EBA
European Biogas Association

Exploring digestate's contribution to healthy soils

About the authors

This document was prepared by Mieke Decorte (EBA), Gabriella Papa (EBA), Marina Pasteris (EBA), Lucile Sever (EBA), Chiara Gaffuri (EBA) and Giulia Cancian (EBA), with the collaboration of Ulysse Bremond (Air Liquide) and Cyril Flamin (ENGIE).

We would also like to thank all those who agreed to be interviewed for this publication: Stefan Graßl (Kompost Biogas), Lisa Deraedt (National Association Biogas Flanders), Céline Wyffels (National Association Biogas Flanders), Aurélien Bardellin (Valbiom), Filip Kuševi (Renewable Energy Sources of Croatia), Jan Habart (CZ Biom), Julie Dajcl (CZ Biom), Bruno Sander Nielsen (Danish Biogas Association), Ahto Oja (Estonian Biogas Association), Nelli Pitkänen (Finnish Biocycle and Biogas Association), Anna Virolainen (Finnish Biocycle and Biogas Association), Pascale Chenon (VoxGaia), Laurine Duclos (ATEE), Verena Pfahler (Fachverband Biogas), Vassileios Diamantis (HABIO), Vassilis Stamogiannis (HABIO), Attila Kovacs (National Biomethane-Biogas Green Energy Industrial Association), Seamus Crickley (Renewable gas Forum), Sean Finan (IRBEA), Noel Gavigan (IRBEA), Guido Bezzi (CIB), Lorella Rossi (CIB), Andis Karklins (Latvian Biogas Association), Baiba Brice (Latvian Biogas Association), Ton Voncken (Platform Groen Gas), Beata Wiszniewska (Polish Biomethane Organization), Michał Tarka (Polish Biomethane Organization), Jaime Braga (APPB), Dávid Kan o (Slovak Biogas Association), Sara Milner García (BIOVIC), Angelika Blom (Avfall Sverige) and Andrea Hjärne (Avfall Sverige).

About the EBA

The EBA believes in the potential of renewable gases in Europe. Founded in 2009, the association is committed to the expansion of sustainable biogases production and use across the continent. EBA counts on a well-established network of nearly 300 national associations and other organisations covering the whole biogas and biomethane value chain throughout Europe and further afield.

Contact

European Biogas Association
info@europeanbiogas.eu
+32 24 00 10 89
www.europeanbiogas.eu

Imprint

Date: March 2024

Design: Pif.agency

Photo credits

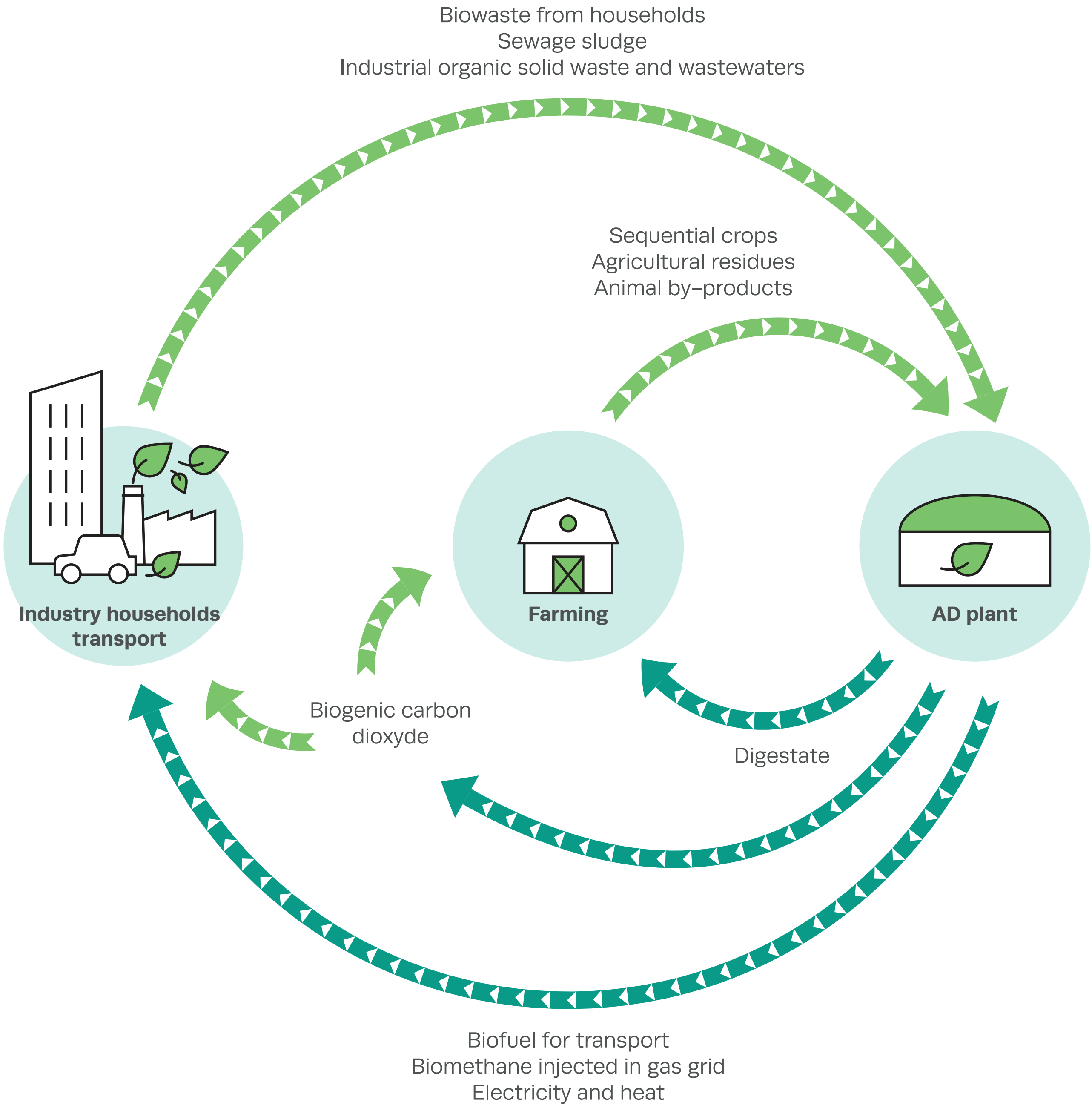
Pages 1, 5, 26, 28-29, 32, 39 : Shutterstock
Pages 8, 17, 25 : Canva

Table of contents

Chapter 1 What is digestate?

During the anaerobic digestion (AD) process, biogas is produced alongside a valuable residual stream known as digestate (Figure 1). While a portion of the organic compounds from the initial feedstocks is converted to biogas during the process, the mineral fraction remains largely intact in the digestate, making it an appealing organic-mineral fertiliser.

Figure 1: Schematic overview of the inputs and outputs of the biogases production process



Digestate has the potential to drive Europe's agricultural sector towards regenerative practices and offers an attractive, sustainable alternative to commonly used synthetic fertilisers. The incorporation of digestate or its derivatives in EU agronomic practices contributes to the achievement of the strategic objectives for resource efficiency, the circular economy, and overall environmental stewardship. Utilising digestate enables a reduction in synthetic fertiliser usage as stipulated by the Farm to Fork strategy[1], promotes effective soil management and restoration, addresses mineral imbalances and tackles the deficiency of organic matter in soils as outlined by the EU Soil Strategy[2]. Moreover, it facilitates efficient carbon capture, aligning with ongoing developments in EU carbon farming policies.

The further expansion of biogas production in Europe will see the generation of increasing amounts of digestate. Leveraging its significant advantages will yield benefits for farmers, local communities, and producers alike. Beyond offering an alternative to synthetic fertilisers, the AD process facilitates the sanitation of organic wastes and animal manures, helping to break the chain of pathogen transmission. This not only mitigates adverse impacts on human and animal health but also contributes to controlling plant pests and diseases.

Digestate conveys cost savings to farmers by optimising the utilisation of their own resources and reducing their reliance on costly synthetic fertilisers. The concentration of readily available minerals, such as nitrogen, is higher in digestate compared to the same organic material in its raw form, thus increasing its fertilising efficacy. Furthermore, volatile organic compounds (VOC) are either reduced or eliminated during the AD process, leading to a significant reduction in odour emissions that would otherwise occur during the application of the raw materials as fertiliser.

Finally, due to its good fertilising properties, digestate is much less likely to be disposed of inappropriately (e.g., landfilling, or open storage) compared to raw organic waste. This mitigates the risk of water, soil, and air pollution resulting from high concentrations of minerals within confined spaces.

This paper dives into the production of digestate, highlighting what happens in the digester and which types of digestate exist (Chapter 2). It then goes on to analyse the utilisation of digestate by further exploring its agricultural properties and application, range of end-uses in Europe and novel application routes (Chapter 3). Further on, the positive impacts on the environment, climate and soil health are investigated (Chapter 4) and market strategies are explored (Chapter 5). The paper concludes with a regulatory framework analysis for digestate at EU and national level (Chapter 6).

1 https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf

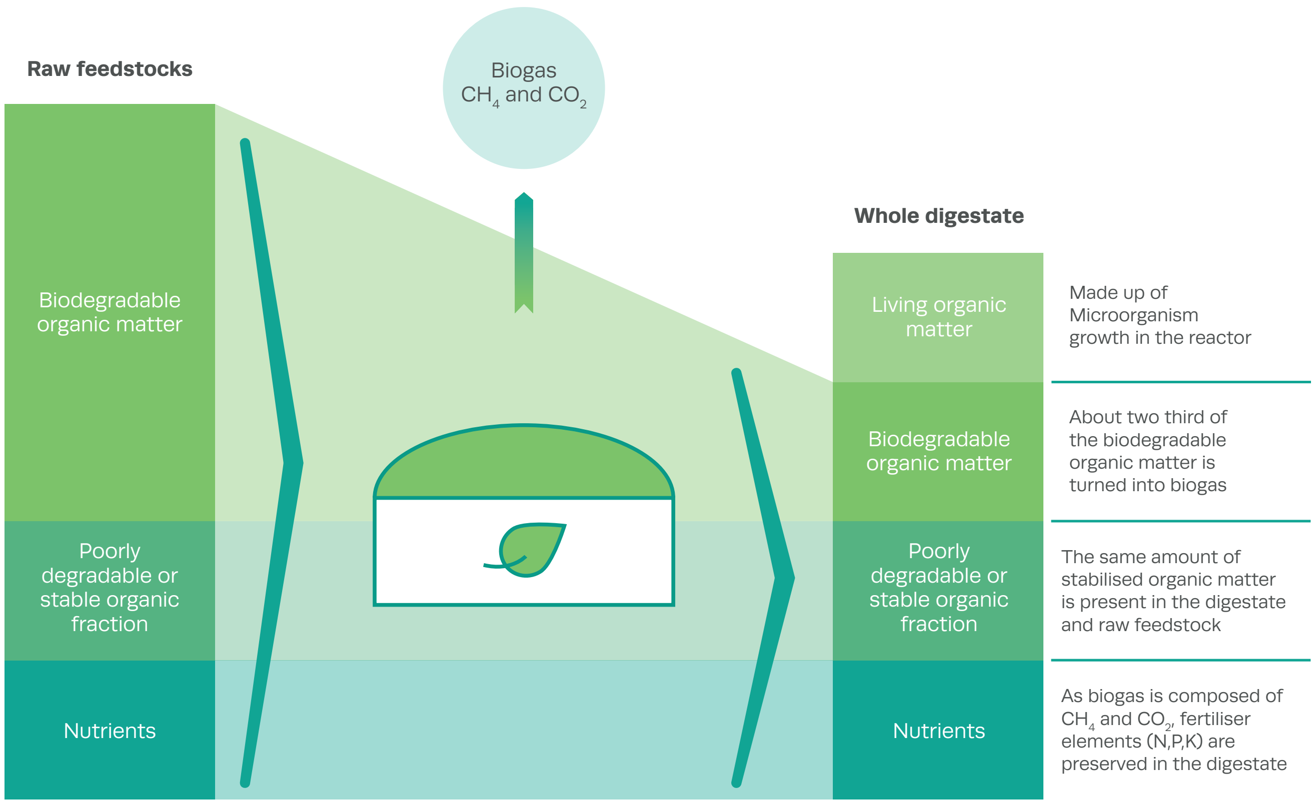
2 https://environment.ec.europa.eu/topics/soil-and-land/soil-strategy_en

Chapter 2 Production of Digestate

What happens in the digester?

Feedstocks for AD are largely composed of organic materials, minerals, and water. The organic materials have different levels of biodegradability. During the digestion process, different families of microorganisms degrade complex organic elements into simpler molecules. About two-thirds of the biodegradable organic matter is transformed into biogas, composed of CH_4 and CO_2. The final composition of the digestate depends on the input materials, the type of digestion process as well as the possible presence of post-treatments.

Figure 2: What happens in the digester?
(source: reworked from "l'utilisation des digestats en agriculture [3]")



3 https://www.actu-environnement.com/media/pdf/news-37779-agroparistech-guide-epandage-digestats-methanisation.pdf

Three forms of organic matter

Organic matter is found in three forms in digestate:

- **The poorly biodegradable, or stable, organic fraction** consisting of lignin and cellulose. This fraction serves as a precursor of humus material, thus improving the clay-humus complex of soils.
- **The living organic matter,** composed of microorganisms. These microorganisms transform and store organic elements into mineral elements accessible to plants through mineralisation.
- **The biodegradable fraction** consisting of soluble sugars and hemicellulose, which are highly mineralisable. It serves as an energy and nutrient source for soil bacteria and earthworms.

Most of the biodegradable organic substrate is transformed into biogas. The rate of degradation of labile organic matter depends on factors including the nature, residence time and process configurations of the inputs.

The same amount of stabilised organic matter is present in the digestate and the raw feedstock. Consequently, digestate retains its ability to form humus, which remains unchanged compared to the substrates from which it originates. When the digestate is spread on soils, this stable organic matter can bind with the clay, thereby enhancing the clay-humus complex essential for water and nutrient retention. Furthermore, the porosity of the soil is improved, which is essential for microbial activity and thus the carbon and nitrogen cycles.

Thanks to its organic fraction, digestate can provide a long-lasting increase in organic carbon and nitrogen pools, enabling a sustained release of carbon and nitrogen useful to sustain microbial growth and plant nutrition.

Digestate reduces the microbial activity of the soil.

Under investigation

Soil microbial activity is important to soils, among others, because it breaks down organic matter in the soil (such as dead plant materials) into nutrients that plants can use for growth.

The response of the soil microbial communities to digestate application depends on the characteristics of the digestate and soil type*,**. Different soil types respond differently to the application of digestates. While some studies suggest that the application of digestates increases soil biomass and microbial activity, further studies are necessary to determine the impact of digestate on microbial activity in soil, taking into account varying digestate compositions and soil types.

* Vautrin F. et al., 2024 The short-term response of soil microbial communities to digestate application depends on the characteristics of the digestate and soil type Applied Soil Ecology Volume 193, January 2024, 105105

** Nielsen, K.; Roß, C.-L.; Roß, C.; Hoffmann, M.; Muskolus, A.; Ellmer, F.; Kautz, T. (2020) The Chemical Composition of Biogas Digestates Determines Their Effect on Soil Microbial Activity. Agriculture, 10, 244

Nutrients are preserved during digestion

As biogas is composed mainly of CH_4 and CO_2, the total quantity of fertilising elements N, P, K, and trace elements of the substrate are preserved in the digestate. Some of these elements are transformed in the AD reactor. The organic nitrogen in the substrate (mainly proteins and urea) is partly mineralised via an ammonification process into ammoniacal form (NH_4^+), which is then converted by nitrification to (NO_3^-), a readily available source of nitrogen for plants. The ammonium/organic nitrogen ratio in digestate is higher compared to the raw feedstock. Even if the total content of nitrogen (combined organic and mineralised) remains the same during digestion, the percentage of readily available minerals in the form of ammonium increases.

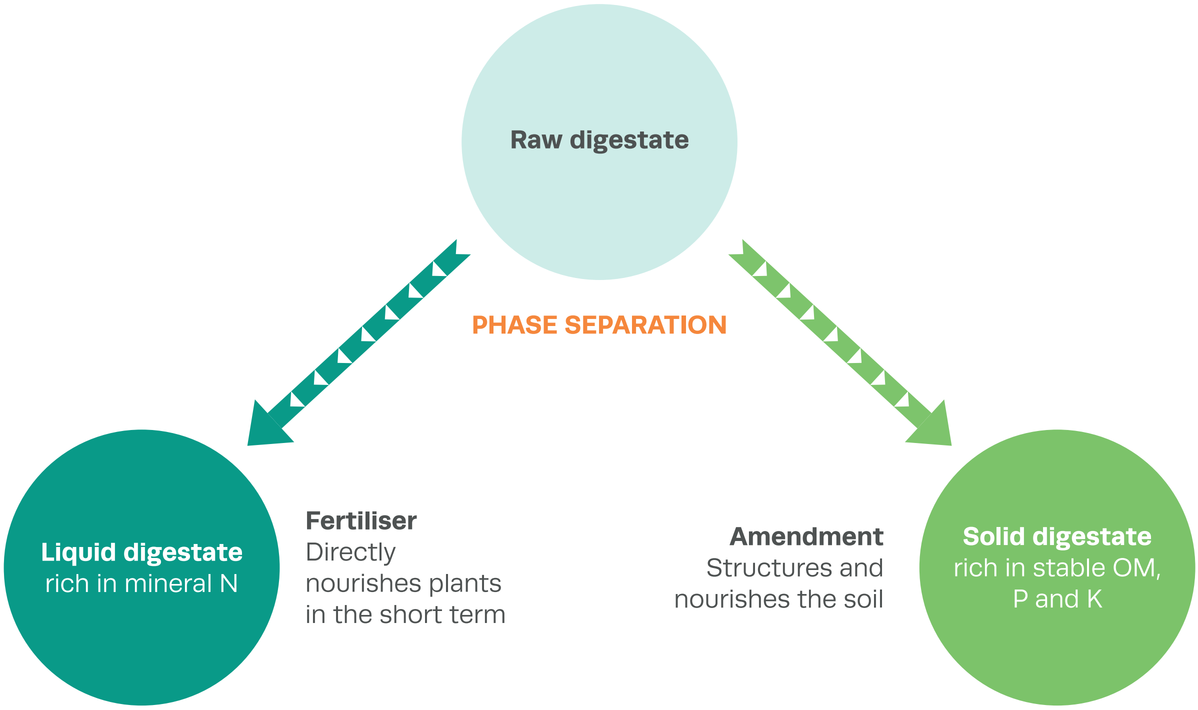
Types of digestate

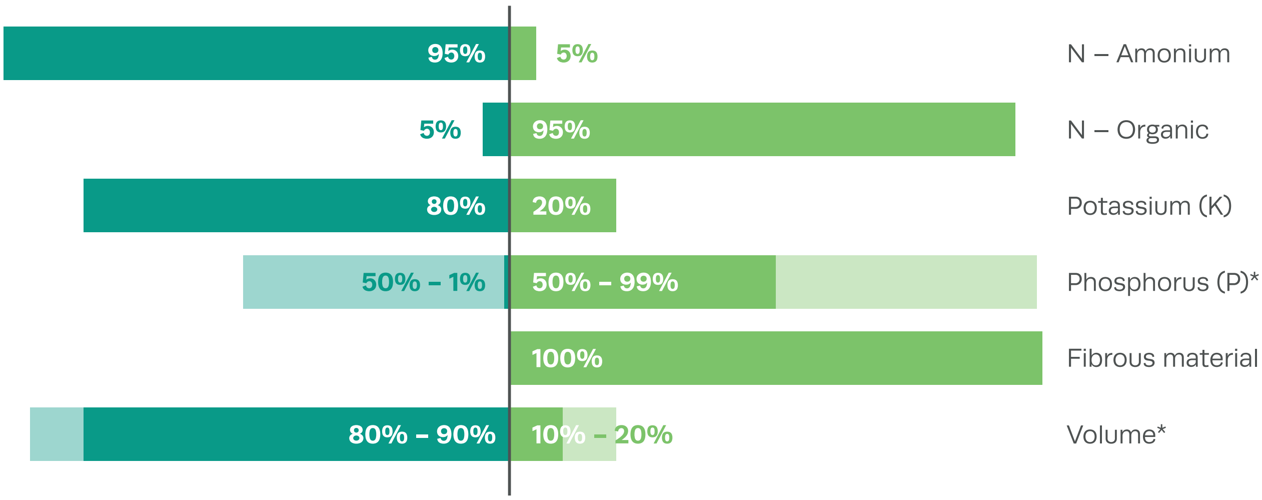
Whole digestate is the direct output from digesters and can be used without processing. For the purposes of volume reduction and nutrient management (to reduce transport costs, ease spreading and increase nutrient value) digestate can, however, be separated into solid (fibres) and liquid fractions using separation techniques.

The first step in processing is often mechanical separation into liquid and solid fractions. This is achieved, for example, with centrifuges, decanter screw presses, sieve belt presses or drums. Coagulants and flocculants can further improve separation efficiencies. Nutrients are not distributed equally between liquid and solid fractions after separation (Figure 3). The phosphates largely migrate to the solid fraction and nitrogen and potassium are mostly found in the liquid fraction. The solid part is often dried or composted to facilitate its further management and mobilisation.

Depending on the initial feedstocks used and digestion technology applied, the dewatering of the digestate can vary in ease or difficulty. High-fibre materials greatly increase dewaterability.

Figure 3: Digestate separation into a liquid and solid fraction
(source: reworked from "l'Utilisation des digestats en agriculture [4]" and Guilayn et al. 2018 [5])





* Depend on the use of coagulants / flocculants for solid phase separation
** Depend on the technique used

4 https://www.actu-environnement.com/media/pdf/news-37779-agroparistech-guide-epandage-digestats-methanisation.pdf

5 Digestate mechanical separation: Efficiency profiles based on anaerobic digestion feedstock and equipment choice Guilayn et al. 2018

Liquid fraction digestate

The liquid fraction of digestate typically contains high levels of nitrogen and can be applied to the fields of nearby farms or be further processed for upgrading.

Nutrient extraction from the liquid fraction of digestate has been extensively explored and documented, highlighting the variety of technological options to produce concentrated biobased fertilisers. Plant operators employ a wide range of digestate conditioning and treatment technologies. The most relevant treatments of liquid fraction digestate are:

- **Ammonia stripping and scrubbing:** This chemical-physical process recovers ammonia from the N-rich liquid stream of digestate in three steps: (1) NH_4^+/NH_3 balance is shifted to the ammonia side by increasing the temperature (to around 70-80°C) and sometimes adjusting the pH (which is typically between 8-10). Subsequently, (2) NH_3 is removed (stripped) from the liquid digestate into the gas phase by a counter current air or stream flow into a packed bed tower reactor. Finally (3), the resulting NH3 in the air or steam is collected (scrubbed) by causing it to react with a strong acid solution, such as sulphuric acid. This reaction yields a commercial-grade fertiliser solution, ammonium sulphate. The current Technological Readiness Level (TRL) is up to 9.

- **Membrane filtration:** With the finest filtration membranes (Reverse Osmosis or RO), only water passes through the membrane pores and the other molecules are retained. This process produces a demineralised water permeate and mineral-rich concentrate. Phosphorus is present to a lesser extent, as the phosphates largely remained within the solid fraction during the separation phase. The liquid digestate undergoes prefiltration in a membrane cascade before reaching the finest filtration membranes. These two steps are necessary to remove coarser particles. The TRL is up to 9.

Solid fraction digestate

The solid fraction is stable and rich in carbon and phosphorus. The reduced volume facilitates transport to a wider region. It can be used as a soil conditioner or further treated.

There are various options for further processing of the solid fraction of digestate. It can be composted to further stabilise it, or dried and pressed into fertiliser pellets. Conversion to pellets facilitates both transport and use. Other processing technologies include:

- **Pyrolysis and gasification:** After drying to reduce its water content below 15%, solid fraction digestate can undergo thermochemical conversion via either pyrolysis or gasification. These processes involve subjecting the dried digestate to high temperatures either in the absence of oxygen (pyrolysis) or with a controlled amount of oxygen (gasification). The resulting products are renewable oil (from pyrolysis) or syngas (both from pyrolysis and gasification), together with char. Char can be used in several ways, such as application to soils as a carbon sink, or as an adsorbent for purifying water or gas. The TRL is 9.

- **Hydrothermal carbonisation:** In contrast to pyrolysis and gasification, the hydrothermal carbonisation (HTC) technique eliminates the need for a drying step. The solid fraction of digestate is treated at mild temperatures (180-280°C) under pressurised conditions[6] and low residence time (5-120 min). Water acts as a solvent solubilising nitrogen and phosphorus. The resulting carbon-rich hydrochar product can be applied as a soil improver or as an adsorber matrix. The current TRL is 8[7].

6 https://ohioline.osu.edu/factsheet/fabe-6622

7 https://www.theseus.fi/bitstream/handle/10024/702973/Eslava-Ursuga%2C%20Angela%20Maria.pdf?isAllowed=y&sequence=3

Volumes of digestate produced in Europe

Through consultation with its members, the European Biogas Association (EBA) has estimated Europe's total digestate production based on the current and potential European production of biogases [8]. Total digestate production volumes were calculated for 2022, 2030 and 2050 (Table 1). The total volume of digestate produced in 2022 is estimated at 31 million tonnes (Mt) dry matter (DM). By 2030, 75 Mt DM of digestate can be produced, whereas the total digestate potential for 2050 is 177 Mt DM of digestate.

Using the average nutrient compositions of digestate (see Chapter 3), the total amounts of nutrients available in digestates in 2022, 2030 and 2050 are obtained. Results show that in total, digestate produced in 2022 contained 1.7 Mt nitrogen (TKN[9]), 0.3 Mt of phosphorous (P) and 0.2 Mt of potassium (K). By 2030, the nutrient potential of digestate reaches 4.1 Mt nitrogen (TKN), 0.7 Mt phosphorous (P) and 0.4 Mt potassium (K). By 2050, these values will further increase to give 9.7 Mt nitrogen (TKN), 1.7 Mt phosphorous (P) and 0.8 Mt potassium (K).

Table 1: Total digestate production volumes [Mt dry matter (DM)] and nutrient content (Mt) in 2022, 2030 and 2050

Parameter	2022	2030	2050
Total digestate production (Mt DM/year)	31	75	177
Nutrient content (Mt)			
Nitrogen (TKN)	1.7	4.1	9.7
Phosphorous (P)	0.3	0.7	1.7
Potassium (K)	0.2	0.4	0.8

According to Fertilizers Europe [10], total nutrient demand in Europe, based on the average value of the three growing seasons 2018/2019, 2019/2020 and 2020/2021 is 11.1 Mt nitrogen, 2.8 Mt phosphorous and 3.1 Mt potassium per year. Comparing the total nutrient demand in Europe with the nutrient volumes that can be provided through digestate usage highlights the considerable share digestate can cover.

European digestate production per country

Depending on market and agronomic conditions, the types of digestate produced differ between countries. Whereas the recognition and valorisation of digestate is garnering attention by farmers, comparable and consolidated data on its production in the different European countries is still limited. An overview of digestate production volumes in 2022 in selected European countries is provided below.

- **Switzerland** produces 182,000 tonnes DM of digestate, of which 55,000 tonnes DM is

8 Details on the methodology applied can be found in the EBA Statistical Report, 2023

9 TKN: total Kjeldahl nitrogen

10 Fertilizers Europe (2021). Forecast of food, farming and fertilizer use in the European Union 2021-2031. https://www.fertilizerseurope.com/forecast-of-foodfarming-and-fertilizer-use-in-the-european-union-2021-2031/

whole digestate. A large portion of the digestate produced is separated, resulting in 48,000 tonnes DM liquid fraction digestate and 49,000 tonnes DM of solid fraction digestate. 30,000 tonnes DM of compost were produced from digestate in 2022. Most of the digestate in Switzerland is used directly as a biofertiliser; a small portion is used in horticulture.

- **Denmark** produces a total of 15.8 Mt (fresh matter) of whole digestate. Most of the digestate comes from manure. At least 4 pilot scale plants for the pyrolysis of digestate are under construction on Danish biogas plants and this pathway is considered important for the future.

- In **Italy**, the total amount of digestate from agricultural feedstocks in 2022 amounted to 3 Mt DM. The integration of anaerobic digestion at composting facilities in Italy is widespread. Therefore, digestate from municipal organic waste is often sent directly for composting at the same plant.

- In 2022, **Poland** produced nearly 4.4 Mt of whole digestate (fresh matter). The digestate is applied directly to neighbouring agricultural land, without separation taking place.

- **Serbia**'s biogas production results in 20,918 tonnes DM of liquid fraction digestate and 18,271 tonnes DM of solid fraction digestate. All digestate is separated into a liquid and solid fraction. Both the liquid and solid fractions are then directly used as biofertilisers on neighbouring agricultural land.

- In **Sweden**, the total amount of non-separated digestate produced in 2022 was 263,283 tonnes DM, of which over 50% was obtained from sewage treatment plants and nearly 30% from agricultural substrates (mainly manure). The remaining 20% is derived from co-digestion plants. Little separation of digestate into liquid and solid fractions takes place in Sweden and digestate upgrading (except for the dewatering of sewage digestate) is not common in the country. The vast majority (90%) of digestate is used in agriculture.

- In 2022, **Slovakia** produced a total of 1,396,648 tonnes (fresh matter) of whole digestate. Most of the country's digestate comes from agricultural feedstocks and nutrients are delivered back to the soil via its direct use as fertiliser.

- In the **United Kingdom**, digestate is generally classified in two categories: digestate with waste status and digestate with a product status. Total digestate production was 705,771 tonnes DM in 2021. The production of whole digestate amounted to 331,158 tonnes DM. Plants with separation units produced a total of 256,290 tonnes DM of liquid fraction digestate and another 118,323 tonnes DM of solid fraction digestate. The production of compost from digestate is not yet being quantified. A small number of the UK's facilities aerobically mature separated digestate and a small portion of plants co-compost their digestate at a composting facility, where it is combined with other biodegradable streams. Relatively little digestate in the UK is upgraded.

- **Ukraine** produced 119,167 tonnes DM of non-separated digestate, of which 76% was generated from agricultural feedstocks. The majority of digestate is directly used as a biofertiliser on neighbouring agricultural land.

Chapter 3 Utilisation of Digestate

Agricultural properties and applications

The most established and conventional use of digestate in Europe is its application as organic fertiliser and soil amendment. Its direct application on farmland has been proven to increase nutrient availability for plants, with beneficial effects on crop growth[11],[12]. Typically, the percentage of ammoniacal nitrogen is higher in the digestate than in the original raw material, which increases its fertiliser value. For example, the nitrogen uptake from animal slurry digestates has been reported to be 10 to 20% higher than from the undigested slurry[13],[14]. As with every fertiliser, however, proper management is required to exploit its full potential and maximise the efficiency of nutrient use.

The agronomic value of digestate application is twofold. Digestate provides:

1). Nutrients for plant growth, ensuring crop yields.

2). Stabilised organic matter, increasing the humus content of soil and facilitating carbon sequestration.

An excellent fertiliser with recycle available nutrients

After AD, the mineral part of the initial feedstock remains almost completely in the digestate. Recycling the digestate back to soil contributes to closing nutrients cycles such as nitrogen (N), phosphorus (P) and potassium (K) for more efficient crop growth. Compared with conventional system, it also allows an effective use of resources and mineral balance within a circular economy approach. Thanks to AD, nutrients recycling is enhanced by the higher percentage of readily available minerals in the digestate compared to the initial feedstocks. Apart from NPK, digestate can also contain other macro- and microelements, such as magnesium, which increases its actual economic and agronomic value.

As is the case for mineral nitrogen, digestate contains nitrogen in organic form that was not degraded during AD. Part of this nitrogen mineralises during the year following the addition, under the action of living soil organisms. The other part is stored in the organic matter of the soil (humification). The humified fraction will then mineralise at the same speed as the organic matter in the soil. Consequently, two types of effects of digestate can be considered for nitrogen feeding of crops:

- Short-term effect linked to the mineral nitrogen and mineralised organic nitrogen;
- Long-term effect linked to the modification of the stock of organic nitrogen in the soil.[15]

11 Herrera, A., D'Imporzano, G., Clagnan, E., Pigoli, A., Bonadei, E., Meers, E., & Adani, F. (March 2023). Pig Slurry Management Producing N Mineral Concentrates: A Full-Scale Case Study. *ACS Sustainable Chemistry & Engineering, 11*(19), 7309-7322. DOI: 10.1021/acssuschemeng.2c07016

12 Reuland, G., Sigurnjak, I., Dekker, H., Sleutel, S., & Meers, E. (2022) Assessment of the Carbon and Nitrogen Mineralisation of Digestates Elaborated from Distinct Feedstock Profile. Agronomy, 12, 456. https://doi.org/10.3390/agronomy12020456

13 Tambone, F., & Adani, F. (April 2017). Nitrogen mineralization from digestate in comparison to sewage sludge, compost and urea in a laboratory incubated soil experiment. *Journal of Plant Nutrition and Soil Science, 180*(3), 355-365. https://doi.org/10.1002/jpln.201600241

14 European Commission, Joint Research Centre, Huygens, D., Orveillon, G., Lugato, E., Tavazzi, S., Comero, S., Jones, A., Gawlik, B., & Saveyn, H. G. M., (2020). *Technical proposals for the safe use of processed manure above the threshold established for Nitrate Vulnerable Zones by the Nitrates Directive* (91/676/EEC).

15 L'utilisation des digestats en agriculture, les bonnes pratiques à mettre en œuvre.

When applying digestate, nitrates leaching should be carefully considered

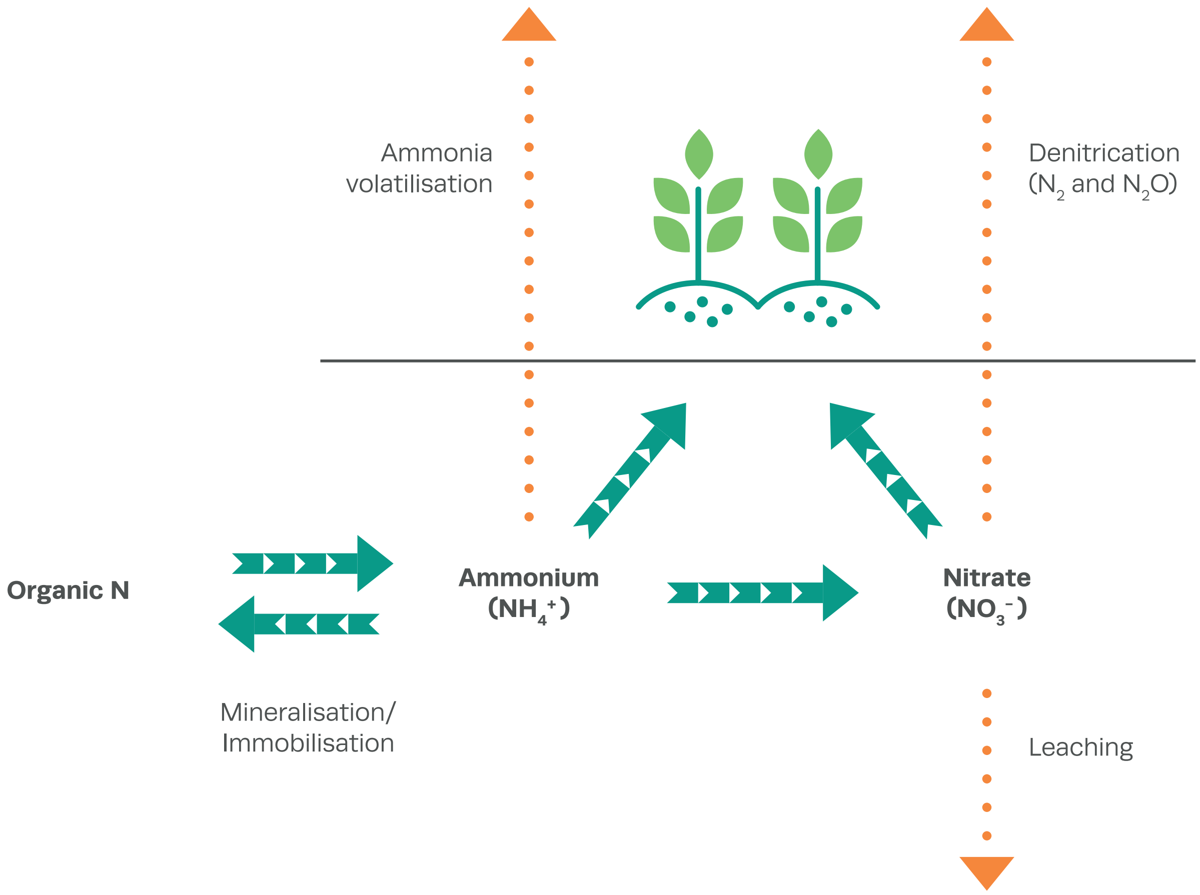
FACT

After spreading the digestate, nitrification by soil bacteria converts nitrogen in ammoniacal form (NH_4^+) into nitrate ions (NO_3^-). Whereas NH_4^+ cations are retained by the negatively charged soil, NO_3^- can freely move in the soil solution. Nitrates can either be absorbed by the plant roots or lost through leaching into the deeper layers of the soil, finally reaching ground-water and rivers. Although nitrate leaching should be carefully monitored when applying digestate, it should be noted that a similar or higher risk of nitrates leaching exists when applying synthetic fertilisers.

To mitigate leaching risks, adhering to the appropriate spreading period and considering weather conditions is paramount. Additionally, employing CULTAN (Controlled Uptake Long Term Ammonium Nutrition)* technology for fertilisation proves beneficial in enhancing nutrient efficiency and minimising the potential for leaching. Dosing should be adapted to crop requirements and nitrogen mineralisation should be taken into consideration during winter periods. The application of digestate can be coupled with the winter cultivation of catch crops able to retain nitrogen and other nutrients. Finally, at the biogas plant itself, sufficient digestate storage capacity is pivotal to allow spreading at the optimal time.

* Nabel et al., (2018) Frontiers in Plant Science 9 1095. doi: 10.3389/fpls.2018.01095

Figure 4: Illustration of nitrates leaching



A valuable soil improver, building up soil organic carbon

Digestate contains significant amounts of stable organic carbon compounds with a high humification potential, which increases the humus content of the soil, improving fertility and facilitating carbon sequestration. This increases the capacity of the soil to retain water and nutrients such as ammonium in ammoniacal form, thus reducing nitrate leaching. In contrast to the exclusive use of conventional synthetic fertilisers, long-term fertilisation with digestate enhances soil structure, soil aeration and water storage capacity. Furthermore, well-structured soil helps to foster its microbial community and, ultimately, its carbon use efficiency. Thanks to digestate's ability to store carbon in soils, digestate application is both a sustainable soil management practice and a carbon farming practice.

Typical digestate compositions

The composition of digestate depends on the nature of the substrate, the type of micro-organisms in the reactor and the operational conditions and configurations during AD (e.g. Hydraulic Retention Time, Organic Loading Rate, mixing type, temperature and pH). The substrates should contain balanced nutrients to promote bacterial growth in the reactor and are key to maintaining the quality and safety of the digestate. Due to the great variability of the inputs used, it is difficult to precisely link agronomic characteristics to the digestates produced.

EBA summarised literature results and reviews to determine the typical composition of both agricultural-based digestate and biowaste-based digestate (Table 2).

Table 2: Average nutrient composition of agricultural and biowaste-based digestate, according to literature review (source: EBA Statistical Report 2023)

	DM g/kg FM	TOC g/kg DM	TKN g/kg DM	N-NH4 g/kg DM	P g/kg DM	K g/kg DM	Ca g/kg DM	Mg g/kg DM	Data source
Agricultural	57	297	67	34	14	9	16	5	[16], [17], [18], [19], [20], [21]
Biowaste	n.a.	227	46	36	8	27	3	18	[22], [23], [24], [25]

16 Pigoli, A., Zilio, M., Tambone, F., Mazzini, S., Schepis, M., Meers, E., Schoumans, O., Giordano, A., & Adani, F. (2021). Thermophilic anaerobic digestion as suitable bioprocess producing organic and chemical renewable fertilizers: A full-scale approach. *Waste Management, 124*, 356-367. https://doi.org/10.1016/j.wasman.2021.02.028

17 Tambone, F., Orzi, V., D'Imporzano, G., & Adani, F. (2017). Solid and liquid fractionation of digestate: Mass balance, chemical characterization, and agronomic and environmental value. *Bioresource Technology, 243*, 1251-1256. https://doi.org/10.1016/j.biortech.2017.07.130

18 Reuland, G., Sigurnjak, I., Dekker, H., Sleutel, S., & Meers, E. (2022) Assessment of the Carbon and Nitrogen Mineralisation of Digestates Elaborated from Distinct Feedstock Profiles. *Agronomy, 12*, 456. https://doi.org/10.3390/agronomy12020456

19 Barduca, L., Wentzel, S., Schmidt, R., Malagoli, M., & Joergensen, R. G. (November 2020). Mineralisation of distinct biogas digestate qualities directly after application to soil. *Biology and Fertility of Soils, 57*, 235–243. https:// doi. org/10. 1007/ s00374- 020- 01521-5

20 Möller, K., & Müller, T. (2012). Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. *Engineering In Life Sciences. 12*, 242–257. https://doi.org/10.1002/elsc.201100085

21 Barampouti, E. M., Mai, S., Malamis, D., Moustakas, K., & Loizidou, M. (2020). Exploring technological alternatives of nutrient recovery from digestate as a secondary resource. *Renewable and Sustainable Energy Reviews, 134*, 110379. https://doi.org/10.1016/j.rser.2020.110379

22 Bauer, L., Ranglová, K., Masojídek, J., Drosg, B., & Meixner, K. (2021). Digestate as Sustainable Nutrient Source for Microalgae—Challenges and Prospects. *Applied Sciences, 11*(3), 1056. https://doi.org/10.3390/app11031056

23 Sheets, J. P., Yang, L., Ge, X., Wang, Z., & Li, Y. (October 2015). Beyond land application: Emerging technologies for the treatment and reuse of anaerobically digested agricultural and food waste. *Waste Management, 44*, 94–115. https://doi.org/10. 1016/j.wasman.2015.07.037

24 Jimenez J., Grigatti M., Boanini E., Patureau D., Bernet N., (2020) The impact of biogas digestate typology on nutrient recovery for plant growth: accessibility indicators for first fertilization prediction. Waste Manag. 42020:117:18-31. 10.1016/j.wasman.2020.07.052

25 García-López, A.M.; Delgado, A.; Anjos, O.; Horta, C. Digestate Not Only Affects Nutrient Availability but Also Soil Quality Indicators. Agronomy 2023, 13, 1308. https://doi.org/10.3390/agronomy13051308

Digestates can be grouped, based on qualities such as C, N, P, solids, and organic matter. Depending on the total solids (TS) concentration and the feedstock type, the digestates can be classified in core sources as follow[26]:

- Liquid fibrous (e.g. crop residues silage, cattle slurry)
- Liquid sewage sludge
- Liquid pig slurry
- Slurries co-digested with silage and green wastes (dry anaerobic digestion)
- Municipal solid wastes (dry anaerobic digestion)
- Fibrous feedstock (dry anaerobic digestion of cattle manure and green waste)

Sustainable agronomic practices for digestate applications

As with every fertiliser, digestate application on soil needs to be carefully monitored during the whole crop growth cycle to ensure that digestate contributes positively to the nutrient balance. To contribute to the Circular Economy strategy and to the Green Deal objective of reducing nutrients losses by 50% by 2030 while enhancing soil fertility, digestate application must be calibrated to the nitrogen need of the crop to ensure that:

- The available ammonium is taken up as efficiently as possible by the crop as soon as digestate is applied. To avoid the risk of nitrate leaching, farmers must aim at the best nutrient use efficiency[27]. To this end, farmers must adjust the digestate application to specific time periods and growth states on the field.
- The biodegradable organic nitrogen part in the digestate, which will continue to mineralise over time, must be controlled. Monitoring should be implemented to ensure that further digestate inputs consider the continuous nitrogen uptake by the crops.

To avoid nitrogen leaching, digestate application can be coupled with the growth of catch crops able to retain nitrogen and other nutrients[28], [29].

Direct injection of digestate in the soil, along with appropriate digestate storage, are proposed as a successful practice to mitigate odours and emissions before, during and after digestate application [30].

26 Jimenez J., Grigatti M., Boanini E., Patureau D., Bernet N., (2020) The impact of biogas digestate typology on nutrient recovery for plant growth: accessibility indicators for first fertilization prediction. Waste Manag. 42020:117:18-31. 10.1016/j.wasman.2020.07.052

27 García-López, A.M.; Delgado, A.; Anjos, O.; Horta, C. Digestate Not Only Affects Nutrient Availability but Also Soil Quality Indicators. *Agronomy* 2023, 13, 1308. https://doi.org/10.3390/agronomy13051308

28 De Notaris C., Rasmussen J., Sørensen P., Olesen J.E., (2018) Nitrogen leaching: A crop rotation perspective on the effect of N surplus, field management and use of catch crops. Agriculture, Ecosystems & Environment 255, 1, 1-11

29 Justes E.E., Rechauchère O., Chemineau P. (2012) The use of cover crops to reduce nitrate leaching: Effect on the water and nitrogen balance and other ecosystem services. INRA., 8 p. ffhal-03231464 https://hal.science/hal-03231464/document

30 Orzi, Valentina & Riva, Carlo & Scaglia, Barbara & D'Imporzano, Giuliana & Tambone, F & Adani, Fabrizio. (2017). Anaerobic digestion coupled with digestate injection reduced odour emissions from soil during manure distribution. The Science of the total environment. 621. 168-176. 10.1016/j.scitotenv.2017.11.249.

Digestate application causes increased odours

MYTH

Any biological process involving microbial metabolism leads to the generation of volatile organic compounds (VOCs) and odours. These emissions can cause annoyance and pose potential harm or toxicity to human health. In this context the AD process plays an important role in reducing VOC emissions: two third of the biodegradable organic matter is turned into biogas during the AD process, leaving a biologically stable product. This results in significantly reduced VOC emissions and odours during digestate application compared to its raw materials.

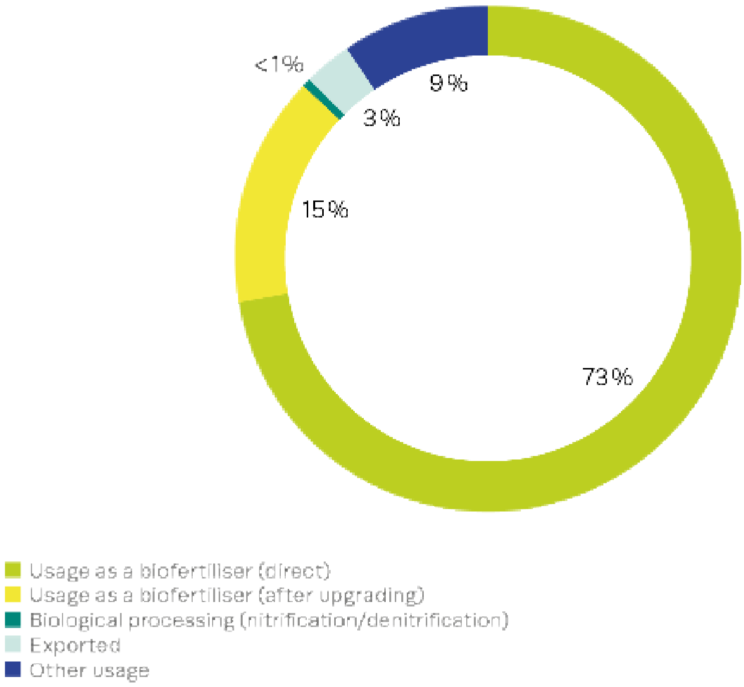
In addition to VOC emissions, ammonia (NH_3) and nitrous oxide (N_2O) emissions may occur during digestate application. The gaseous ammonia emissions are derived from the ammonium ion (NH_4^+) contained in the digestate. Effective mitigation strategies are, however, available. These include direct digestate injection into the soil, real-time nutrient monitoring, and precision agriculture methods*. Acidifying digestates or slurries to a pH of about 6 can inhibit NH_3 volatilisation, with practices such as applying acids during digestate storage or spreading reducing emissions significantly.

* Yan X., Ying Y., Kunkun Li K., Zhang Q., Wang K., (2024) A review of mitigation technologies and management strategies for greenhouse gas and air pollutant emissions in livestock production. Journal of Environmental Management 352, 120028.

Digestate end-uses in Europe

Based on available data[31], it is estimated that 73% of Europe's digestate is applied directly as a biofertiliser and about 15% of the digestate produced is upgraded before being applied to agricultural fields (Figure 4). The remaining digestates go to other applications such as horticulture, soil production, landfill coverage, biological processing, etc., or is exported.

Figure 5: Digestate end uses in Europe



31 Data available to the EBA database for Austria, Belgium, Bulgaria, Croatia, Norway, Poland, Serbia, Slovakia, Slovenia, Sweden, Switzerland, and Ukraine

Novel digestate applications

The use of digestate extends beyond its traditional application in agriculture, underscoring its value not only for nutrient recovery and soil amendments, but also for a range of other applications. These include the production of carbon materials for energy storage applications, the synthesis of nanomaterials, char, biofuels, as well as for microbial products having a broad application in the food and feed and chemical industries[32],[33].

Research and innovation are critical for the development of novel and competitive digestate valorisation options. Figure 5 summarises different digestate upgrading and processing routes. Some of the best examples of innovative applications in this area are:

- **Digestate for the cultivation of insects:** The growth of insects on digestate to produce protein is increasingly attracting research interest[34]. During the EU project VALUEWASTE[35], the pilot plant located in waste management facilities in Murcia (Spain) successfully demonstrated the valorisation of biowaste into food and feed ingredients through insects that feed on the solid digestate. The solid digestate is taken to a pilot black soldier fly rearing unit[36], which produces dried larvae. Later, these are transformed into flour with a high protein content. Examples on insect production from digestate at commercial scale by different companies in Europe show promise[37], yet additional research and development are needed.

- **Digestate as a pretreatment agent:** Liquid digestate proves to be effective as a pre-treatment agent to enhance biogas production from lignocellulosic biomass. For example, digested swine manure was used to improve the biogas production from straw, demonstrating the effect on recalcitrant biomass[38],[39],[40]. This pre-treatment approach could accelerate AD start-up and facilitates the digestion of bioplastics, offering benefits for the management of municipal organic waste[41].

32 Wang W, Chang J-S, Lee D-J., (2023) Anaerobic digestate valorisation beyond agricultural application: Current status and prospects. Bioresource Technology 373, 128742, https://doi.org/10.1016/j.biortech.2023.128742

33 Selvaraj P.S, et al., (2022) Novel resources recovery from anaerobic digestates: Current trends and future perspectives, Critical Reviews in Environmental Science and Technology, 52:11, 1915-1999, DOI: 10.1080/10643389.2020.1864957

34 Fu S-F., Wang D-H, Zhong X., Zou H, Zheng Y. (2022). Producing insect protein from food waste digestate via black soldier fly larvae cultivation: A promising choice for digestate disposal. Science of The Total Environment 830, 15, 154654 https://doi.org/10.1016/j.scitotenv.2022.154654

35 The Biorefine Cluster Europe. Valuewaste. Unlocking new value from urban biowaste. https://www.biorefine.eu/projects/valuewaste/

36 Entomo Agroindustrial. Industrial solutions for the treatment of organic matter using insects. https://entomoagroindustrial.com/en/

37 EntomoAgroindustrial https://entomoagroindustrial.com/en/

38 Zheng, H. M., Tang, F.Y., Lin, Y.Q., Xu, Z.Y., Xie, Z.H., & Tian, J. (2022). Solid-state anaerobic digestion of rice straw pretreated with swine manure digested effluent. *Journal of Cleaner Production, 348*, 131252. https://doi.org/10.1016/j.jclepro.2022.131252

39 Ma, S., Li, L., Ren, X., Zhu, W., & Wang, H. (2022). A green pretreatment strategy using CO2 and acidogenesis liquid digestate as reagents for biomethane enhancement from corn stover. *Industrial Crops and Products, 189*, 115844. https://doi.org/10.1016/j.indcrop.2022.115844

40 Liu, H., Pang, B., Zhao, Y., Lu, J., Han, Y., & Wang, H. (June 2018). Comparative study of two different alkali-mechanical pretreatments of corn stover for bioethanol production. *Fuel, 221*, 21–27. https://doi.org/10.1016/j.fuel.2018.02.088.

41 Cucina, M., Soggia, G., Nisi, P., Giordano, A., & Adani, F. (June 2022). Assessing the anaerobic degradability and the potential recovery of biomethane from different biodegradable bioplastics in a full-scale approach. *Bioresource Technology, 354*, 127224. https://doi.org/10.1016/j.biortech.2022.127224

- **Digestate in electrochemical processes:** Digestate can be used as a feeding substrate for Microbial Fuel Cells (MFC) and Microbial Electrolysis Cells (MEC) to produce electricity and H2 from methane (TRL 5).

- **Digestate as a medium for hydroponics:** The use of digestate in hydroponics has been tested and found to promote comparable plant growth to conventional fertilisers. Further studies can enhance the availability of nutrients in digestate for hydroponics (TRL 5)[42].

- **Production of volatile fatty acids (VFAs):** In the AD process, bacteria produce VFAs as intermediates during the methane formation process. A portion of these VFAs is still present in the digestate and can be extracted. VFAs are valuable as renewable building blocks for chemicals. For example, they serve as direct metabolic precursors for bioplastics (TRL 5).

- **Biostimulants – biobased and bioactive fertiliser:** Digestate has bio-stimulant properties. Specific biochemical fractions enhance plant and root growth, germination rates, nutrient mobilisation and photosynthesis. The stabilised organic matter in digestate can be optimised though specific AD strategies – the bio-stimulant effect depends on the feedstock used, for example[43] BioBoost treatment generates granular biostimulants to be used in ornamental greenery and organic farming (TRL 8-9).

- **Recovery of bio-ammonia:** Digestate contains high amounts of ammonium, which can be extracted as ammonia. This bio-ammonia is directly available after extraction and purification and can be further used, for example, to produce biohydrogen[44,45,46]. While specific TRL for fossil ammonia reforming is close to commercial maturity, the ongoing R&D efforts in this field are proving successful in enhancing the efficiency and sustainability of converting bio-ammonia to green hydrogen.

- **Microalgae growth:** The liquid fraction of digestate is a nutrient-rich solution that can be used as a low-cost medium for the growth of microalgae. The resulting microalgae biomass is rich in lipids and can be converted into high-grade fuel, proteins as a feed source, high value biofertilisers or bioplastics. The current TRL of algae growth on digestate in Europe is at stage 7, with ongoing research focusing on enhancing efficiency and sustainability[47].

42 Sakuma, S., Endo, R., & Shibuya, T., (June 2023). Acidophilic nitrification of biogas digestates accelerates sustainable hydroponics by enhancing phosphorus dissolution. *Bioresource Technology Reports, 22*, 101391. https://doi.org/10.1016/j.biteb.2023.101391

43 Scaglia, B., Nunes, R. R., Oliveira Rezende, M. O., Tambone, F., & Adani F. (August 2016) Investigating organic molecules responsible of auxin-like activity of humic acid fraction extracted from vermicompost, *Science of The Total Environment, 562,* 289-295. https://doi.org/10.1016/j.scitotenv.2016.03.212

44 Babson D.M. (2013) Anaerobic digestion for methane generation and ammonia reforming for hydrogen production: A thermodynamic energy balance of a model system to demonstrate net energy feasibility. Biomass and Bioenergy 56, 493-505.

45 https://www.wrotefarm.com/index-eng.php

46 Grasham O. et al. (2020) Hydrogen via reforming aqueous ammonia and biomethane co-products of wastewater treatment: environmental and economic sustainability *Sustainable Energy Fuels*, ,4, 5835-5850 DOI:10.1039/D0SE01335H

47 https://www.alg-ad-dst.com/

Figure 6: Overview of selected digestate valorisation routes

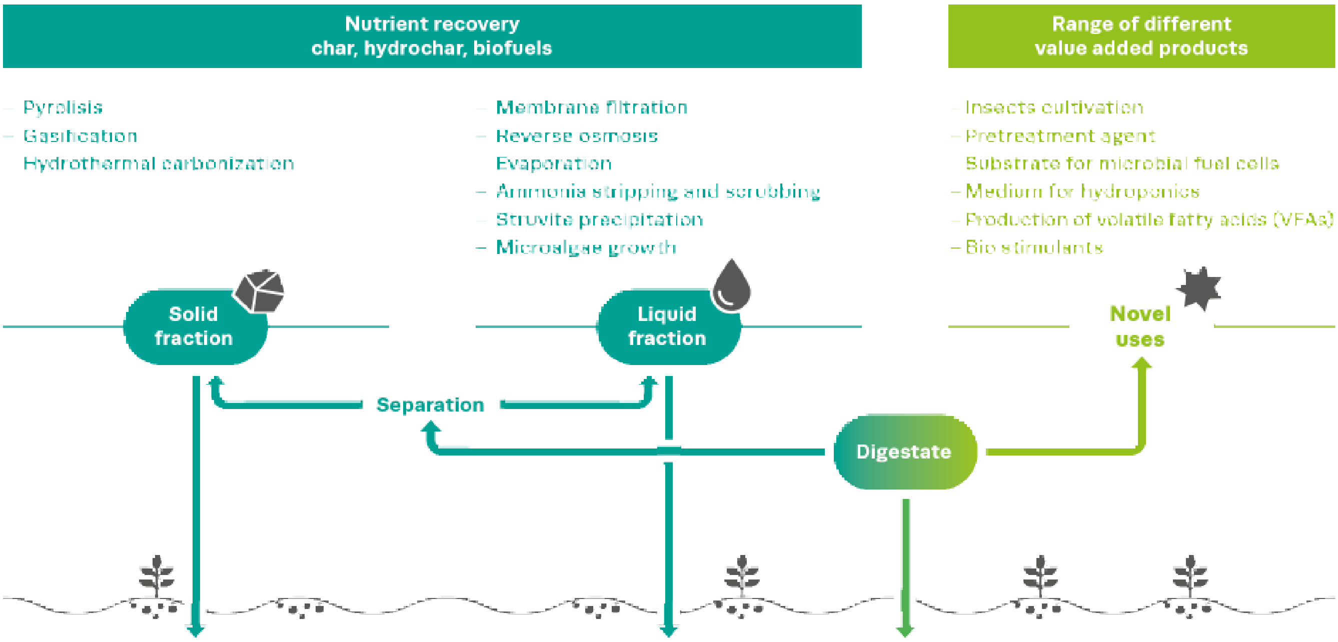
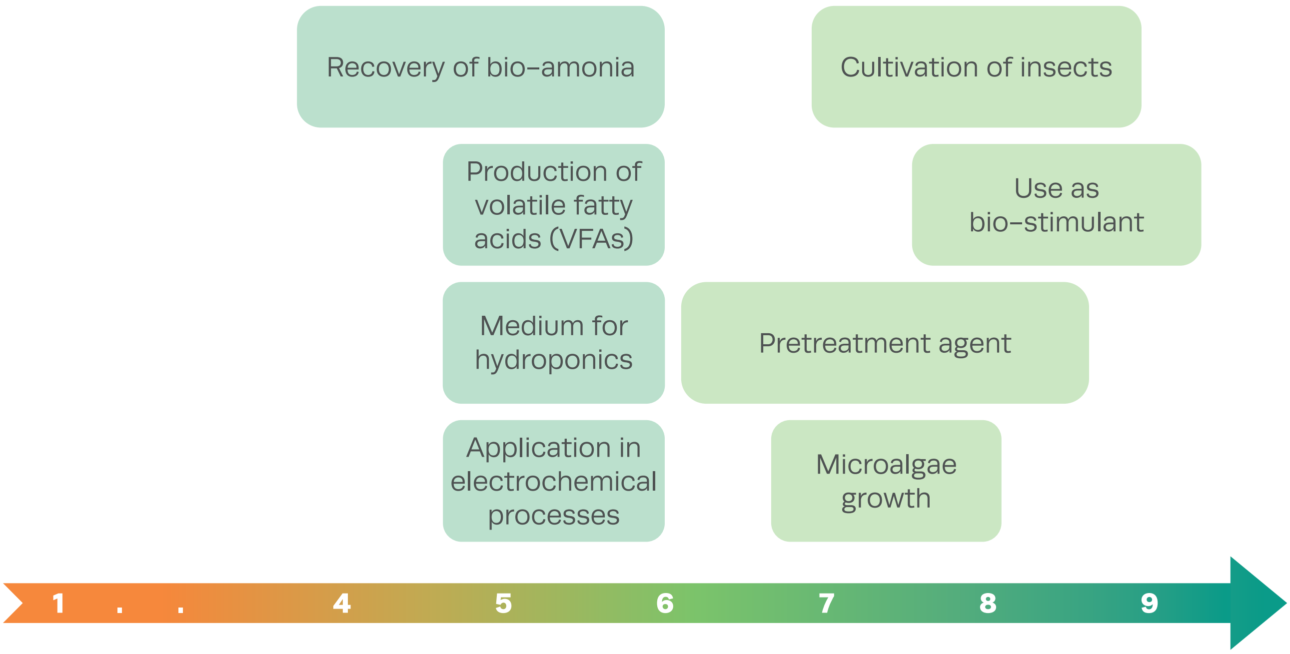


Figure 7: TRL of novel digestate applications



Chapter 4 Positive impact on environmental, climate and soil health

Positive impact on the environment

Digestate environmental impacts include energy recovery, nutrient recycling, contribution to soil health, odour reduction and sanitation properties. Table 3 illustrates the AD environmental performance as an organic waste and byproduct management practice, compared to composting, incineration, landfill, and no treatment of the biowaste.

Table 3: Comparison between anaerobic digestion, composting, incineration, landfill, and no treatment as organic waste and byproduct management practices

	Anaerobic digestion	Composting	Incineration	Landfill	No treatment
Energy recovery	Yes; energy is recovered in the form of biogases	No	Limited; the generated heat from waste incineration is often used to drive turbines and generate electricity	Limited; landfill gas can be recovered from landfills.	No
Nutrient recycling	Yes; nutrients are preserved in the digestate during digestion	Limited; compost retains high fraction of initial carbon, but loses nutrients	Limited; nutrients can be recovered from the ash after incineration	No	Limited; for some byproducts such as manure, nutrients can be recovered when applied without treatment.
Contribution to soil health	Yes; digestate contributes to humus formation	Yes; compost contributes to humus formation	No	No	No; untreated organic waste or byproducts can result in high concentration of minerals in a reduced place, with risks for soil health.
Odour reductions	Yes; odours are reduced during anaerobic digestion	Yes; odours are reduced during the composting process	Yes	Limited; proper landfill management practices are required to reduce odours	No
Sanitation	Yes; anaerobic digestion has sanitation properties	Yes; composting has sanitation properties	Yes	No	No

Digestate has a lower environmental impact compared to raw manure

FACT

In biogas plants, manure and other agricultural by-products undergo a substantial maturation and stabilisation process during the anaerobic digestion process. As a results, digestate has reduced natural occurring methane emissions and odours compared to raw manure. In particular, the AD process typically breaks down the more biodegradable organic fraction (e.g. carbohydrates) and concentrates the poorly degradable organic fraction (e.g. lignin). Consequently, digestate has a higher degree of biological stability compared to its raw materials *. A high degree of biological stability results in a lower impact on the environment: the average methane and nitrous oxides (N_2O) emissions from digestate is typically reduced to 59% compared to raw untreated manure **, ***.

---

* Tambone F., Genevini P., D'Imporzano G., Adani F., (2009) Assessing amendment properties of digestate by studying the organic matter composition and the degree of biological stability during the anaerobic digestion of the organic fraction of MSW. Bioresource Technology 100, 3140–3142.

** Riva, C., Orzi, V., Carozzi, M. et al. (2016). Science of the Total Environment 547: 206–214.

*** Adani F. et al., 2020, Ch.5.2 In. Biorefinery of inorganics: recovering mineral nutrients from biomass and organic waste Erik Meers, Faculty of Bioscience Engineer, Laboratory of Analytical Chem, Gerard Velthof, Evi Michels, Rene Rietra, Wageningen University. (Eds) DOI 10.1002/9781118921487.

Digestate is a safer fertiliser compared to its raw materials

FACT

Due to its exceptionally good fertilising properties, digestate is much less likely than raw organic waste to be disposed of inappropriately (in landfill or open storage). This significantly reduces the risk of water, soil and air pollution resulting from high concentrations of minerals in a reduced space. Furthermore, animal and plant pathogens that may be present in the original feedstock are either vastly diminished or wholly eradicated, due to the technical and thermal pre-treatment of the feedstock and the microbial conditions inside the digester (in particular the combined factors of temperature, microbial competition and ammonia production)*. Although further work is required to evaluate in detail the impact of digestate and treatments such as pre and post pasteurisation, which further sanitise the digestate, research indicates that digestion plants have the capacity to minimise the risk of any pathogens**. These positive functions not only overcome the negative effect on human and animal health but also contribute to the control of plant pests and diseases. National quality assurance schemes have already been implemented in several member states to ensure that operators comply with quality standards for digestate and prevent negative effects of digestate application to the soil***.

---

* Jiang, Y., Xie, S. H., Dennehy, C., Lawlor, P.G., Hu, Z. H., Wu, G. X., Zhan, X. M., & Gardiner, G. E. (March 2020). Inactivation of pathogens in anaerobic digestion systems for converting biowastes to bioenergy: a review. *Renewable and Sustainable Energy Reviews, 120*, 109654 https:// doi.org/10.1016/j.rser.2019.109654

** Redhead, S., Nieuwland, J., Esteves, S., Lee, D.-H., Kim, D.W., Mathias, J., Cha, C.-J., Toleman, M., Dinsdale, R., Guwy, A., & Hayhurst, E. (December 2020). Fate of antibiotic resistant E. coli and antibiotic resistance genes during full scale conventional and advanced anaerobic digestion of sewage sludge. PLoS ONE, 15(12), e0237283. https://doi.org/10.1371/journal.pone.0237283

*** van Midden, C., Harris J., Shaw L., Sizmur T., & Pawlett M. (November 2023). The impact of anaerobic digestate on soil life: A review, *Applied Soil Ecology, 191*, 105066. https://doi.org/10.1016/j.apsoil.2023.105066

Positive impact on climate

Digestate drastically reduces greenhouse gas emissions in the food, feed, beverage and agricultural sectors. Specific emissions associated with agriculture include manure management and the production and use of synthetic fertilisers. Digestate reduces GHG emissions in different manners:

1). **Avoiding GHG emissions from open decomposition of organic matter.** All organic materials can release powerful GHGs such as CH_4 and NO_x, if they are left uncovered. This includes household waste in the form of sewage sludge and biowaste, agricultural leftovers such as manure and straw, as well as waste from food and beverage processing. Digestion avoids these unwanted emissions, as the organic matter is taken to the closed and controlled environment of AD plants. In the biogas facility, methane is captured and utilised instead of being released into the atmosphere.

2). **Digestate reduces the energy-intensive production of synthetic fertilisers.** Europe's food and feed production is heavily dependent on industrially manufactured synthetic fertilisers. The Haber-Bosch process fixes most of the nitrogen used in agriculture and accounts for 1-2% of world's total energy consumption and 3-5% of the world's natural gas consumption[48]. Digestate reduces synthetic fertiliser production and usage because it reduces nitrogen losses in comparison to the direct application of raw manure and other biowastes as fertilisers. The reduction of synthetic fertilisers usage includes 1) the part of raw manure that would otherwise go to biological processing with the nitrogen content being converted to atmospheric nitrogen (N_2) and lost to the atmosphere; 2) thanks to anaerobic digestion, the recovery of biowastes that would otherwise go to incineration, landfill or be left untreated; 3) increased availability of nutrients in digestate compared to its raw materials.

3). **Soil carbon sequestration.** In the AD reactor, 20 to 95% of the ingoing organic matter is converted into biogas[49]; and the remaining organic matter is present in a more stable form. This residual carbon has a higher potential for sequestration in the form of soil organic carbon, thus enable soils to serve as carbon sinks[50].

4). **Digestate's transport routes are usually shortened, resulting in low GHG emissions.** This is due to the decentralised nature of anaerobic digestion. Farmers have an interest in minimising transport costs and enabling owners and co-owners of biogas plants to produce their own fertilisers at competitive costs.

Positive impact on soil health

Soils are the foundation of our agri-food system. They regulate nutrient, carbon and water cycles and provide a habitat for biodiversity. Soils also play an essential role in the circular economy and adaptation to climate change.

Nevertheless, today 60 to 70% of the European soils are unhealthy[51] due to climate change, extreme weather events, unsustainable soil management, intensification of agricultural practices, industrial, etc. The costs of soil

48 Estimates widely acknowledged with the scientific and industrial communities.

49 Möller, K., & Müller, T. (May 2012). Effects of Anaerobic Digestion on Digestate Nutrient Availability and Crop Growth: A Review.

50 https://4p1000.org/

51 Commission Staff Working Document accompanying the EU soil strategy for 2030 of 17 November 2021 SWD(2021)323 final.

degradation are estimated to exceed 50 billion euros per year[52].

The application of digestate to agricultural soils is recognised as a sustainable soil management practice in the recent European Commission proposal for Soil Monitoring Law. The stable organic fraction of digestate sustainably enriches the humus content of the soil. If digestate is separated, the humus-forming fraction is found mainly in the solid fraction[53].

Humus formation is critically important for soils due to several reasons:

- **Nutrient retention:** Humus acts as a reservoir for essential plant nutrients such as nitrogen, phosphorus, and potassium. It can hold onto these nutrients in a form that is accessible to plants, preventing them from leaching away with water.

- **Soil structure improvement:** Humus helps improve soil structure by binding soil particles together. This creates pore spaces in the soil, enhancing water infiltration and retention, as well as allowing for better root penetration and aeration.

- **Water retention:** Humus has high water-holding capacity, helping soils retain moisture during dry periods and reducing the risk of water runoff and soil erosion.

- **pH buffering:** Humus can buffer soil pH, helping to maintain a stable environment for soil organisms and plant roots. This is important because extreme pH levels can inhibit nutrient availability and biological activity.

- **Microbial habitat:** Humus provides a conducive habitat for soil microorganisms, including beneficial bacteria and fungi. These microorganisms play crucial roles in nutrient cycling, decomposition of organic matter and overall soil health.

- **Carbon sequestration:** Humus is rich in organic carbon and its formation contributes to the sequestration of carbon dioxide from the atmosphere.

Overall, humus formation is essential for maintaining fertile, productive soils that support healthy plant growth and ecosystem functioning.

52 Commission Staff Working Document, Impact Assessment Report accompanying the proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law), SWD(2023) 417 final, Part 1/5, p. 5.

53 Fachverband Biogas e. V. (German Biogas Association). (2018). Digestate as Fertilizer.

Chapter 5 Marketing strategies and case studies

Economic consideration

The availability of digestate on-site, especially in rural areas, reduces synthetic fertiliser use costs. As fertilisers are produced on-site, transportation costs are also reduced. As the market for digestate as an organic fertiliser develops, its commercialisation will also provide an additional income to farmers. The use of digestate boosts soil health and thus contributes to maintaining high crop yields and farm activities. A further revenue streams for farmers could also be opened if they were to be rewarded for carbon capture and storage in the soil. Biogas farming allows a significant reduction in the environmental impact of agricultural systems, ensuring adaptation to climate change and more stable, safe, and high-quality agricultural production.

The use of digestate and digestate upgrading technologies is particularly interesting to promote the transfer of nutrients from areas with nutrient surplus to be used in areas where such a surplus does not exist. Digestate upgrading technologies can reduce the volume and thus concentrate nutrients, allowing of easier and cheaper transport.

Marketing strategies

Operators of biogas plants have to make a number of marketing decisions concerning the economically optimal use of digestate. The crucial factor is which target customer groups the digestate will be sold to. The design of the product, the sales channel, communication, and price all depend on this.[54]

Thus far, most biogas plants have been de-livering their digestate untreated to farms, preferably to areas very near to the plant. This is particularly true for liquid fraction digestate. Upgrading of digestate, possible coupled with adaption of the nutrient content and standar-disation, taps into new sales markets, such as private gardeners. The three main factors to consider are:

- **The design of the product:** the use of various upgrading technologies allows a range of products, as describe in Chapter 2, to be produced. For example, farms can use unprocessed digestate with low dry matter content. Private gardeners, on the other hand prefer solid products such as pellets or concentrated liquid products.
- **The distribution path:** Farmers are more likely to be served directly by the plant operators. Private gardeners, on the other hand, usually buy their fertiliser products in garden centres.
- **Pricing:** Large differences exist between customer groups. In nutrient-rich regions, it is quite common for digestate to be sup-plied by plant operators free of charge or even with an additional payment to farmers. In contrast, the product price for private gardeners are several hundred times higher than in the agricultural sector. These prices must, however, also cover the costs of pro-cessing, marketing, and sales.[55]

Two case studies are highlighted below, in which biogas plants have a particular marketing strategy for their digestate.

Egg Energy, Latvia

Key facts:

- **Plant size:** up to 2,000 m^3 of biogas per hour; ongoing expansion up to 3,000 m^3/h which is equivalent to 1,800 m^3/h of biomethane.
- **Location:** Lecava, Latvia
- **Digestate products:**
  - → 7,000 tons/year of pelleted fertiliser from the solid fraction
- **Digestate upgrading technology:** separation with belt press, nitrogen stripping and scru-bbing and pelleting.
- **Start of operation:** 2015

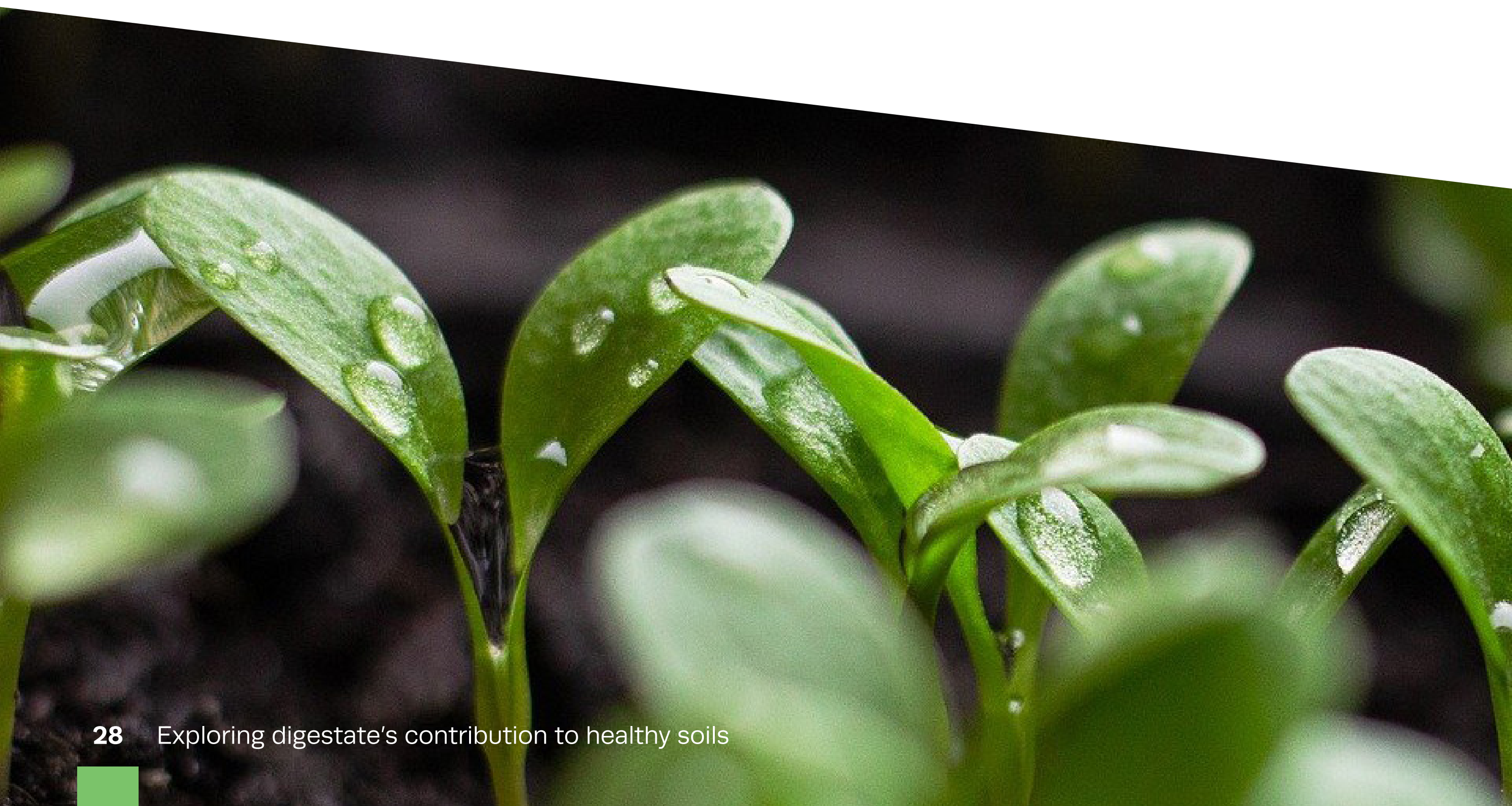
54 Fachverband Biogas e.V., *Digestate as fertilizer* (2018)

55 Fachverband Biogas e.V., *Digestate as fertilizer* (2018)

Egg Energy Ltd processes 85,000 m³ of 100% poultry manure annually. All of it is supplied by Balticovo AS, which is the largest producer of eggs and egg products in Northern Europe. The manure is mixed with water and fed into fermenters. The plant is fully automated and 24h supervised to ensure continuous process and quality control. After fermentation, the digestate is separated via belt press. The solid fraction is pelleted. The result is a highly marketable product: OrganiQ (5mm pellets with NPK 3-7-1). Pasteurisation at 70°C has eliminated all pathogenic organism. Standard wholesale packaging is 1,000 kg big bags. Additionally, any retailing packaging can be provided upon request.

Biogas production at egg energy started in 2015, with the addition of biomethane production in 2024. Currently, a 50% capacity increase of the biomethane upgrading unit is under construction and will result in a total biomethane production capacity of 1,800 m³/h.

OrganiQ: high quality pelleted organic fertiliser with a high content of organic matter, phosphorus (P), sulphur (S), magnesium (Mg) and calcium (Ca). The fertiliser contains the most important micronutrients content for plants such as B, Mn, Cu and Zn.



Guilliams Green Power plant, Belgium

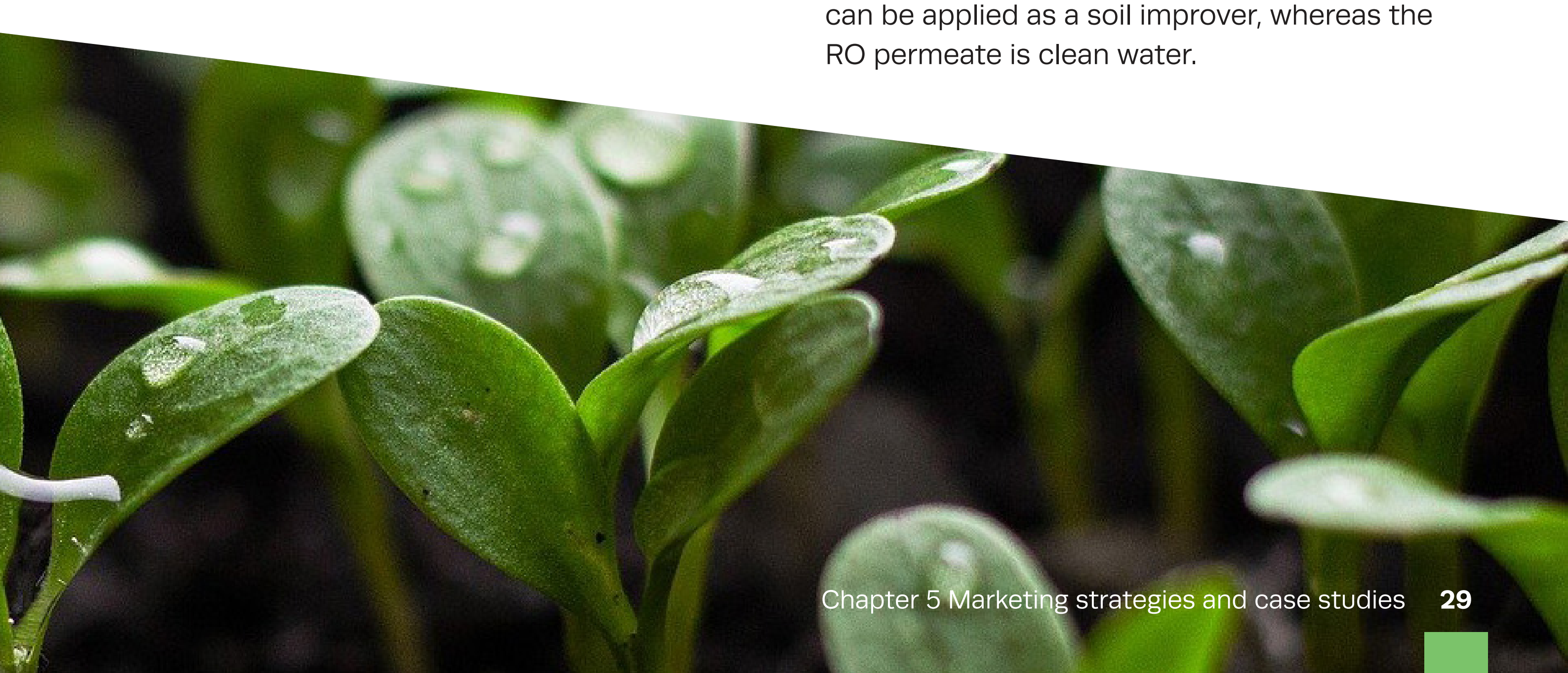
Key facts:

- **Plant size:** 3 MW electric capacity
- **Location:** Boutersem, Belgium
- **Digestate products:**
  - → 200 litres/day clean water
  - → Solid fraction organic fertiliser
  - → Soil improver
- **Digestate upgrading technology:** digestate separation, nitrification/denitrification, ultra-filtration, reverse osmosis.
- **Start of operation:** 2008

The Guilliams Power biogas plant located in Boutersem transforms organic waste (e.g. potato waste, pig farm manure) into renewable energy. The plant is fed with 90,000 tonnes of waste per year, powering a CHP engine of 3 MW electric capacity. Part of the electricity is injected into the grid or used in their car charging station. The plant produces enough electricity to cover the power consumption needs of over 7,800 families or more than 10,000 electric cars.

The digestate that remains from the biogas production undergoes a disinfection process to eliminate bacteria and, after separation, the solid fraction is exported to France as an organic fertiliser. In 2023, the plant decided to step up the circularity of their plant by installing an innovative technology, producing clean water from the digestate's liquid fraction. Since then, the plant is self-sufficient in terms of water supply. The cleaned water can be used for industrial processes or to maintain the green areas of the municipality of Boutersem.

The liquid fraction is fed to two aeration tanks on site where nitrogen removal takes place thanks to the nitrification/denitrification process. The effluent first passes through a rotary sieve before ultrafiltration (UF) takes place. The UF concentrate is then returned to the original aeration tanks. The filtered effluent undergoes further reverse osmosis (RO) treatment, in which salts are removed. The RO concentrate can be applied as a soil improver, whereas the RO permeate is clean water.



Chapter 6 Regulatory Framework

Regulatory framework for digestate at EU level

Several legislations regulate the production, application and marketing of digestate in the European Union. These policies encompass various aspects of digestate management, including its production processes, quality standards, application rates and environmental considerations. They often depend on the input used in the anaerobic digestion process. Policies governing digestate at EU level include the Waste Framework Directive, the Animal By-Products Regulation, the Fertilisers Regulation, and the Nitrates Directive and the Sewage Sludge Directive. Additionally, individual member states may have their own specific regulations and guidelines pertaining to digestate management to ensure compliance with EU directives and to address local environmental and agricultural needs.

On one hand, this framework ensures safe management of digestate and digestate products. On the other hand, its complexity and heterogeneity complicate compliance.

The **Waste Framework Directive 2008/98/EC** (WFD)[56] establishes targets and requirements for recycling and recovering waste materials to reduce the reliance on landfilling and incineration. It sets specific targets for recycling and aims to promote the use of environmentally sound recovery techniques[57] (including recycling), e.g. anaerobic digestion. The WFD introduces the waste hierarchy principle, which prioritises waste management options based on their environmental impact (1/ prevention; 2/ preparing for re-use; 3/ recycling; 4/ other recovery, e.g. energy recovery; and 5/ disposal). The WFD indicates that biowaste entering anaerobic digestion should be counted as recycled when resulting in digestate, which is to be used as a recycled product, material or substance[58]. Article 6 details the end-of-waste status and recommends Member States to take measures to ensure that waste which has undergone a recycling or other recovery operation is considered to have ceased to be waste if it complies with specific conditions. In Member States, the implementation of the WFD varies significantly, resulting in digestate being classified under different types of recovery or recycling operations, which in many cases means that digestate continues to be classified as waste.

In the European Union, the **Fertilising Products Regulation (EU) 2019/2009** (FPR)[59] establishes harmonised rules for the availability of fertilising products in the EU market, including fertilisers derived from digestate. This regulation is a milestone one as it enables recycled organic fertilisers and soil improvers (composts and digestate products) access to the EU internal market so that they can compete on an equal level with synthetic fertilisers. The requirements of the FPR are optional for Member States. Where the products are marketed at national level, Member states may establish different sets of rules[60]. 'Making available on

56 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008L0098-20240218

57 A non-exhaustive list of recovery operations is listed in Annex II.

58 Where the output is used on land, Member States may count it as recycled only if this use results in benefits to agriculture or ecological improvement.

59 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02019R1009-20230316

60 When a digestate producer from a Country A wants to place its product on the market of Country B, it will be able to place its digestate product compliant 1/ with the Fertilising Products Regulation, 2/ with the national waste or fertiliser legislation of Country A, based on the principle of mutual recognition (necessary to obtain an authorisation from national authorities), or 3/ with the national waste or fertiliser legislation in place in Country B.

the market' is defined in the FPR as "*any supply of an EU fertilising product for distribution or use on the Union market in the course of a commercial activity, whether in return for payment or free of charge*". The fertilising product can be composed of several Component Material Categories (CMCs) and will need to be classified in a Product Function Category (PFC). For digestate, two CMCs are generally used – 'CMC 4 Fresh crop digestate' and 'CMC 5 Digestate other than fresh crop digestate', and three PFCs – 'PFC I.A.I. Solid organic fertiliser', 'PFC I.A.II. Liquid organic fertiliser' or 'PFC 3.A. Organic Soil Improver'. Based on the PFC and CMC chosen by the fertilising products manufacturer, different quality assurance schemes (named "modules" in the FPR) will need to be performed with one of the EU notification bodies. The quality assurance of the production process is the conformity assessment procedure whereby the manufacturer fulfils the obligations laid down in the FPR and ensures that the EU fertilising products concerned satisfy the requirements that apply to them. Depending on the PFC and CMC, manufacturers may, for example, need to comply with limits for heavy metals or pathogens, or specific process requirements. Fertilising products certified under the FPR receive the end-of-waste status.

Depending on the substrates used in the anaerobic digestion, additional requirements may be imposed for digestate management. For example, the **Animal By-Products Regulation (EC) 1069/2009 (APBR)**[61] regulates the handling, processing and disposal of animal by-products and derived products. The regulation identifies three categories of animal by-products: Category 1 (highest risk to public and animal health), Category 2 (intermediate risk materials e.g. manure) and Category 3 (low risk materials e.g. catering waste). The ABPR also defines strict requirements for the traceability and identification of animal by-products throughout the production and processing chain, as well as requirements for storage, transportation, and processing facilities. For instance, it sets out rules for biogas plants processing animal by products[62]: the standard transformation parameter is 1 hour at 70°C with particles no larger than 12 mm, but the competent authorities at national level can authorise the use of alternative parameters. The **Regulation (EU) 142/2011**[63] complements the ABPR. Digestate, being a co-product of anaerobic digestion, may contain animal-derived materials if animal manure is part of the feedstock used in the AD process. The ABPR indicates that Category 2 and 3 animal by-products can be used for fertiliser production. In order to be included in a Component Material Category (CMC) under the Fertilising Products Regulation, animal by-products need to reach an end point as per article 5 of the ABPR. There is therefore a direct link between the ABPR and the FPR. The end point for digestate as organic fertilisers and soil improvers was only recently provided by the **Delegated Regulation (EU) 2023/1605**[64]. The end point consists in the digestate being compliant with several requirements of the ABPR (including the standard transformation parameter). Beyond the end point, when digestate from animal by-products is used as a component material under the FPR, the digestate-derived fertilising product is no longer subject to the ABPR.

The **Nitrates Directive 91/676/EEC**[65] will impact the application of digestate derived from animal manure. Adopted in 1991, the Directive addresses the issue of nitrate pollution in surface and groundwaters, which can have adverse effects on aquatic ecosystems and human health. Member states are required

61 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02009R1069-20191214

62 Listed in Annex V of ABPR

63 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02011R0142-20231214

64 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.198.01.0001.01.ENG&toc=OJ%3AL%3A2023%3A198%3ATOC

65 https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1561542776070&uri=CELEX:01991L0676-20081211

to identify areas within their territories where waters are polluted or at risk of pollution from nitrates originating from agricultural sources. These designated Nitrate Vulnerable Zones (NVZs) are subject to specific measures aimed at reducing nitrate pollution. Member states must develop and implement action programmes for each NVZ aimed at reducing nitrate pollution from agricultural activities. These action programmes typically include measures such as the implementation of nutrient management plans, restrictions on the timing and application rates of fertilisers, requirements for manure storage and application, and measures to promote the use of good agricultural practices (the measures to be included are listed in Annex III). One of the measures prescribed is to limit the application of nitrogen from manure and processed manure (including digestate)[66] to 170 kg per hectare per year. In order to reach crop requirement (e.g. 250 kg per hectare per year for certain crops), farmers are therefore compelled to use synthetic fertilisers instead of manure-derived products. As it is a directive, Member States also have some flexibility in the implementation of the rules.

The **Sewage Sludge Directive 86/278/EEC**[67] aims at encouraging the application of sewage sludge in agriculture while preventing negative health and environmental impacts. It sets quality requirements for the sludge and the soil on which it is to be used by setting upper limits on their heavy metal content. It also requires sludge treatment before application[68] and consideration of the nutrient needs of the plants. Finally, the directive prohibits the use of sludge on grassland and soil under fruit and vegetable crops (with certain exceptions). In line with the WFD, some Member States have adopted a national 'end-of-waste' criteria recognising the status of digestate from sewage sludge as product and no longer waste. More information on the implementation of the Directive is available in the last evaluation of the European Commission[69].

66 Indeed, according to the Nitrates Directive, processed manure – including digestate from manure – is considered manure.

67 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A01986L0278-20220101

68 The Directive does not define treatment, so treated sludge could in principle be a product resulting from any treatment, e.g. digestate from anaerobic digestion, compost or even incineration ashes. It must be noted that sewage sludge from urban wastewaters, included in the scope of the Directive, has also often undergone anaerobic digestion.

69 https://ec.europa.eu/transparency/documents-register/detail?ref=SWD(2023)157&lang=en

Regulatory framework at national level

Aiming to outline specific requirements for digestate management at the member state level, the EBA Secretariat conducted numerous interviews with representatives from national biogas associations or leading biogas companies across 20 Member States of the European Union. Table 4. Key aspects of national regulatory frameworks for digestate provides a summary of the findings from this analysis. Access to the in-depth country analysis is available exclusively to EBA members.

Table 4: Key aspects of national regulatory frameworks for digestate

	Inclusion of digestate in a legislation on fertilisers	End-of-waste for digestate	Quality assurance scheme/certification for digestate	Additional rule for digestate
Austria	Yes, in Fertilizer Act and Ordinance	No	No	From 2028, storage for liquid digestate above 240 m³ will have to be equipped with a permanently effective, full-surface cover.
Belgium	No, Royal Decree on marketing and use of fertilisers, soil improvers and cultivation substrates not including digestate	Yes, in Flanders when compliant with the Flemish Regulation On Sustainable Management of Material Cycles and Waste Materials (VLAREMA) and VLACO No, in Wallonia	No in Wallonia Yes, in Flanders, VLACO	
Croatia	Yes, but under revision	Yes, when compliant with the Law on Fertiliser Products (NN 39/2023) and Regulation on the Cancellation of Waste Status (NN 55/2023)	No	
Czechia	Yes, in Act on Fertilisers 156/1998 and Decree 474/2000 on the specification of requirements for fertilisers	Yes, when compliant with Act on Fertilisers 156/1998 and Decree 474/2000 on the specification of requirements for fertilisers	No	
Denmark	No, but it can be classified as livestock manure under national law	No	No	When less than 25% of the digestate originates from waste (and more than 75% from livestock manure), digestate is considered livestock manure, leading to a similar effect as an end-of-waste status.

Estonia	Yes, in Regulation n°12 of Ministry of Environment – Requirements for digestate from biogas production from biowaste (but only for digestate from biowaste)	Yes, in Regulation n°12 of Ministry of Environment – Requirements for digestate from biogas production from biowaste (but only for digestate from biowaste)	No	
Finland	Yes, in the Fertilisers Act	No	Yes, "Laatulannoite" certification	
France	No, but other options	Yes, via a Marketing authorisation for digestates or compliance with Digestates Specifications	No	Digestate from animal by-products is treated as waste and requires a spreading plan.
Germany	Yes, in the Farm fertilisers Ordinance and Fertiliser Ordinance	No	Yes, "Gärprodukt NawaRo" Certification and "Gärprodukt" Certification by BGK	
Greece	No, but it can be classified as soil improver under national law	No	No	
Hungary	No	No	No	
Ireland	No	No	No	The use of 'own manures' (only) at an on-farm AD plant for 'own use' does not fall under waste legislation but the import of manures from other sources brings the operation under waste legislation (as they have left original farm for treatment).
Italy	Yes, in Legislative Decree of 29 April 2010, n 75	Yes, for digestate from agri-food activity compliant with requirements in Interministerial Decree 5046 of 25 February 2016	No	Digestate can be classified as "agrozootechnical" or "agri-industry" digestate depending on the feedstocks used. The producer of "agri-industry" digestate must be able to demonstrate the existence of a specific contract with the supplier of the input material. The Italian Biogas Association has established guidelines for the use of digestate in organic farming, in collaboration with organic farming associations.
Latvia	No, the Law on Circulation of Fertilisers does not include digestate	No	No	

The Netherlands	Yes, in the Fertilisers Act, Implementation Decree on the Fertilisers Act and Fertilisers Act Implementation Regulations	No	No	
Poland	Yes, in the Regulation on the implementation of certain provisions of the Act on fertilisers and fertilisation (currently being updated)	Yes, when compliant with the Regulation on the implementation of certain provisions of the Act on fertilisers and fertilisation	No	
Portugal	No, Decree-Law 103/2015 not including digestate	No	No	
Slovakia	Yes, in Fertilisers Act and Fertilisers Decree	Yes, if compliant with the requirements of Fertilisers Act and Fertilisers Decree	No	
Spain	Yes, in Royal Decree 506/2013 on Fertilisers products	Yes, in Royal Decree 506/2013 on Fertiliser products but impossible to meet requirements	No	Since 2022, Royal Decree 1051/2022 on sustainable nutrition in agricultural soils regulating the application of digestate to the soil (including the internal digestate application on the fields of the biogas plant where the digestate is produced) represents a major barrier because it is based on strict requirements of CMC 4 and 5
Sweden	No, but no need because certification possible	No	Yes, SPCR 120 for biofertilisers and REVAQ certification for digestate from sewage sludge	

Key takeaways from the interviews

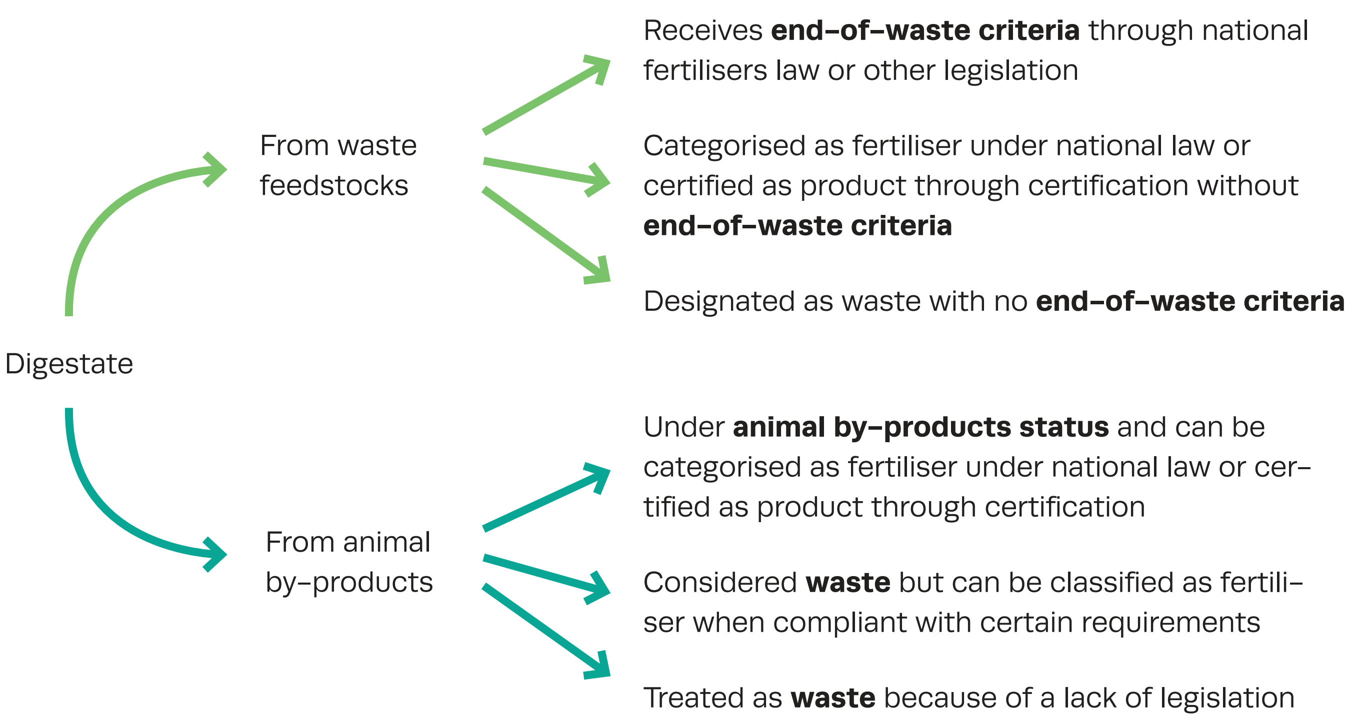
Digestate market:

In some countries (such as Austria, Belgium (Wallonia), France, Germany, Latvia, Sweden), the local digestate market functions effectively, even with free supply or trade against input materials. Consequently, digestate management and regulatory frameworks are not always prioritised by biogas producers in these regions.

Conversely, in other countries—often those grappling with poor water quality[70], eutrophication, and groundwater pollution, and where these issues are under intense scrutiny by citizens and government —digestate usage is more tightly regulated. This heightened regulation can lead to potential challenges in digestate management. In such cases, biogas producers are compelled to seek regulatory (and technical) solutions to better recognise the benefits of digestate and potentially explore export opportunities.

Another crucial factor influencing the digestate market is the connection of biogas plants to the soil. "Industrial" biogas plants, which process industrial waste, household biowaste, or wastewater, typically lack the land needed to apply digestate. In such scenarios, biogas producers must collaborate with nearby farmers to find solutions for digestate application. This challenge may be exacerbated in countries where agriculture relies heavily on intensive livestock farming with limited arable land. This situation contrasts starkly with the model of on-farm biogas, where the biogas plant is integrated into agricultural operations.

Figure 8: General features of national regulatory framework for digestate



70 According to the last implementation report of the Nitrates Directive by the European Commission – https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC1000, countries which need to take urgently extra steps to achieve the objectives of the Nitrates Directive are Belgium, Czechia, Germany, Luxemburg, the Netherlands and Spain.

In general, the regulatory framework for digestate is organised as follows:

- **Digestate from waste feedstocks** (e.g. biowaste, industrial waste, agricultural residues[71]):

    1). ***Digestate receives end-of-waste status through national fertilisers law*** (Croatia, Czechia, Estonia, Poland, Slovakia, Spain) ***or other legislation*** (Flanders, France, Italy[72]). In this case, the administrative burden is not necessarily lessened.

    2). ***Digestate is categorised as fertiliser[73] under national law*** (Austria, Finland, Germany, Greece, the Netherlands), ***or certified as a product through certification*** (Sweden) ***even without end-of-waste criteria***. In this case, even without being granted end-of-waste criteria, the effect is similar to having an end-of-waste status.

    3). ***Digestate is designated as waste with no end-of-waste criteria*** (Hungary, Ireland, Latvia, Portugal, Wallonia): producers must obtain a specific authorisation/certificate of use to apply their digestate or respect a spreading plan (that will need to be frequently updated). This typically entails a high administrative burden and is not conducive to adapting to changes in feedstocks.

  Setting an end-of-waste criteria is not always the primary concern. The key factor is to have clear legislation providing legal certainty for all types of products and requirements that can be easily operationalised, thus avoiding red-tape. Indeed, the significance of retaining the waste classification does not primarily revolve around the administrative burden or regulatory obstacles, but rather the public perception of digestate. As long as digestate is classified as waste, its value is diminished, hindering its broader acceptance and utilisation.

- **Digestate from animal by-products**

    1). ***Digestate has animal by-product status and can be categorised as fertiliser[74] under national law or certified as a product/fertiliser through certification*** (Croatia, Czechia, Finland, Germany, Greece, Italy, The Netherlands, Poland, Slovakia, Spain, Sweden).

    2). ***Digestate from animal by-product is considered waste but can be classified as fertiliser when compliant with certain requirements*** (Austria and France).

    3). ***Digestate from animal by-products is treated as waste because of a lack of legislation*** (Hungary, Ireland, Latvia, Portugal, Wallonia): digestate from animal by-products face similar restrictions as digestate originating from waste.

  Clear legislation will also help to clarify the status of digestate from animal by-products and enable the uptake of this market.

The framework for digestate is complex and far from being harmonised across Member States. It can become even more intricate, as legislative requirements for digestate generally

71 Sometimes digestate from crops or agricultural residues is not considered waste but a by-product.

72 In certain cases.

73 Or soil improver.

74 Or soil improver.

apply to the placing on the market of digestate (e.g. generally defined as free supply or sale). Different sets of requirements depend on the origin, utilisation and marketing conditions of digestate[75].

Quality assurance scheme/certification for digestate:

Quality assurance schemes are particularly useful as a means to build trust in the product with users. They are often designed for digestate originating from biowaste and sewage sludge, input materials which generally yield most concerns in terms of toxicity or environmental impact. Closer monitoring of the process to prove compliance with hygienic standards or when adding additional contaminants to be tested in these products leads to high-quality products more able to build social acceptance.

Main barriers for the uptake of digestate:

- During the interviews, the primary regulatory barrier highlighted by respondents was the Nitrates Directive limit which restricts the application of digestate from manure. For many stakeholders, the authorisation of RENURE products[76] from 170kg of nitrogen per hectare per year[77] to crop requirement would be a first step towards creating a level playing field between organic and synthetic fertilisers.

- The lack of fertiliser/product status for digestate in national law is also a major barrier as it leads to a depreciation of the value of digestate.

- In general, the complexity of the regulatory framework for digestate, especially when farmers are the digestate producers, is an issue.

- Stakeholders agree that the value of digestate as an organic fertiliser and soil improver is not sufficiently acknowledged and that farmers in many countries still mistrust the product. For some stakeholders, digestate-derived products should be further valorised as an alternative to synthetic fertilisers, and the low price of synthetic fertilisers remains the main issue for digestate uptake. Regulatory drivers are crucial to promote the adoption of digestate in agriculture.

75 This includes considering if digestate is: 1/ directly applied to the land belonging to the biogas plant/digestate producer vs. when digestate is freely supplied or sold to another farmer for an application on fields outside the initial biogas plant, 2/ when digestate is made from internal input materials vs. made from input materials collected outside of the biogas plant.

76 https://publications.jrc.ec.europa.eu/repository/handle/JRC121636

77 Nitrates Directive 91/676/EEC https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1561542776070&uri=CELEX:01991L0676-20081211

EBA
European Biogas Association

Follow our activities

X

LinkedIn

Website

Newsletter