drying, additional benefits can be achieved, such as good granulation. Naturally, if the residence time is sufficient, there is a high disinfectioning effect as well. And last but not least, the steam leaving the dryer still contains a significant amount of energy in a useful

[21] SHS – superheated steam.

form: as it is steam, it can be used in a second dryer, or condensed and thus converted to hot water, which can be used for heating or as an energy source in other processes.

2.1 Drying Capacity

The drying capacity (water removal capacity) can be expressed as:

- Amount of wet organic material dried in a time period.
- Amount of water evaporated during the drying per drying time.

As the SHS dryer is operated continuously, the latter method is the more useful. The evaporation rate can be determined:

1. Directly by measuring the amount of steam or condensate leaving the dryer.
2. Indirectly by measuring the input and output compositions of the sludge.

The SHS dryer allows the use of both methods. The drying rate is mainly dependent on the energy flow, which in turn mostly depends on:

- The performance of the superheater.
- The steam fan performance.
- Mixing inside the main chamber

At the current stage, one dryer unit can evaporate 2000 kg of water per hour; larger units are possible to construct, but the current sizes are optimal for most biogas plants of today.

2.2 Superheating and Steam Circulation

One essential part of the SHS drying process is the heat transfer in the *superheater*, i.e. the device which transfers the external heat to the circulating steam. The two mechanisms involved are the external heat transfer, which occurs from the source of energy to the structure of the heat exchanger, usually tubes, and internal heat transfer, which in turn is the transfer of heat to the steam.

In order to determine the local heat transfer coefficient, complex models involving the local geometries can be used. However, for the SHS dryer, a simplified approach can be taken, see Figure 2.

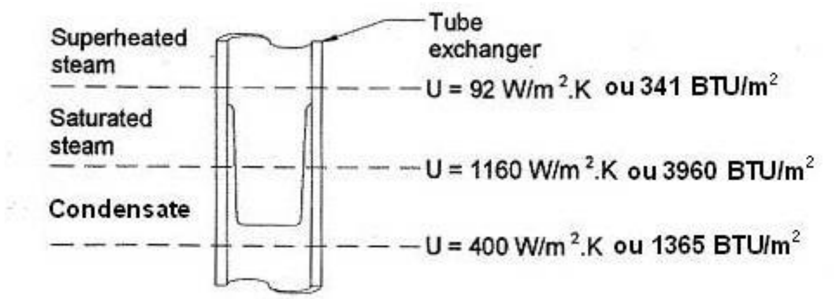


Figure 2. Local heat transfer coefficients for different forms of steam and water.

So, if the source of energy is saturated steam, the heat transfer from the steam to the structure is not the limiting factor, but the heat transfer from the structure to the superheated steam can be. We also need to evaluate the role of the structure.

2.2.1 Heat Flow Through the Structure

After the steam has released its energy, the energy flows through the structure. The factors contributing in the energy flow are:

- Structure material characteristics; namely conductivity.
- Material thicknesses in the structure.

As the wall thicknesses are only a few millimetres and the thermal conductivity of stainless steel type 304 is 15 W/(m °C), the heat flux through the structure is in the range of 1500 W/(m^2 °C), so the structure is not a bottleneck here. If there are significant deposits, the heat transfer can be greatly reduced.

2.3 Flue Gas as Energy Source

If flue gas (or hot air) is used instead of steam as the energy source, some additional calculation methods are needed. To achieve an estimate of the heat transfer coefficient from flue gas to structure, a correlation for heat transfer in turbulent conditions inside the superheater can be used.

It is usually beneficial to test all theories in laboratory scale, and in this case, an interesting finding has been that the heat transfer at the flue gas side behaves almost the same was as at the superheated steam side, so by dimensioning the superheated properly, the system works really well. This means that the dryer is actually a flue gas boiler as well.

2.4 Mixing

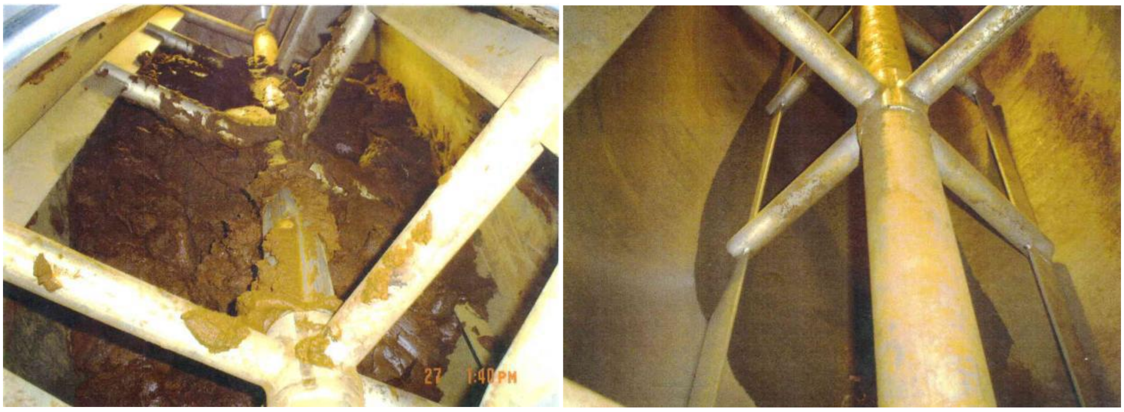
The role of the agitator inside the drying chamber is twofold:

- Mixing and breaking up the structure of the organic material.
- Heating of the organic material, as the agitator contains channels for steam.

Mixing and agitation are very important parts of the drying process, because without mixing, the organic material would form a pile with a very small surface area, and the water inside the organic material would require a very long time to find its way out. The agitation breaks down the structure of the organic material, at first as large lumps and later on in the drying process into smaller and smaller particles. This breaking down significantly increases the surface area, thus greatly helping the drying process.

3. PRACTICAL EXAMPLES

The SHS dryer has been originally designed for drying of waste water sludges, but it performs very well with other sludges and biomasses. Figure 3 shows the outlook of waste water sludge before and after the SHS drying. Figure 4 includes four examples of different sludges after drying. Figure 5 shows the structure and main components of the dryer.



Wet sludge before drying | Dry sludge after water removal

Figure 3. Exampe of a drying test, images before and after the drying.

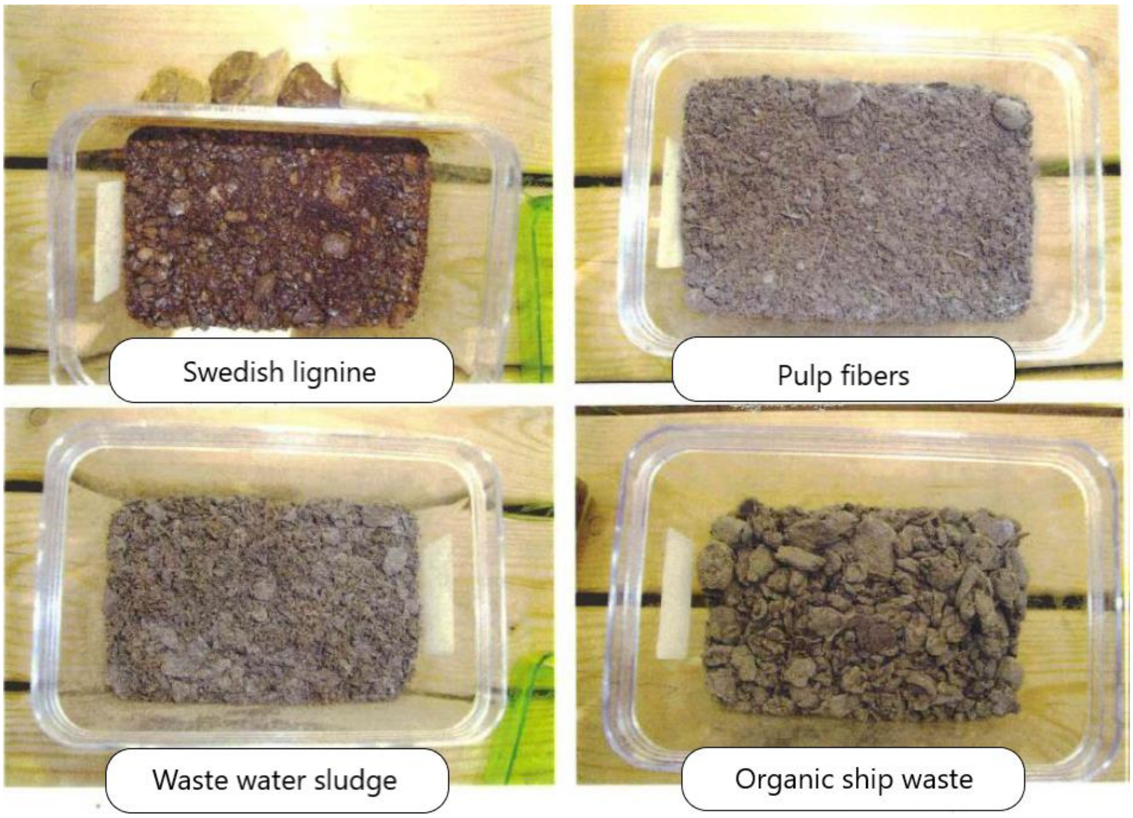


Figure 4. Some sludges after drying (the image has been adapted from the original file).

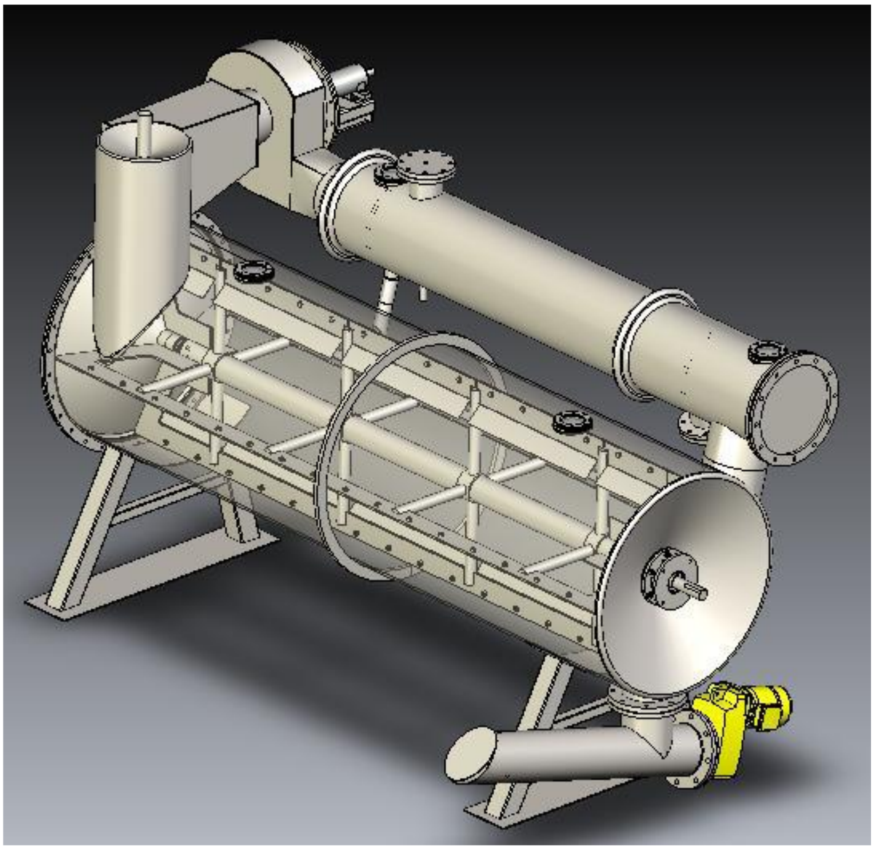


Figure 5. Detailed illustration of the SHS dryer.

4. CONCLUSIONS

Drying with superheated steam is a perfect application for handling of wet materials. The product dried with this method is dry and homogenous in structure.

II. Stronga

Stronga[22] company offers the following drying solutions (*Drying Wet Materials, Bulk Solids & By-Products*, n.d.):

> Stronga has well-proven drying solutions for using available process heat at biogas installations to dry separated digestate fibre from various feedstocks throughout the year.
>
> FlowDrya is designed to use residual heat in the most cost-effective way for drying digestate fibre in its varied forms. In the case of a biogas installation, the Stronga Heatex replaces the waste heat cooler, utilising previously wasted heat into useful drying quality air. Anaerobic Digestion facilities require reliable, high duty cycle equipment operating over 8000 hours a year. FlowDrya perfectly meets these requirements with simple, long life and energy-efficient operation.
>
> Dried, stabilised digestate fibre can be used as; Animal bedding; Stabilised organic fertiliser; Biofuel; Soil improver with landscaping or horticultural potential; Container composts; & more.

[22] https://stronga.com/en/products/wet-materials-by-products/

III. GRAINAS a/s

Grainas[23] company offers a superheated steam dryer (*GRAINAS | Drying | Superheated Steam Dryer*, n.d.):

GRAINAS Superheated Steam Dryer

GRAINAS has developed and produce a Superheated steam dryer with the newest and most efficient drying technology.

Our SHS Dryer is a very energy efficient dryer, where 85 % of the energy from the steam drying can be recycled for district heating or process heating. Now we are making it possible to dry and recycle a number of products in an energy saving and environmental way.

The superheated steam dryer has a various ways of drying materials such as wood chips, slurry fiber, sawdust, straws and pulp. The only requisite for drying is that the product is permeated within the steam circulation. The drying product is made manageable and stock stabile, ex. when slurry fibers from a biogas plant is made into slurry pellets and fuel pellets because of the steam drying.

The waste converts into an easy manageable trading product. It is eco-friendly - and a great amount of plain common sense.

Test Centre for investigating the biomass's potentials

In our test centre we offer experiments with steam drying of various biomasses. Potential clients can receive a full-scaled test with their own raw materials, where we also test the conveying, pelletizing and the splitting of the materials.

With very positive results we have among other things tested fibre fraction from biogas plants, sludge from wastewater treatment plants, wood chips and fruit pulp, also thermal treatment of protein crops in feed. Yet we don't know the steam drying plants full potential, and we think it is very interesting to test new materials. You are always welcome to contact us for a casual talk about the future possibilities in your company.

[23] https://en.grainas.dk/torring

IV. Scolari Srl

Scolari Srl[24] company offers belt drying systems (*Mobile Belt Drying Systems - 2T AS-ASLQ Version - Scolari Srl*, n.d.):

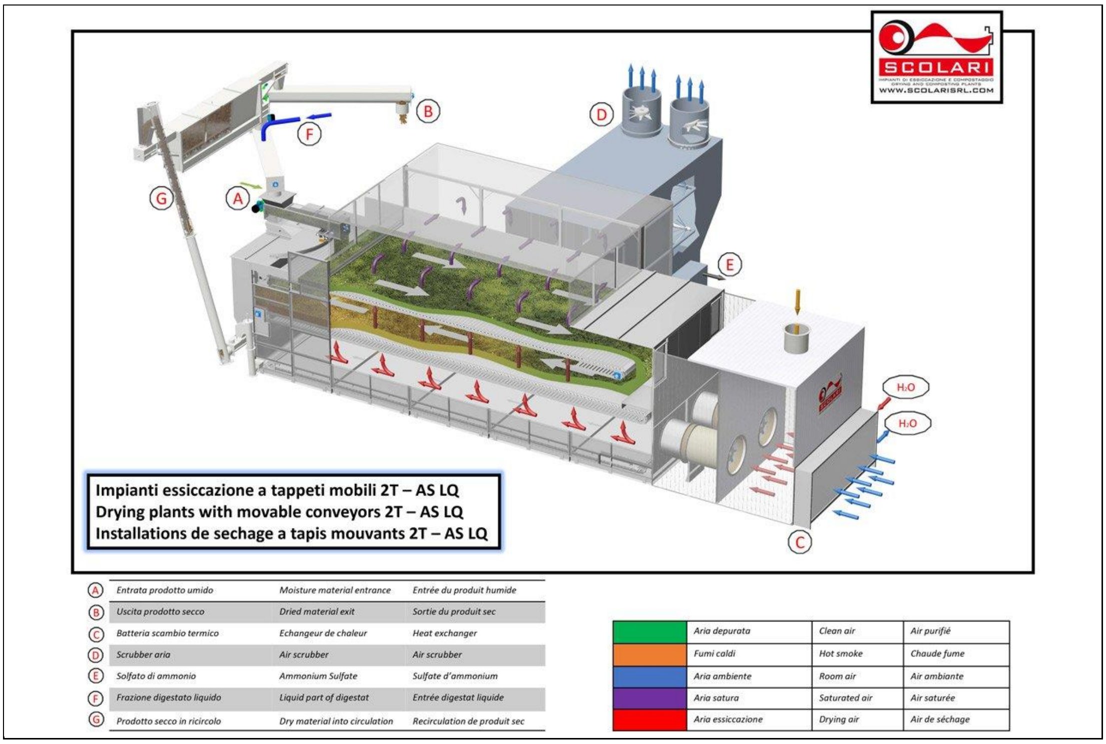
Mobile belt drying systems – 2T AS-ASLQ version

Continuous cycle drying plant with 2 drying belts normally used for drying the solid and / or liquid fraction of the digestate.

The construction features are similar to those of the 2T model.

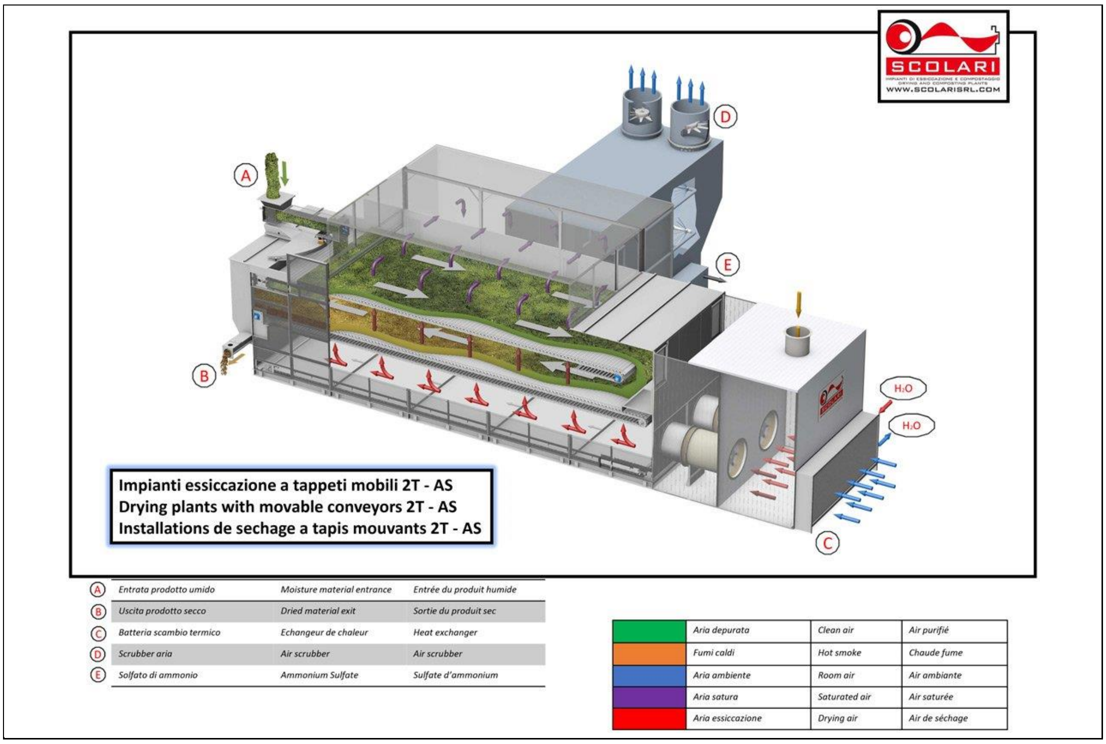
The thermal energy is normally recovered from the hot water and / or from the hot exhaust fumes of the cogenerator.

The plant is complete with a two-stage horizontal scrubber that allows to reduce dust and recover nitrogen in the form of ammonium sulphate



Digestate drying system 2T-ASLQ

[24] https://www.scolarisrl.com/en/industrial-drying-plants-manufacturers/drying-plants-with-movable-conveyors-manufacturers/mobile-belt-drying-systems-2t-as-aslq-version/



Digestate drying system 2T-AS

Digestate drying system. Examples.

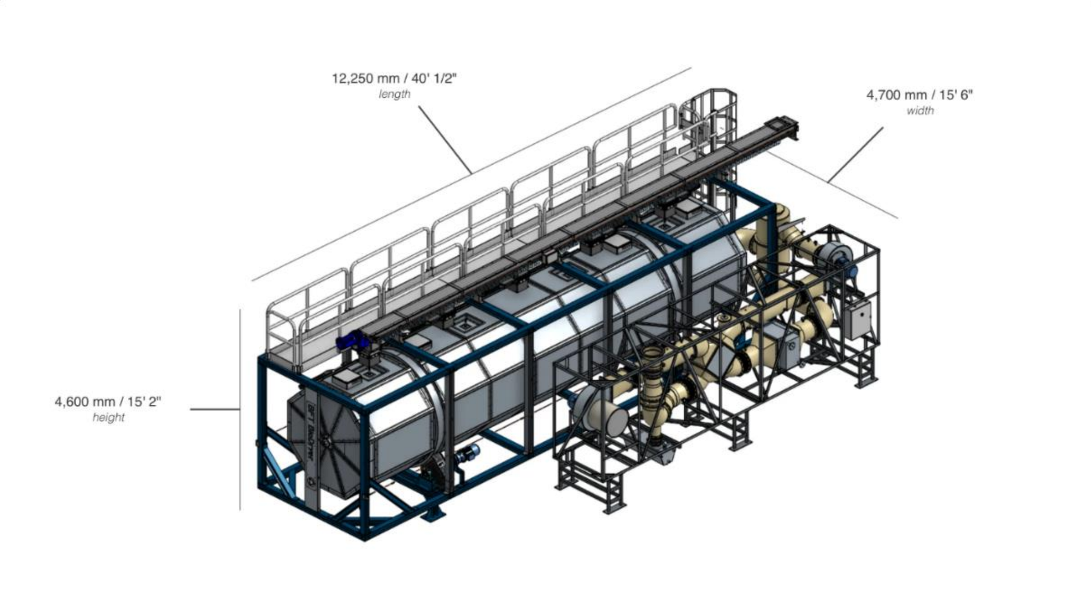
V. Bioforcetech Corporation

Bioforcetech Corporation[25] offers the biodryer (*The BioDryer | Bioforcetech*, n.d.):

> **The BioDryer** is a modular drying unit that dries biosolids using **up to 70% less energy** than any other system on the market. The BioDryer leverages bacteria to generate heat instead of relying on external heat sources. A simple concept, elegantly achieved; each BioDryer can process 1,000 tons of dewatered solids a year with incredibly low operations and maintenance.

BioDryer specs

Process type	Batch
Max capacity	8000 kg
Heat consumption	350 kwh/ton
Electricity usage	30 kwh-ton
Empty weight	12,500 kg
Capacity	~1000 tons/year



BioDryer. Dimensions

[25] https://www.bioforcetech.com/equipment/biodryer

Information from the Specification Sheet:

Introduction

BioDrying is the process by which biodegradable material is rapidly heated through initial stages of composting to reduce moisture and consequently reduce its overall weight and it's the most efficient way to remove water form biosolids and organic waste.

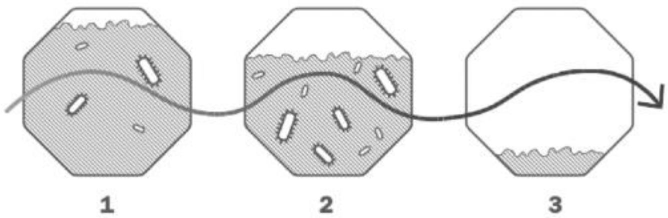
What is the BioDryer

Utilizing controlled air and bacteria, the BioDryer dries biosolids through a three-phase process. Remarkably, it can dry 8 wet tons of biosolids in as little as 56 hours. When compared to belt and drum drying methods, the BioDryer requires only 50% of the thermal energy and 30% of the electricity, making it highly efficient.

BioDryer is designed to be modular. Each machine can work independently or together as a system, we can meet the drying capacity that you need. This type of solution allows for easier plant design and guarantees a quicker installation.

Built with Biology

Much like the control of oxygen, heat, and bacteria for sludge digestion, the Bioforcetech BioDryer uses air and bacteria to dry biosolids in a three phase process. The BioDryer is specifically designed for biosolids, but it can also efficiently dry other similar organic waste streams from various industries by utilizing the energy generated by bacterial activity.



Phase 1

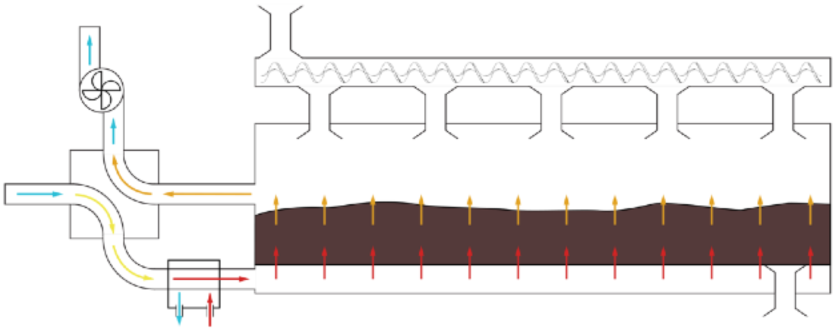
Air is pushed through the biosolids to cultivate thermophilic bacteria, microorganisms that create heat. As these microbes release heat into their environment, the BioDryer chamber increases in temperature to 150°F and the water in the biosolids begins to evaporate.

Phase 2

The thermophilic bacteria flourish, generating large amounts of heat. This causes the bulk of the moisture in the chamber to evaporate without any external heat source. The BioDryer unit continues to modulate airflow in order to maximize this process. What is normally the largest energy toll on other dryers is completely passive in the BioDryer.

Phase 3

The passive heat has evaporated so much moisture that the bacteria are not able to proliferate further, reducing their energy output. To compensate, the BioDryer introduces an external hot airflow to finish off the drying process.



Outstanding Performance

The BioDryer is expertly designed to maximize energy efficiency, saving both electrical and heat energy while effectively drying a significant volume of biosolids annually. The table below illustrates the BioDryer's throughput (for a single module) and energy performance, showcasing its efficiency in relation to the solid content of the input biosolids*.

Biosolids solids content	Wet tons / year	kWhe / wet ton	MMBtu / wet ton
17%	936	38	1.31
19%	964	37	1.27
21%	994	36	1.23
23%	1026	35	1.19
25%	1059	34	1.16
27%	1095	33	1.12

* This data is estimate on digested municipal biosolids, considering 8,300 hours per year of automated operation.

Modularity

The BioDryer is engineered with modularity at its core. Every unit is standardized, capable of treating around 1,000 wet tons of input material annually. To scale up the treatment of biosolids, additional BioDryer units can be effortlessly installed in parallel. This modular approach allows for a cumulative capacity increase of up to 12,000 wet tons per year.

Feedstock and Process Information

Process type	Batch
Biosolids input solid content	>= 17%
Input material characteristics	Material must "flow", With particle size <= 1 inch
Biosolids output solid content	<= 95%
Max batch capacity	16,000 lbs

Utilities Required

Potable water	1/2" NPT, between 35 and 50 PSI, max instant peek of 20 gpm
Pneumatic air	1/2" NPT, between 100 and 115 PSI, max instant flow 3.28 cfm @ 115 PSI
Condensates discharge	1" NPT. Max instant flow 2 gpm
Process water (hot water loop)	1 1/2" flange ASME B16.5, class 150, 40 gpm @70 PSI and 205 °F
Electricity	Ph, 480 V, 60 Hz, 125 A braker, max contemporaneous load 45 A

VI. Dorset Green Machines B.V.

Dorset Green Machines B.V.[26] offers dryers using waste heat at biogas plants (*Digestate - Dorset Group*, n.d.):

> Dorset has developed a concept for using the residual heat at biogas installations. By deploying a Dorset Dryer, use can be made of its residual heat during the entire year. The Dorset Dryer can, amongst others, be used for drying digestate.
>
> The drying installation is designed to use residual heat in a highly cost-effective way. In case of a biogas installation, the drying installation replaces the emergency cooler. With a 500 KW installation, for instance, only two ventilators are used, which means that electricity consumption hardly rises. The airflow through the product is kept extremely low, so as to prevent dust from being generated. When drying digestate, it is also necessary to clean the air.

Drying in Containers. (*Digestate - Dorset Group*, n.d.)

Drying Procedure.

Dry Substance

From 4w% ---> 12%

From 8% ---> 85%

From 12% ---> 85%

From 25% ---> 85%

[26] https://www.dorset.nu/green-machines/solutions/digestate/

VII. Oranicco Ltd (ecoDRYER)

Oranicco Ltd[27] offers dryers which harness the surplus thermal energy left unused by AD plants (*Organicco | EcoDRYER | Digestate Dryer*, n.d.):

ecoDRYER Digestate Dryer

Anaerobic digestion (AD) is a great way to enhance the value of a business by extracting biogas from leftover organic matter. The value of this process can be further enhanced by converting the digestate by-product into a quality organic fertiliser.

Organicco's 'ecoDRYER' harnesses the surplus thermal energy left unused by AD plants and uses this to heat and dry the digestate. This ensures that running costs are minimal, as not only is the digestate being recycled but the heat of the AD system! is utilised in the process.

A rotary drum helps granulation of the fertiliser which is sanitised before being continuously discharged from the system. Unlike digestate, this output is biologically inactive and ready for immediate use.

The system is highly automated. The feedstock is automatically pumped into the 'ecoDRYER' producing the fertiliser for collection. Organicco will also offer to buy the fertiliser, adding an additional revenue stream to compliment the biogas production.

[27] https://organicco.uk/products/ecodryer/

Custom Configuration

Our dryer interacts with AD plant on all levels, from feeding to utilisation of thermal energy. Therefore, understanding the current operation is the first priority before proposing a solution. Each dryer is unique to suit each customer, and the aim is to provide only the most efficient and quality solutions.

Organicco use only the best materials and labour and prides itself on the quality of products. All clients can be sure each system will not only optimise AD plants performance, but will be durable and long lasting. To reflect this Organicco provide competitive warranties and service contracts.

Any size

Volume is not a problem. Organicco's systems process daily from as little as 5 tonnes per day up to 30 tonnes per day. In addition, the modular design ensures that increasing the system size is cost effectively managed.

Superior Design

All systems are manufactured using only the finest materials and workmanship. The design and manufacture of all our systems is carried out in high-tech facilities using the most reputable suppliers and engineers guaranteeing quality, reliability and longevity.

Typical Applications

The application of the '*eco*DRYER' is not limited to AD operators; many other businesses can benefit from what the '*eco*DRYER' offers. The system can dry a variety of material such as digestate, slurry, farmyard manure, woodchip, sewage, general waste and sludge.

VIII. Jumbo group smart dry GmbH (Dryer)

Jumbo group smart dry GmbH[28] offers exhaust gas drying solution (*Gärreste - Jumbo Group Smart Dry GmbH*, n.d.):

Generally

The liquid manure ordinance, liquid manure storage, nutrient balance and the application of liquid fermentation residues are presenting biogas operators with ever greater challenges. Due to further reduced deployment times, even more storage volume must be kept available, higher storage volume is associated with high investment costs and possibly a reclassification in the Major Accidents Ordinance.

Shorter deployment times lead to even higher costs. All of this is flanked by soil compaction, road strain, nitrogen loss, provision of cost-intensive application technology, additional workload and costs. Exhaust gas drying not only represents an economically very interesting solution, but also improves the overall situation of the biogas plant significantly and is active environmental protection. Emissions are significantly reduced in the process.

The exhaust flow contains 50% of the thermal waste heat of a CHP. In most cases, this is routed unused through the exhaust pipe into the atmosphere. With the exhaust gas flow of a CHP alone, on average 50% of the entire fermenter mass can be dried from e.g. 7% dry substance to 90% dry substance. This reduces overall storage volume by half 50% while reducing yield.

Digestate drying

Our exhaust gas drying is the ideal solution to these problems. The exhaust gas flow contains 50% of the thermal energy of your CHP. With this energy, some of which escapes unused into the atmosphere via the exhaust, a good 50% of the liquid fermenter mass can be dried in a NAWARO standard system. While the liquid evaporates completely and is released into the atmosphere, all nutrients remain concentrated in the dried digestate. You have a valuable fertilizer for your own area or for marketing.

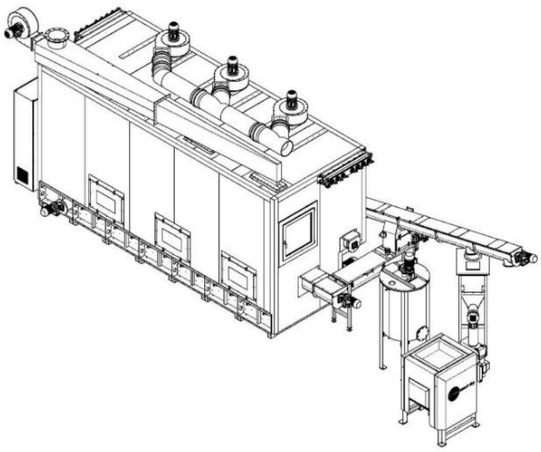
In the drying process, the hot exhaust gases from your CHP are fed into the material cloud of the dryer. Due to the high temperatures and the resulting thermodynamics, a kind of turbo drying occurs with an incomparable efficiency. The evaporation rate per liter of water is around 700W and is therefore at the limit of what is physically possible. Liquid fermentation residue is mixed to approx. 70% moisture via a dry return and mixing screw and fed into the dryer.

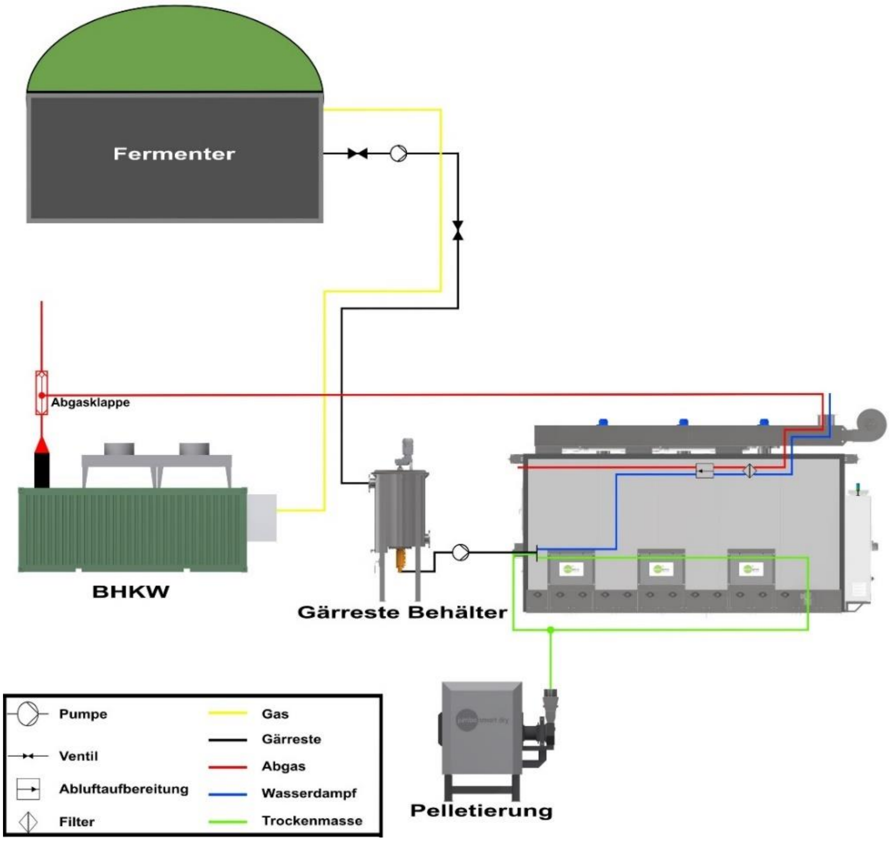
After a run of less than 6 minutes, the water content is reduced to a residual moisture of 10% and discharged from the dryer.

[28] https://jumbo-group.de/en/gaerrest/

Pelleting follows immediately after the drying process.

The dry and dusty fermentation residues are processed into dust-free pellets. These are storable, spreadable and represent an ideal marketing product. Extensive hygienization also takes place through the application of hot gas.





The entire process runs fully automatically and constantly adapts to changing outputs via an intelligent control system. It doesn't matter whether your CHP has less gas available or different power ranges are used via control energy, the dryer and the drying process regulate themselves fully automatically.

An ARC (active remote control) monitors the process in real time and saves all drive, temperature and control-relevant data every 5 seconds. This ensures largely unmanned 24/7 operation. The amount of energy supplied and the throughput are measured in real time for the CHP bonus determination and recorded in accordance with the EEG.

IX. THERMO-SYSTEM GmbH

Thermo-System GmbH[29] offers a few approaches to solar drying (*SolarBatch | THERMO-SYSTEM - Green Drying Solutions.*, n.d.):

SolarBatch

The SolarBatch concept is a batchwise process for drying sewage sludge, digestate and various other substrates.

The material to be dried is brought into the drying hall, usually by wheel loader or push-off trailer. Using free solar energy and with the help of the Electric Mole, a fully automatic turning robot, and a ventilation system, the material is uniformly dried to the desired DS[30] content. Removal is again carried out by means of a wheel loader. Due to its simplicity and robustness, the THERMO-SYSTEM SolarBatch concept is the most widely used worldwide. A further development of the Electric Mole with the 3D laser scanning system LiDAR allows an additional increase in performance and a simplified operation.

The application possibilities of the concept are manifold: SolarBatch is not only suitable for drying a wide variety of drying goods, but is also characterized by a particularly high scalability. For example, the capacity of plants already realized ranges from 200 t to 170,000 t of sludge throughput per year.

ADDITIONAL HEAT INPUT

Our Plus concepts are the solution of choice when heat energy is available. By introducing additional low-temperature heat, the drying capacity of the plant can be massively increased and the dependence on seasonal fluctuations significantly reduced.

Suitable heat sources include, for example, CHP waste heat, waste heat from industrial processes, biomass heating, heat pumps, etc. For the Plus concept, this additional heat energy can be used from as low as 30-40°C and on a fluctuating basis. Our ClimaControl control system ensures optimum energy utilization. The heat input is provided by air heating coils and/or floor heating.

Our many years of experience (since 1999) and a wide range of applications (realized plants from 50 kW to 20 MW) ensure that extremely economical concepts can be realized even in very confined spaces.

[29] https://www.thermo-system.com/en/solarbatch-1

[30] DS – Dry Solids

SLUDGE LOGISTICS

In the SolarBatch process, the material to be dried is brought into the drying chamber by means of a wheel loader, push-off truck or similar and roughly distributed in piles. The Electric Mole takes over the fine distribution, turning and mixing. Removal is again done by wheel loader, direct loading onto a truck is also possible. We develop and optimize the corresponding customized logistics concepts in close cooperation with our customers.

https://youtu.be/Y8N_ug7aEbE

CLIMACONTROL

The optimized process control with the ClimaControl software enables highly efficient drying, as all plant components are controlled and regulated. This approach ensures that drying conditions are constantly optimized and adjusted fully automatically.

VENTILATION SYSTEMS

All plants are equipped with speed-controlled recirculation and exhaust fans. The recirculation fans on the hall ceiling ensure optimum overflow of the substrate and thus contribute to uniform drying.

The exhaust fans optimize air exchange with the environment and ensure the discharge of saturated air from the drying hall.

Our patented MoviVent system, consisting of speed-controlled recirculation fans on a pivoting unit, contributes to further optimization of drying: the inward and outward pivoting fans remove moisture boundary layer on the sludge surface more effectively and over a wider area, further maximizing drying performance.

EXHAUST AIR TREATMENT

Although ClimaControl control minimizes emissions and odors, treatment of exhaust air is useful and necessary under certain conditions, such as unstabilized or poorly stabilized sludge, high local requirements, or close proximity to residential or commercial areas.

Since the optimum exhaust air treatment concept depends on the specific conditions, we use different solutions, such as biofilters or scrubbers, depending on the requirements.

The Electric Mole

The Electric Mole is a fully automatic turning robot and is used in SolarBatch and StorageDryer concepts. The robot distributes, turns, mixes and aerates the sludge evenly and in accordance with the plant configuration and drying conditions.

The machine consists of a minimum of moving parts and features an extremely robust stainless steel construction. Since the turning robot moves freely through the drying hall, the hall dimensions (width-length) are very flexible. In addition, the Electric Mole can be removed from the hall at any time. This additionally favors the ease of maintenance and redundancy of the plant. In addition, references with more than 20 years of operation underline the efficiency and longevity of this solution.

A further development of the Electric Mole with the 3D laser scanning system LiDAR enables an additional increase in performance and simplified operation.

X. SolarTiger® GmbH

SolarTiger® GmbH[31] offers a solar drying solution (*SOLARTIGER .:. SolarTiger®*, n.d.):

SolarTiger®

The SolarTiger® technology stands for efficient solar drying of sewage sludge and bulk materials.

The strong point of the SolarTiger® technology is the mass reduction through the evaporation of water with minimum energy use.

This way sewage sludge becomes a sustainable raw material for energy production.

Thanks to the innovative hexagonal rotating drum the SolarTiger® technology combines different important functions of solar drying with minimum use of electric energy.

- Turning the sewage sludge in order to always have wet material on the surface
- Aeration to hold the sewage sludge aerobic and to avoid unpleasant odours
- To transport the sewage sludge along the longitudinal axis of the drying hall
- Distribution of the sewage sludge after its input to the drying hall.

With the SolarTiger® technology also external sources of heat can be used to increase the dry matter content at the end of the drying process.

If the SolarTiger® technology is applied to dry very odour-intensive sludges, we offer the possibilities to use our SolarTiger® -AO method or to install air treatment.

We dimension your solar drying plant!

[31] http://www.solartiger.at/en/products/solartigerr.html

Rotating Drum

In the SolarTiger® technology a hexagonal rotating drum ensures an evenly granulated dry product as well as sufficient aeration of the drying material.

The height adjustable, rotating drum is mounted on a frame and aerates the sludge during the drying process with paddles which are fixed on the hexagonal drum-shaft.

This crane-like frame runs longitudinal through the hall. The immersion depth of the drum in the sludge can be adjusted continuously.

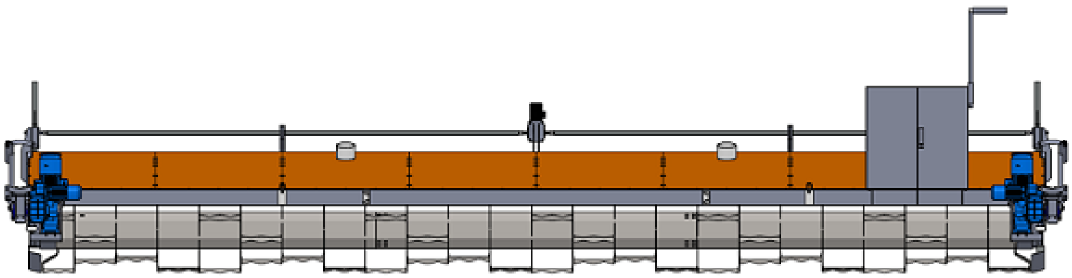
Due to the innovative hexagonal shape of the drum, the solar drying gets even more energy-efficient.

- The idle power demand is reduced considerably.
- The drum is balanced at the best. This way the possible area output and the processed sludge amout can be increased significantly at the same level of motorization.
- Due to the gains in area output, the aeration is intensified. Thereby unpleasant odours can be prevented even more effectively.

The operation of the SolarTiger® technology is very simple and works essentially automatically. Personnel costs can be kept very low and there are no technical skills required to operate the solar drying.

The drum is operated via touch panel on the switchboard.

Depending on customer requests the delivery is adapted to the application and the drying material.



Appendix 7. Solutions for thermochemical conversion and combustion of the digestate.

1. Combustion in a cogeneration unit of a biogas plant[32]

1.1. FerroPower

FerroPower website[33] contains the following solution (*Ferro Power - A Mobile Power Station*, n.d.):

> A mobile power station operated at the source of non-recyclable waste: ideal for utilising local energy sources.
>
> A modular power plant built in containers for local energy production.
>
> What can be used as fuel? By-products from industry, circular economy, agriculture and healthcare as well as communities (MSW).
>
> Suitable for heat production: options include cooling, steam and electricity production.
>
> Performance under optimal conditions:
>
> - Nominal capacity 1 MW (can be duplicated)
> - Heating output 8000 MWh/a
> - Cooling output 4000 MWh/a
> - Electricity output 750 MWh/a
> - Good efficiency
> - Purifies all harmful compounds, according to directives
> - Fuel handling capacity 250-350 kg/h, depending on the fuel quality
> - No need for a solid foundation
> - Can be relocated within weeks

[32] On-site combustion of the digestate.
[33] https://ferropower.fi/

1.2. HoSt Group

HoSt Group[34] offers the following solutions:

a) **Biomass-fired heat & power plants** (*Biomass-Fired Heat & Power Plants (CHP) | HoSt Group*, n.d.):

Features

- 1-10MWe, 8-25MWt, for sawmills, wood working, timber industry, district heating, process industry, food & beverage, greenhouses
- Lowest emissions in the industry
- Highest electrical and thermal efficiency
- High availability & performance
- Low civil & building costs
- Integrated flue gas cleaning
- Carbon capture technology easily integratable

Low-grade wood waste as fuel

HoSt biomass heat and power plants have a large range of fuel flexibility. And are capable of handling fuel particle size of up to 35 cm with varying moisture contents from 10% to 60%. Even fuels with a low ash melting point, high ash content or high chlorine or sulfur content can be utilized.

[34] https://www.host-bioenergy.com/solutions/boiler-plants/biomass-heat-power-plants/

High efficiency & availability

Electrical efficiency of over 25% can be achieved through a high-pressure steam boiler and a multistage turbine. Installations boast over 8,400 annual running hours, with >96% availability. Optimal combustion control enhances efficiency, with over 130% overall efficiency when paired with a flue gas condenser. The boiler design enables steam production up to 480°C and 90 bar. Operational costs are minimized via robust design, quality equipment from renowned European manufactures, high availability, high level of automation and limited maintenance intervals. Contact us to request more information on biomass combined heat and power plants.

b) **Hot water boilers** (*Hot Water Boiler Plants - Hot Water Boilers | HoSt Group*, n.d.):

Hot water for heating & processes

- Versatile, sustainable, and reliable hot water production
- Supply for heating or specialized processes
- Greenhouses, district heating, process industry, wood-processing industry, food & beverage industry, textile industry, and more

Low-grade wood waste as fuel

HoSt hot water boiler plants have a large range of fuel versatility. And are capable of handling wood particles of up to 35 cm with varying moisture contents from 10% to 60%. Even fuels with a low ash melting point or high chlorine or sulfur content can be utilized.

2. **Thermochemical conversion in a gasifier/pyrolysis/HTC unit of a biogas plant**[35]
    2.1. **Evac Group Oy**

Evac Group Oy offers Evac HydroTreat® hydrothermal carbonization solution[36] (*Evac HydroTreat - Evac*, n.d.):

> Evac HydroTreat® is an innovation that revolutionizes the handling of organic wet waste onboard vessels. The novel innovation remarkably decreases the vessel's environmental footprint; it provides a safer, more sustainable way to deal with organic waste streams, such as food waste and bio sludge, without emissions or plastic waste to the sea or gas emissions into the atmosphere.
>
> The hydrothermal carbonization (HTC) process for wet organic waste handling transforms food waste and biosludge into biochar. The biochar is sterile, stable, and easy to store onboard the ship while offering several opportunities to be utilized once landed.
>
> - Game-changing product for organic waste treatment
> - No harmful emissions into the atmosphere or sea
> - Available for passenger vessels of most sizes

Evac HydroTreat in Evac Research Center in Hyrylä, Finland

Key benefits

- No emissions into the sea or to the atmosphere
- Extremely energy-efficient process

[35] On-site thermochemical conversion of the digestate.
[36] https://evac.com/products/evac-hydrotreat/

- Turns waste into a valuable product

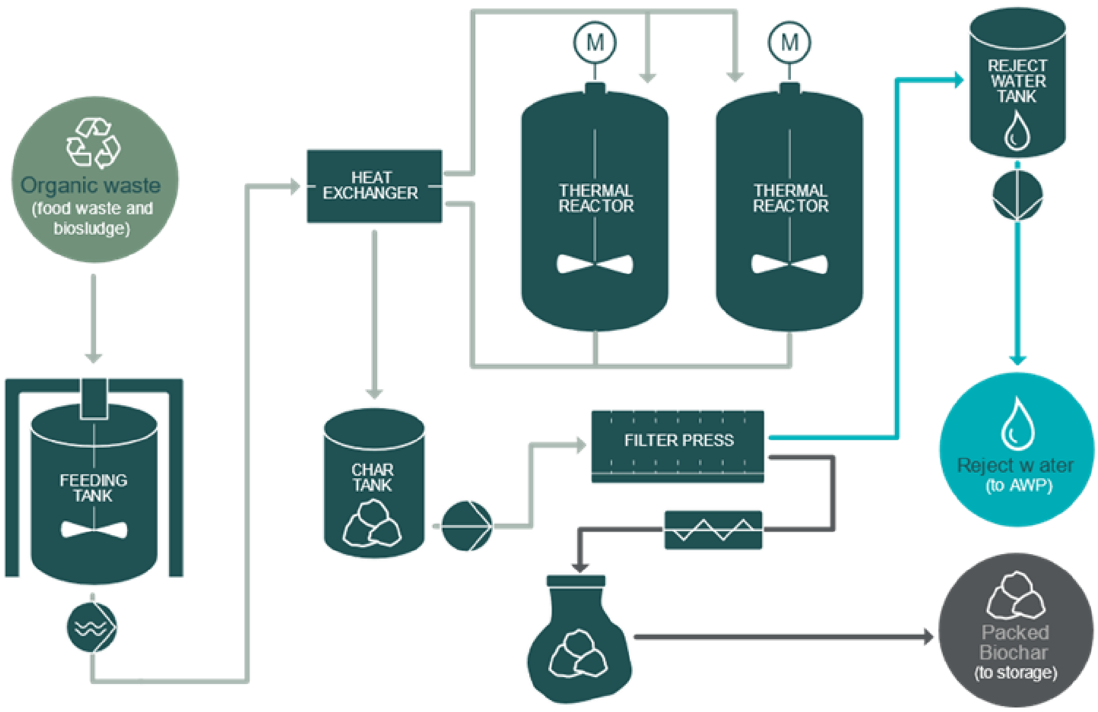
Technical data

Modular design, suitable for passenger vessels from approx. 500 people on board all the way to ships with 8000 people on board.

Organic waste to valuable material

Wet waste consists of food waste from restaurants, crew galleys, and bio-sludge from wastewater treatment. Troublesome storing and landing a massive amount of waste makes onboard treatment an attractive option. By using Evac HydroTreat® the volume of wet organic waste can be decreased up to 90%.

In the Evac's HTC process, organic material with high water content is exposed to increased temperature. The heat launches a chemical process, where the feeding material breaks down into carbon molecules. The resulting carbon and water mixture can be easily dried, leaving solid material called biochar. With a high carbon content, biochar acts as a carbon capture and storage. The stream of reject water is treatable in a wastewater treatment system.



Over 80% decrease in CO_2 emissions

The energy consumption of Evac HydroTreat® is just a fraction of a conventional waste handling process with thermal dryers. Adding to that the fact that the process does not involve any incineration, means that HydroTreat® produces only a small portion of CO_2 emissions.

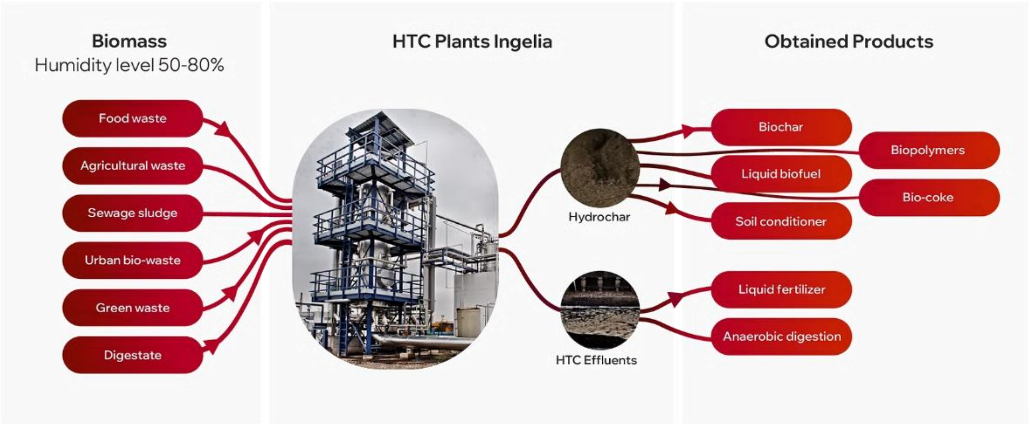
Sustainable waste management for passenger vessels

Evac HydroTreat® is available for most passenger vessels, from small expedition vessels all the way to the largest cruise ships. The solution helps to reduce the fleet´s environmental footprint and meet the MARPOL Annex IV and V regulations.

Evac HydroTreat® process is also suitable for land-based solutions, where organic side streams are generated.

2.2. Ingelia

Ingelia[37] company supplies industrial HTC plants with its own and patented technology (*Tecnología IngeliaHTC | Transformación de Residuos En Negocios Sostenibles*, n.d.):



Input materials

Ingelia's HTC plant processes mixtures of organic waste from different origins and humidity levels without prior pre-treatment.

It also prevents odour problems and reduces waste transport, allowing for more economical and sustainable management.

The HTC Plant

The plant is modular and scalable.

Plant size adjusted to available residue.

Automated process.

Without external thermal energy needs.

Short return on investment.

Products obtained

The hydrochar produced is a high-value solid bioproduct, rich in carbon and hydrogen. This guarantees a wide and diversified market demand, complying, among others, with the specifications of ISO/17225/8.

[37] https://www.ingelia.com/en/tecnologia

HTC liquid effluent has a valuable bionutrient content, and can be used as a fertilizer or as a substrate in anaerobic digestion plants, increasing methane production.

HTC plant in Immingham, UK

Demonstration plant for the UK market, green and organic waste

1 HTC module with post-treatment equipment

Nominal treatment capacity: 0.6 tons/hour of organic residues

Hydrochar powder nominal capacity: 150 kgs/hour

In operation since 2018.

A sustainable solution for digestates

Anaerobic digestion plants can process the digestates produced to valorise them in bio-products.

2.3. Geneset Powerplants Oy

Geneset Powerplants Oy[38] offers renewable energy technology solution (*Renewable Energy Technology*, n.d.):

Solution

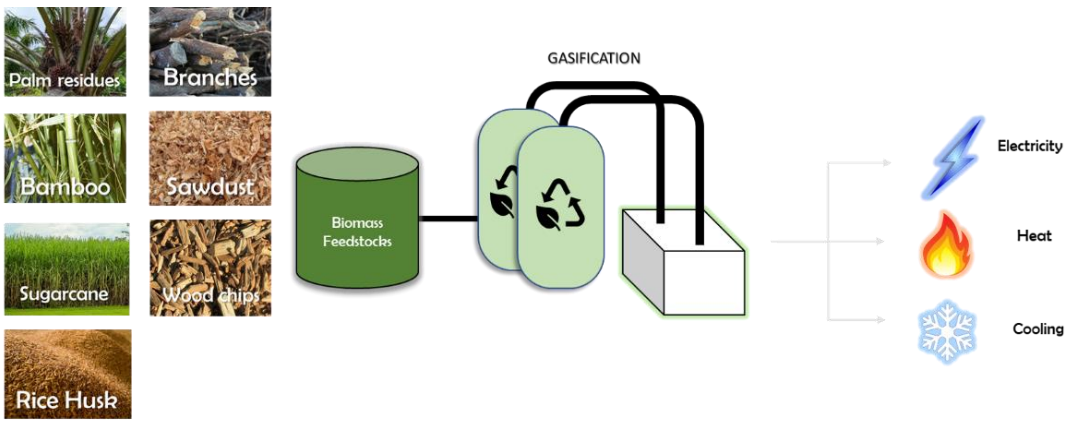
Geneset renewable energy solutions power small towns, industry sector or farm grids with extendable system for when electricity consumption increases. These sources power all appliances connected to the hybrid grid while charging the battery bank using the excess power for future use.

Hybrid off-grid system

Standalone hybrid grid systems provide grid-quality electricity supply for off-grid areas. Geneset provides hybrid systems with biomass gasification, solar photovoltaics, wind turbines, battery banks and generators. The set-up is tailored to fully utilize the local renewable energy resources and provide free reliable electricity for off-grid areas without need for expensive grid extensions and polluting fossil fuels.

Biomass Gasification

Thermal gasification turns biomass or waste fuel into producer gas, which can then be used in heat and power production. The fuel can originate from wood, forestry wastes and agricultural residues. The energy can be used as heat in industrial processes, as electricity using gas engine or gas turbine, or in combined heat and power (CHP) production. Combined heat and power production is very efficient, allowing more than 90% of the energy contents of the fuel to be harnessed.



[38] https://www.geneset.com/renewable-energy/technology

2.4. HoSt Group

HoSt Group[39] offers Gasification systems (*Gasification* | *HoSt Energy Systems*, n.d.):

> As a turn-key supplier of sustainable energy plants, HoSt's main focus is on applications where the syngas is burned to produce steam for use in a steam turbine. HoSt, in combination with partners, is developing and demonstrating a technology where the produced gas is used in gas engines. We provide the following types of gasification systems:
>
> - Standard gasification plants (1-5 t/h)
> - Specialty plants (>5 t/h)
>
> 
>
> **Technology suitable for 'difficult fuels'**
>
> Several fuels like straw, sunflower husks, and grasses are difficult to process in combustion systems due to the low melting temperatures of the ashes and the fouling of the downstream boiler components. In the fluidized bed gasifier temperatures can be controlled at levels as low as 750 – 800 °C. Since the syngas is combusted at high temperatures in the syngas burner, no problems with emissions will arise. Boiler fouling in combustion systems is mainly caused by the presence of alkali metals (Na, K, P) in the flue gasses. In the HoSt gasifier concept, the produced syngas first is cooled down to around 500 °C. Then, the ash is removed and the syngas is burned. At these low temperatures, the alkali metals condense on the ash particles and are removed from the syngas with the ash. Due

[39] https://www.host-bioenergy.com/solutions/gasification/

to this removal of alkali metals, no excessive fouling can take place in the boiler, increasing reliability and decreasing maintenance costs.

As an example, in a conventional system burning sunflower husk, the boiler has to be stopped every two to four weeks in order to manually clean the heat-exchanging surfaces. In general, a boiler stop requires two to four days to cool down, clean, and start up again. A gasifier boiler system can be operated for several months between maintenance stops.

2.5. Oranicco Ltd (ecoENERGY Waste-to-Energy)

Organicco Ltd offers[40] waste-to-energy system (*Organicco | EcoENERGY | Waste-to-Energy*, n.d.):

ecoENERGY Waste-to-Energy

A waste to energy (W2E) system, which uses a gasifier to produce fuel to generate electricity and thermal energy.

As an optional feature, ''ecoENERGY' can be integrated with the ecoHERO unit for producing and capturing the CO_2 emissions from the ecoENERGY. It is captured into a compressed liquid form thus making the entire process carbon negative thus helping meet net-zero targets. The captured CO_2 becomes another saleable commodity and usuable in many applications such as refrigerant.

How it works

The process starts by feeding feedstock into the gasifier, which produces syngas. It goes through a two-stage clean-up process before used as a fuel for producing combine heat and power (CHP). The exhaust from the CHP is pumped into the primary aerobic digester tank and passes through a secondary aerobic digester. It is then treated in a wet-scrubber and a regenerative catalyst scrubber before being released into atmosphere.

Fuel

The gasifier process produces hydrogen and becomes fuel for the CHP. Carbon dioxide and nitrogen are also produced. Both these gases are non-combustible,

[40] https://organicco.uk/products/ecoenergy/

and nitrogen is captured in the aerobic digester in a granular form. The CO_2 emission from aerobic digester is captured as compressed liquid CO_2.

Why gasification?

Solid biomass fuels are usually inefficient and can only be used for certain limited applications. The direct combustion is generally ineffectual, smokey and difficult to control. In addition, it converts solid fuel to thermal energy and whilst it is possible that heat from this process can be used in cooking, heating space and water or in generating steam (usually with low efficiency), this generation of power requires a high/medium pressure steam boiler along with a steam engine or turbine with accessories. This increases costs and difficulties for small power needs (a few kilowatts to megawatts), this conversion technology is not only capital intensive and complex, but also very inefficient. Gasification is far more efficient and cost effective.

Typical Applications

- Agriculture & Farming
- Municipal Food Waste
- Food Manufacturers & Abattoirs
- Airports & Ship Port
- Hotels & Resorts
- Supermarkets & Shopping Complexes
- Universities & Institutions
- Mining & Fishing Industries
- Zoos & Leisure Complexes

2.6. Jumbo group smart dry GmbH (PyroDry)

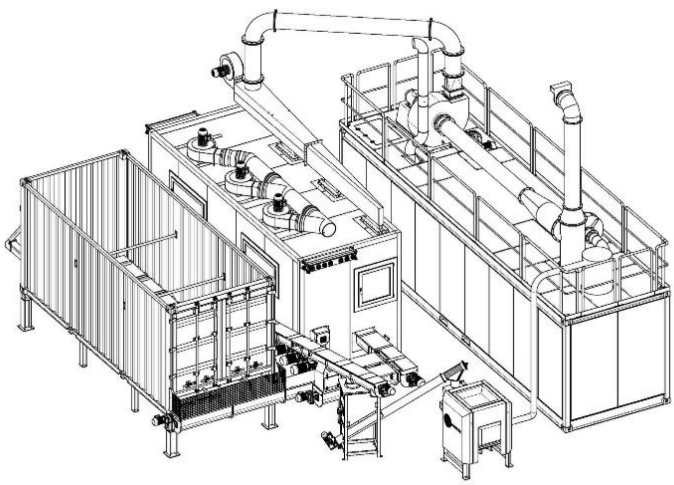
Jumbo group smart dry GmbH[41] declares self-sufficiency of the combination of pyrolysis and drying (*PyroDry - Jumbo Group Smart Dry GmbH*, n.d.):

What is PyroDry

PyroDry® combines pyrolysis (T:Craker) with drying (STR SpeedRotation Dryer series) and thus forms the basis for a completely energy self-sufficient operation.

In cooperation with the NGE company, a pyrolysis reactor was developed, which makes the entire thermal energy from the pyrolysis process available to the drying process in the form of 300°C hot exhaust gas.

This makes it possible to operate the drying and pyrolysis process without the supply of external energy. The system consists of biomass feed, drying, pelleting and the pyrolysis reactor. They form a closed unit. This makes PyroDry the most efficient system for treating wet biomass.



PyroDry

Compared to incineration, pyrolysis offers a number of advantages:

1. Lower emissions

In contrast to incineration, which releases large amounts of carbon dioxide and other greenhouse gases, pyrolysis releases significantly fewer emissions. This is because oxygen is not supplied during pyrolysis to fully burn the material.

[41] https://jumbo-group.de/en/pyrodry/

2. Increased energy recovery

Pyrolysis can be considered as a method of generating energy as the material is broken down into different components.

3. No External Power

Pyrolysis can be carried out at high temperatures that can be generated from the reaction itself. Therefore, the own demand for pyrolysis can be lower compared to incineration.

4. Avoidance of pollutants

Since no oxygen is added to the pyrolysis, the formation of pollutants such as nitrogen oxides (NOx) and sulfur oxides (SOx) is lower.

5. Product Manufacturing

Incineration is designed for the total destruction of the raw material, while pyrolysis produces several products from the raw material by breaking down the ingredients. The pyrolysis gas is produced, which can be used thermally, while the chemically stable carbon together with the mineral content results in a carbonaceous product (carbonate, biochar, TerraPreta).

This is used in a variety of ways, e.g. as activated carbon in the purification of liquids and air, as an additive in composting to improve soil. The phosphorus in biochar is fully available to plants.

Biochar from KS carbonisate

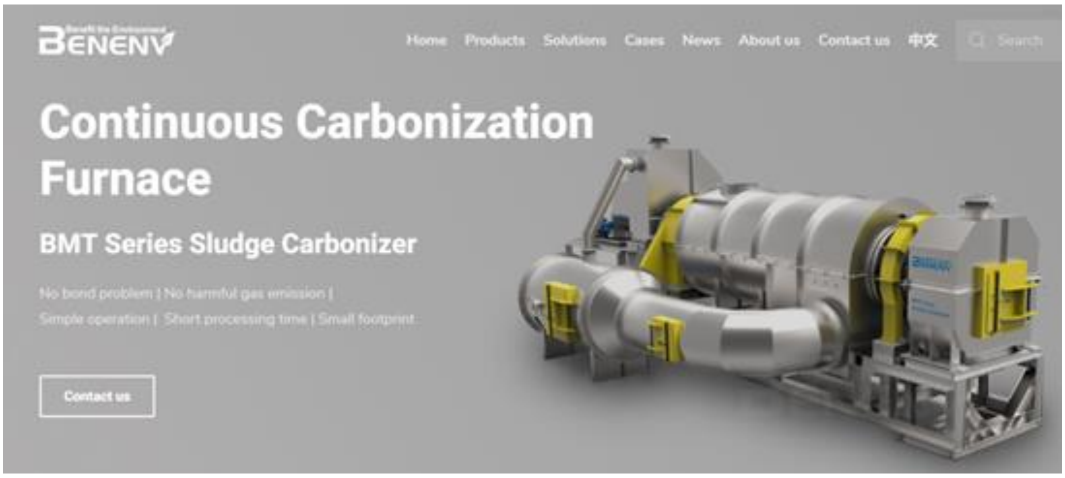
During pyrolysis, carbon from biomass is stored in the form of biochar. Sewage sludge pyrolysis is an excellent alternative way of utilizing sewage sludge. It is used decentrally at the sewage treatment plants. This avoids cost-intensive and environmentally harmful transport.

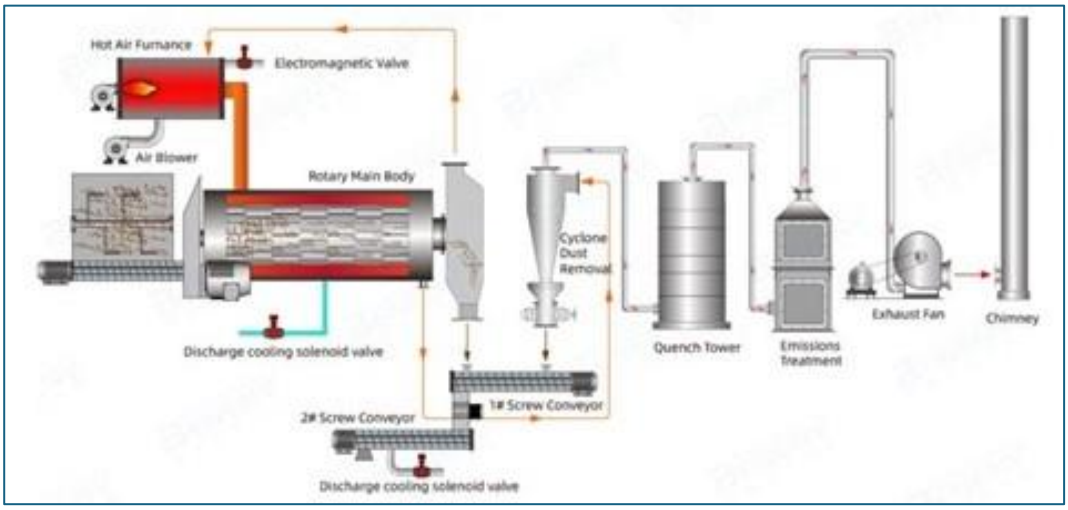
Dewatered sewage sludge is dried independently in the PyroDry® Energie and converted into carbonate (biochar). All chemical components, medical residues, microplastics and PFAS are almost completely destroyed by the high temperatures.

What remains is a carbon-containing pellet which has a wide range of applications as a product. It can be used as activated carbon to keep air and liquids clean. Activated carbon can be used to remove phosphorus and nitrogen from wastewater, as well as pathogenic microorganisms such as bacteria, viruses and parasites. Activated carbon removes organic compounds such as pesticides and herbicides, pharmaceutical residues, industrial chemicals and other organic compounds such as trihalomethanes, which result from the reaction of chlorine and organic compounds, from wastewater.

2.7. Benenv Group (BMT Series Sludge Carbonizer)

Benenv Group offers Continuous Carbonization Furnace[42] (*Continuous Carbonization Furnace*, n.d.).





Process flow

Specifications

- Any specification changes shall not be announced in advance.
- Please request drawings when designing.

Model	Dimension (mm)			Weight (ton)	Capaticy (kg/h)	Power (kw/h)
	L	W	H			
BMT-150	5300	3800	3200	11	150	5.5
BMT-300	7400	4100	3600	18	300	8.3
BMT-500	10800	8700	4200	27	500	20
BMT-1000	13200	10400	5300	57.5	1000	37
BMT-1500	15600	11500	6500	82.5	1500	62.5

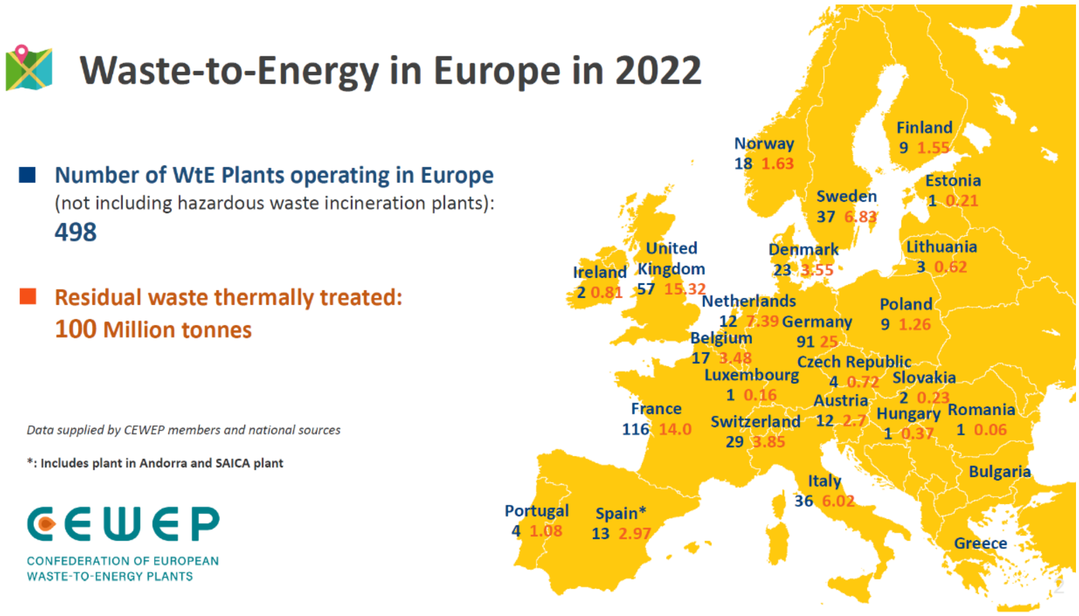
[42] https://en.benenv.com/continuous-carbonization-furnace.html

Appendix 8. Possible solutions for digestate transportation to third parties.

1. Overall information

Information in this Appendix is presented in terms of the technical feasibility of using bio-waste with relatively low calorific value and relatively high moisture content as fuel.

We see the following information on CEWEP[43] Website[44] (*CEWEP - The Confederation of European Waste-to-Energy Plants*, n.d.):



Regarding the national waste-to-energy sector we see the following information on EastCham Finland Ry website[45] (*Waste-to-Energy Solutions - EastCham Finland Ry*, n.d.):

> Finnish waste-to-energy plants are the most modern in Europe. In 2021, there are ten waste-to-energy power plants operating in Finland with a total capacity of approximately 1.9 Mt/a

[43] Confederation of European Waste-to-Energy Plants
[44] https://www.cewep.eu/waste-to-energy-plants-in-europe-in-2022/
[45] https://www.eastcham.fi/finnishwastemanagement/municipal-solid-waste/recycling-and-recovery/kampanjan-alasivun-alasivu/

Energy recovery from waste in Finland: 10 Waste-to-Energy plants [in 2021]

Location:	Power plant:	Organization:	Capacity: (tons/year)
1. Vantaa	Vantaa Waste-to-Energy plant	Vantaa Energy Ltd	360 000
2. Riihimäki	Waste-to-Energy plant	Fortum Plc.	150 000
3. Riihimäki	Waste-to-Energy plant 2	Fortum Plc.	120 000
4. Kotka	Korkeakoski Power Station	Kotka Energy Ltd	100 000
5. Lahti	Kymijärvi II Gasification Power plant	Lahti Energy Ltd	250 000
6. Leppävirta	Riikinvoima Eco Power plant	Riikinvoima Ltd	145 000
7. Mustasaari	Westenergy Waste-to-Energy plant	Westenergy Ltd	190 000
8. Oulu	Laanila Eco Power plant	Oulu Energy Ltd	120 000
9. Tampere	Tammervoima Waste-to-Energy plant	Tammervoima Ltd	160 000
10. Salo	Korvenmäki's Waste-to-Energy plant	Lounavoima Ltd	120 000

Most of Finland's waste-to-energy plant capacity is under municipal control. There are several different models by which waste-to-energy plants are owned and operated:

1) There are four **municipal energy companies:**

- KotkanEnergia
- Lahti Energia
- OulunEnergia
- VantaanEnergia (city of Vantaa owns 60% and city of Helsinki 40%)

2) The biggest plant owner in Finland is the **government-controlled energy company** Fortum Plc. which also treats hazardous waste and generates energy from it. Fortum's largest owner is the Finnish state with a share of almost 51 percent.

3) The third form is a **joint venture of an MWMO and an energy company**, as is in the case of Tammervoima, Lounavoima.

4) The fourth form of plant ownership is **a joint venture of several MWMOs together or jointly with an energy company**:

- Westenergy owned by six MWMOs
- Riikinvoima owned by eight MWMOs and Varkauden Aluelämpö Ltd.

In addition, more than 20 conventional power plants have a license to co-incinerate waste derived fuels, like a variety of solid fuels prepared from municipal, construction and industrial waste (SRF= Solid Recovered Fuel; RDF = Reduce Derived Fuel; REF = Recovered fuel). Also, waste derived fuels can be co-fired in cement kilns. Today less than 10 plants are co-incinerating waste derived fuel.

Waste incineration and its emissions are subject to strict regulation in Finland. Incineration is regulated by the Waste Incineration Regulation, which is based on the EU Industrial Emissions and environmental permits for plants and their control ensure that waste incineration plants do not cause significant environmental and health damage. BAT (best available technologies) conclusions have been drawn up at EU level for waste incineration which set e.g. emission levels for airborne emissions and monitoring requirements. BAT conclusions for waste incineration are renewed approximately every 10 years. The emissions of co-incineration are also strictly regulated and are based on the share of co-fired waste.

2. Information about solid waste fuels within the frame of WOIMA Corporation solutions

Regarding fuel calorific value and moisture content, we can find the following information in "Brochure: wasteWOIMA®" from the website of WOIMA Corporation[46] (*Downloadable Content, Brochures and Cases - Woima Corporation*, n.d.):

> The *waste*WOIMA® is capable of handling a wide range of non-toxic solid waste fuels, such as
>
> • municipal solid waste (MSW)
>
> • refined waste fuels (REF, RDF or SRF)
>
> • industrial and commercial waste (ICI)
>
> • construction and demolition waste (CDW)
>
> **• agricultural waste (AW)**
>
> • waste wood and
>
> • different biomasses, such as EFB, rice husk.
>
> There are two grate options available depending on the calorific value of the fuel
>
> 1) Air-cooled grate for low calorific value waste fuels with **LHV between 7 and 17 MJ/kg**
> 2) Water-cooled grate for high calorific value waste fuels with **LHV between 14 and 24 MJ/kg**
>
> The **maximum moisture of the waste fuel is 55%.** The plant automatically adjusts itself to variations in fuel quality and quantity to deliver a constant stream of energy.

Brochure "Use case: WOIMA Ecosystem for 250 Tons Per Day of MSW" contains the following information regarding the fuel (*Downloadable Content, Brochures and Cases - Woima Corporation*, n.d.):

> The WOIMA Ecosystem is capable of handling a wide range of non-toxic solid waste fuels, such as
>
> • municipal solid waste (MSW)
>
> • refined waste fuels (REF, RDF or SRF)
>
> • industrial and commercial waste (ICI)

[46] https://woimacorporation.com/

• construction and demolition waste (CDW)

• wastewater treatment sludge

• agricultural waste (AW) and

• different biomasses, such as EFB, rice husk…

The **fuel calorific value range is 5 – 24 MJ/kg with moisture up to 65%.** The Ecosystem automatically adjusts itself to the variations in fuel quality and quantity to deliver a constant stream of energy.

3. Information about incoming waste properties within the frame of BMH Technology Oy solutions

BMH Technology Oy website[47] contains the following information about incoming waste properties within the frame of Waste to Electricity Processes (*BMH Technology - Waste to Electricity*, n.d.):

> BMH Technology offers solutions for all combustion and conversion technologies, such as gasification or pyrolysis for production of chemicals and alternative fuels. In addition to new builds, the existing power plants can be easily modified into using SRF/RDF as their primary fuel.
>
> The supreme fuel flexibility built into BMH's solutions enables combustion of a wide range of fuels. In power plant solutions delivered by BMH, SRF/RDF can also be co-fired with biomass, peat, agro-based and fossil fuels in power generation.

Examples of Waste to Electricity Processes

	MSW_1	MSW_1	MSW_2	ICW	Mixed Waste
Incoming Waste Properties*					
CV_{MSW} (Calorific Value)	6 - 8 MJ/kg 1 430 - 1 910 kcal/kg	6 - 8 MJ/kg 1 430 - 1 910 kcal/kg	10 - 12 MJ/kg 2 390 - 2 870 kcal/kg	18 - 23 MJ/kg 4 300 - 5 500 kcal/kg	15 - 18 MJ/kg 3 590 - 4 300 kcal/kg
$Moisture_{MSW}$	45% - 55%	45% - 55%	30% - 40%	5% - 10%	25% - 35%
Typical Input Requirement	1 000 tpd	1 000 tpd	600 tpd	400 tpd	600 tpd
Objective	SRF/RDF Quality	SRF/RDF Yield	SRF/RDF Yield	SRF/RDF Quality	SRF/RDF Yield
Process					
Pre-Treatment	x				
TYRANNOSAURUS® SRF/RDF Process	x	x	x	x	x
Fine Shredding				x	x
Notes	The separated organics can go, for example, to anaerobic digestion.	For high yield solutions, sorting is balanced based on waste quality and required CV.	For high yield solutions, sorting is balanced based on waste quality and required CV.	Premium quality fuel production requires high-quality input material and the finest particle size.	By altering the mixing proportions the homogenity of the fuel can be better managed.
Ready SRF/RDF Properties*					
$CV_{SRF/RDF}$ (Calorific Value)	11.8 MJ/kg 2 820 kcal/kg	7.4 MJ/kg 1 770 kcal/kg	12.3 MJ/kg 2 940 kcal/kg	24.2 MJ/kg 5 780 kcal/kg	18.3 MJ/kg 4 370 kcal/kg
Moisture	47%	56%	36%	8%	30%
SRF/RDF Output	270 tpd	760 tpd	510 tpd	340 tpd	528 tpd
SRF/RDF Yield	27%	76%	85%	85%	88%
Rejects	13%	22%	11%	12%	8%
Recyclables and others	60%	2%	4%	3%	4%
Fuel Power	37 MW_f	65 MW_f	73 MW_f	95 MW_f	112 MW_f
Generated electricity**	11 MW_e	20 MW_e	22 MW_e	29 MW_e	34 MW_e

MSW_1 = Typical Asian MSW with high organic, moisture and inerts content. Abrasive for equipment.
MSW_2 = Typical European MSW, a smaller quantity of organics and inerts and the moisture content is lower compared to MSW_1.
ICW = Typical Industrial and Commercial Waste, consisting mostly of dry packaging materials.
Mixed Waste = Typical European type MSW mixed together with ICW. Proportions might fluctuate.
*Properties for incoming waste are based on general data and experience. Properties for ready SRF/RDF are based on specific cases.
**Actual produced electricity depends on chosen power plant technology.

[47] https://www.bmh.fi/plant-solutions/waste-refining-solutions/waste-to-electricity/

According to the website of BMH Technology Oy, Waste-to-Electricity solutions were delivered to Lahti and Rauma, and Waste-to-Fuel solutions were delivered to Lahti, Finland. (*BMH Technology - Waste to Electricity Solution Delivered to Lahti, Finland*, n.d.; *BMH Technology - Waste to Electricity Solution Delivered to Rauma, Finland*, n.d.; *BMH Technology - Waste to Fuel Solution Delivered to Lahti, Finland*, n.d.)

4. Information about fuel properties for Valmet BFB Boiler

Valmet Oyj website contains the following information about fuels for bubbling fluidized bed (BFB) boiler (*Valmet BFB Boiler Utilizing Bubbling Fluidized Bed Technology*, n.d.):

> **For renewable biomass and various recycled fuels**
>
> One of the advantages of the boiler is the possibility to use fuels **with high moisture content and low heat value.** Typical such fuels include **wet biomasses and different types of process sludges.**
>
> Dry biomass is suitable fuel as well and references are ranging between 15 to 65% moisture content.
>
> Many boilers have a wide variety of fuels and the mixture may contain biomass and recycled fuels. Typical recycled fuels are recycled wood, recovered industrial waste and even processed municipal waste (RDF).

Valmet BFB boiler, for example, was delivered to Seinäjoen Energia in Finland (*Valmet Delivered Boiler and Heat Recovery Handed over to Seinäjoen Energia in Finland*, n.d.).