BIOMETHANE INDUSTRIAL PARTNERSHIP

USE AND VALORISATION OF DIGESTATES:
A PRACTICAL REVIEW

DEC 2025 // PREPARED BY TASK FORCE 2

BIP Europe
Biomethane Industrial Partnership

This report is the result of a joint effort across multiple Task Forces and was led by Task Force 2 of the Biomethane Industrial Partnership, with contributions from the other BIP Task Forces and input gathered through a consultation of external stakeholders.

The core drafting team consisted of:

- Claire Lisse Speisser, TotalEnergies
- Lorella Rossi, Consorzio Italiano Biogas (CIB)
- Mirco Garuti, Centro Ricerche Produzioni Animali (CRPA)
- Piero Gattoni, Consorzio Italiano Biogas (CIB)
- Yvette Jones, Gas Networks Ireland (GNI)

The Task Force was co-chaired by DG GROW of the European Commission, EnviTec Biogas, and the European Waste Management Association (FEAD).

Design by: Giulia Rossi

Disclaimer

The opinions expressed are those of the authors only and should not be considered as representative of the European Commission's official position. Therefore, the findings and the content of the report do not engage the responsibility of the Commission towards any third party.

Imprint

Date
December 2025

ISBN
9 782960 342871

Contact
Avenue des Nerviens 85
1040 Brussels
Belgium

www.bip-europe.eu

secretariat@bip-europe.eu

Use and valorisation of digestates: a practical review

Executive Summary

Biogas, and from it biomethane, is a renewable gas primarily produced during a process known as anaerobic digestion (AD). Organic biodegradable material (such as manure, crops, food residues, biowastes and other biodegradable materials) is fed into AD tanks as feedstock. This material is partly broken down by the micro-organisms in the AD tanks resulting in the production of biogas, which is primarily comprised of biogenic methane and carbon dioxide. This process also occurs organically in nature as organic material decomposes, but with AD, instead of the gas being released into the atmosphere, it is captured in the AD tank. The resulting biogas can be combusted in Combined Heat and Power (CHP) plant to produce electricity and heat or upgraded to "biomethane" through the removal of the carbon dioxide (CO_2) and other minor components and impurities. Biomethane can be used as a direct replacement for natural gas (e.g. injected into the gas grid or used as a transport fuel) and the removed biogenic CO_2 can be utilised by industries, such as horticulture and manufacturing, as green CO_2.

In addition to biomethane and green CO_2, there is another product generated during the AD process called digestate. Digestate is the remaining substrate of the AD process and is a nutrient-enriched organic material, which remains after the biogas has been extracted[1]. The separation of whole digestate into two fractions (a liquid fraction and a solid fraction) is a common practice in most AD plants.

Biogases produced by anaerobic digestion (AD) are rapidly growing in importance in Europe. The European Commission (EC) recognises the significant role biogases can play in achieving the European Union's (EU) clean energy objectives and diversifying the EU's gas supplies. Its REPowerEU Plan of 2022 introduced a new target for EU biogas and biomethane production of 35 billion cubic metres (BCM) per year by 2030. An increase in biogases production will result in a corresponding increase in digestate production and availability.

To date the main rationale for investments in biogas and biomethane production has been to produce and sell renewable energy (in relation to biogas, primarily for local use in CHPs), generating new revenues and replacing fossil energy. There are, however, other benefits. The use of biomass in an anaerobic process allows for the capture of methane and ammonia emissions; this avoids the uncontrolled release of emissions into the atmosphere when the biomasses might otherwise be used in agriculture directly onto the land, stored without covering or put into landfill. In addition, digestates[2] make the nutrient content more readily available to plants and so can reduce reliance on fertilisers produced by energy intensive processes using fossil fuels. Digestates

[1] This report focuses on anaerobic digestion; however, it could be expanded in the future to cover other biogas production processes such as pyro-gasification.
[2] Referring here to untreated or "raw" digestate.

also contain organic carbon which improves organic matter levels in the fields to which it is applied (Chapter 1).

The storage of organic carbon in the soil is a strategy for CO_2 reduction in the atmosphere: it contributes to reducing the greenhouse effect. The return of digestate to the soil, the recycling of nutrients, and the storage of stable organic carbon in the soil allow for the closure of a farm's biological cycles (primarily the carbon cycle). For this virtuous circular economy model to deliver its full benefits, digestate[2] needs to be managed, used efficiently and deployed correctly (Chapter 2). When applied as a fertilising product (e.g. as a soil improver), digestate needs to support the cropping cycle and respect environmental regulations.

In certain regions of Europe there is an excess of nutrients[3] [4] such as nitrogen (N) or phosphorus (P). Consequently, in some regions, not all digestate can be applied locally and there might be a need for it to be processed into added-value exportable compost, or organic or organo-mineral fertilisers. Several companies have successfully developed such processes, with proven economic and environmental benefits (Chapter 3). Digestate-based compost, organic and organo-mineral fertilisers are thus promising co-products of biogas/biomethane production. However, several obstacles currently impede their further development (Chapter 4) and need to be addressed to ensure that benefits of using digestates for fertilisation and soil amendment are fully realised.

While it is increasingly recognised that digestate has a role to play in regenerative agricultural practices and facilitating efficient carbon storage, in particular offering considerable advantages compared to the spreading of raw manure (e.g. lower gas emissions, lower run off risks, more stable organic carbon), it requires proper management. Soil is not a confined environment in which CO_2 is permanently stored in the form of organic carbon. The organic carbon in the soil increases with additional inputs, which must be greater than the unavoidable losses due to natural respiration and oxidation. Therefore, it is necessary to ensure the increase of the total amount of carbon in the cultivated system, enhancing the plant-related photosynthetic activity and inputs of stable organic matter from digestate. In addition, conservative agricultural

[3] Walnut project, available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5ff558e34&appId=PPGMS

[4] Fertimanure project D.1.4 Report on the Nutrient Imbalance Analysis, available at: https://www.fertimanure.eu/en/publication/consult/16

practices that preserve carbon in the soil should be encouraged and used (e.g. reducing soil tillage such as ploughing which can lead to high carbon emissions from the soil).

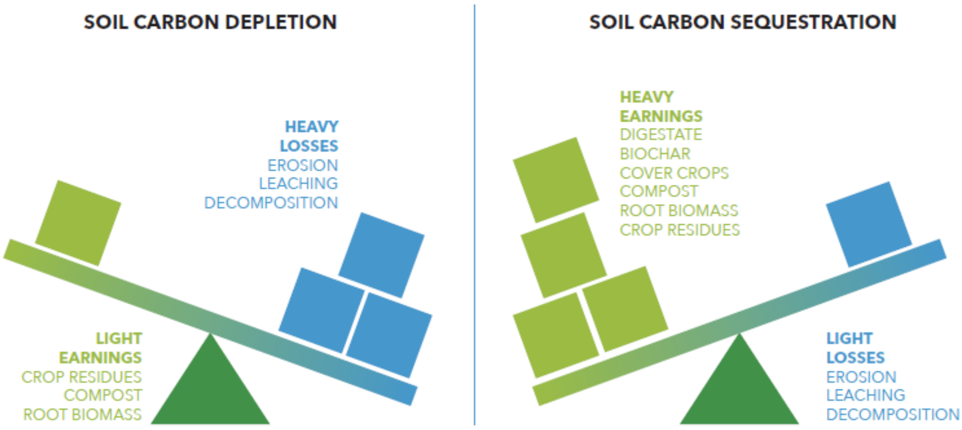

Figure 1 Positive carbon balance is the goal of organic fertilisation (Source: Farming For Future Position Paper)

It is now imperative to move from fertilisation techniques based only on mineral elements to an integrated management technique of nutrients that also considers the carbon inputs.

This report is based on the knowledge gathered by the experts of Task Force 2 of the Biomethane Industrial Partnership. It summarises key good practices which maximise the benefits of the use of digestates[2] for plants, soil, and the environment, focusing on commercially available processes and practical experience.

Table of Contents

1. European production of digestate:

What are we talking about?

1 European production of digestate: what are we talking about?

During the AD process, feedstock is biologically degraded into two main products:

- Biogas, consisting mainly of biogenic methane (CH4) and CO2. Biogas is used to produce electricity and heat or biomethane, which can be a direct substitute for natural gas (a fossil fuel).
- Digestate, a material that, compared to the starting feedstock, is more homogeneous, with a higher moisture content due to the anaerobic degradation of the organic matter. The more stable organic matter remains present in the digestate that also contains other nutrients, such as nitrogen (N), phosphorus (P) and potassium (K), derived from the input feedstock. The optimal destination for digestate is the soil where it can help preserve its fertility and provide nutrients for crops and organic carbon for the soil.

The whole digestate produced during the AD process can be separated at the AD site into liquid and solid digestate using solid-liquid separation equipment. In this report, the expression "untreated digestates" refers to whole, liquid or solid digestate which is not further processed through post-treatments technologies for nutrients removal/recovery, separation, extraction or concentration. The whole digestate is considered the most basic form of digestate. Further processing or upgrading usually allows better agronomical results but incurs higher costs.

The direct utilisation of untreated digestates for fertilisation or soil amendment is also currently the most straightforward and cost-effective option for farms and biogas/biomethane producers as further processing of digestates into digestates-based fertilisers (DBF) entails additional costs and energy consumption. As will be explained in this chapter, the use of digestate provides benefits for soil and plants beyond that of non-digested feedstocks and reduces the need for fossil-based fertilisers and extracted raw materials such as phosphate rocks. In addition, biogas/biomethane production generates additional revenues and cost savings in relation to the production of renewable energy.

1.1 How anaerobic digestion impacts on digestate properties?

Whole digestate contains the residual organic matter or carbon that has not been converted into biogas (CH_4 + CO_2) during the AD production process, as well as microbial biomass and mineral elements. Where wastes are used for feedstock, some extraneous elements, depending on their quality, could be present (i.e. microplastics, chemicals, traces of elements with potential toxic effects for environment, metals, pharmaceuticals). The chemical composition (NPK i.e. nitrogen, phosphorous and potassium; macro and microelements) of the digestate depends on the initial feedstock. However, the AD process transforms the initial feedstock in the following main ways:

- AD improves nutrient availability. The total amount of nitrogen (N) from feedstock remains in the whole digestate. A large part of the organic N is transformed[5] into mineral nitrogen

[5] MethaPolSol project, Girault et al. (2019).

as ammonia ($N-NH_4^+$), thus becoming immediately available for plant growth. The ammonium content ($N-NH_4^+/N$) is typically between 35% and 65%, but this depends on several factors, such as the ratio $N-NH_4^+/N$ and the total N in the initial feedstock, and the anaerobic digestion process.

- AD leads to more stable organic matter. The organic carbon is reduced (lower C/N ratio) as approximately two thirds of the organic carbon is transformed into gas (CH_4 and CO_2), but it is more stable. Cooke et al. (2023) reported significant organic matter stability of digestates compared with cow manure or corn residues: after 180 days, about 70% of carbon digestate remained in the soil. While in the case of cow manure only 50% of carbon was stable into the soil and 25% in the case of corn residues. Hence, although digestate contains less organic carbon than the initial feedstock, the use of digestate has been found to lead to stable or slightly increased organic carbon in soil. During the process of anaerobic digestion, the easily degradable part of the organic feedstocks is converted into biogas through microbial transformations. The residue, digestate, thus contains more complex and difficult to degrade organic molecules such as lignocellulosic plant fibres and complex proteins, compared to raw feedstocks such as manure (Tambone et al., 2010). In another example, Béghin-Tanneau et al. (2019) compared the Priming Effect (PE)[6] induced from fresh corn silage with that of digestate obtained from the same feedstock after anaerobic digestion. Results demonstrated higher native organic matter consumption when the fresh corn silage was added, leading to a net loss of soil organic carbon in form of CO_2 emissions. In contrast, digestate showed negative PE ensuring carbon retention in soil, because the organic carbon in the digestate is more stable than the carbon in the undigested feedstock and this "recalcitrant" carbon leads to an increase in the soil organic carbon (SOC) content (Tampio et al., 2024 ; Angst et al., 2023). It is important to note that the balance of carbon and nitrogen (called the C/N ratio) in digestate is similar to that found in natural soil organic matter. This helps prevent the breakdown of the soil's original organic material.
- AD reduces pathogens but has no impact on contaminant levels. AD improves significantly the hygienic-sanitary quality of the initial feedstock (Chojnacka & Moustakas, 2024)[7]. Temperatures and operation modes (retention times of AD and storage time of digestate) affected inactivation efficiencies significantly. A higher level of sanitisation is achieved faster in thermophilic conditions (50-55°C) than mesophilic (30-45°C). Under thermophilic conditions the effectiveness of inactivation of the pathogens is determined by the intrinsic heat resistance of the individual species, environmental stress conditions in the digesters and the retention time. However, studies have shown that pathogens can also be inactivated in mesophilic conditions (Álvarez-Fraga et al., 2025; Côté et al., 2006; Goberna et al., 2011; Govasmark et al., 2011; Smith et al., 2005). In mesophilic conditions, the

[6] The Priming Effect (PE) is an increase or decrease in the decomposition of soil organic carbon caused by activation (positive PE) or deactivation (negative PE) microbiology processes resulting in consumption of organic matter.

[7] According to "L'utilisation des digestates en agriculture, les bonnes pratiques à mettre en œuvre", available at: https://fertiliser-avec-des-digestats.fr/, a mesophilic AD process (37°c) removes 99% of pathogens and a thermophilic AD process (55°c) 99.9%.

temperature is not the main reason for the inactivation of pathogens because other factors such as microbial competition, ammonia and fatty acid concentrations, pH values and, overall, a high efficiency of the process affect positively the pathogens' reduction during AD. However, digestates could contain contaminants from the initial feedstock, which may include heavy metals, PCBs, PFAs, antibiotic residues, or microplastics (Bünemann et al., 2024; O'Connor et al., 2022). Agri-based feedstock used in AD is typically characterised by the absence of plastics or glass and consequently the resulting digestate does not contain these types of contaminants (but may contain pesticide residues as other food or feed residues). Regarding the potential presence of other pollutants, such as persistent organic pollutants (AOX, PAHs, NPE, DEHP, PCBs, Dioxins/Furans), targeted surveys have shown that concentrations are usually low (Al Seadi et al., 2012; ARPAE Emilia-Romagna, 2016; ARPAE Emilia-Romagna Sez. Bologna, 2014; ARPAV Regione Veneto, 2013).

- AD reduces odours. Manure is an important source of plant nutrients, but field application is a source of odorant emissions, which can be a major nuisance in rural areas. Anaerobic digestion is effective in reducing potential odour emissions with a more stable organic matter. When digestate is spread on soil, odours emitted are much lower than those from soils on which untreated slurries are used. Digestate is highly biologically stable with reduced olfactory impacts (Lemes et al., 2023; Orzi et al., 2018; Page et al., 2015).
- Digestate has a neutral or positive impact on soil microbiology. Digestate has a higher content of microorganisms (capable of turning organic N into ammonium once in soil), as well as more soluble sugars and hemicellulose which can feed earth worms and bacteria. A recent literature review (Karimi et al., 2023) has analysed the results in 56 scientific articles published since 2008 and suggests neutral to positive effects with the use of digestates on soil microbiology. The 56 articles investigated the effects of digestates on soil microbiology according to 23 microbial parameters. In comparison with fossil-based mineral fertilisation, 65% of the results indicate no difference, 25% of a positive difference and 3% a negative difference. In comparison with another organic fertiliser, 47% of the results indicate no difference, 26% a positive difference, and 17% a negative difference. The literature review concludes a need for more long-term studies on different soil and crop types. Additionally, research is also needed to understand the effects of digestate application on soil organisms as the impact on soil health depends largely upon doses and types of digestate (Van Midden et al., 2023).

TABLE 1 COMPARISON OF UNDIGESTED INITIAL FEEDSTOCK AND DIGESTATE PROPRIETIES

	Initial feedstock	Digestate
Nutrient content and availability	Each feedstock has a typical nutrients (N-P-K) content	N-P-K contribution from feedstock is the same in the final digestate. Ammonium form of Nitrogen is increased compared to initial feedstocks due to mineralization of organic nitrogen
Organic matter	Organic matter	Stabilised organic matter, relevant for soil fertility
Pathogens	Potentially high pathogen levels in certain feedstock	Reduced pathogen levels
Odours	It can be odorous due to easily degradable organic matter content and not optimal storage conditions	Typically, less odorous due to anaerobic stabilisation
Environmental impact	Methane emissions from storage	AD can reduce methane emissions through biogas production and proper storage of the digestate
Soil application	Used as a fertiliser for soil mainly when manure-based feedstock	Properly used as a fertiliser and soil improver with benefits for soil health. It can be separated into liquid and solid fractions for specific application

1.2 Characteristics of whole digestate

Examples of average chemical and physical compositions of whole digestates originating from different agri-based feedstock are described in Table 2. In relation to agri-based feedstock, the dry matter content (Total Solids) spans from 4% to 10% depending on the feedstock source and the technological aspects of the anaerobic digestion plant (mixing systems, organic loading rate, hydraulic retention time). Total nitrogen is about 4-7 kg/t and on average 54% is in ammoniacal form. Phosphorus concentration is about 1 kg/t, while potassium is about 4-5 kg/t.

TABLE 2 CHEMICAL COMPOSITION OF WHOLE DIGESTATE OBTAINED FROM VARIOUS AGRI-BASED FEEDSTOCK IN ITALY (FOR ILLUSTRATION)

		pH	Total Solids (TS)	Volatile Solids (VS)	Total Organic Carbon	Total Kjeldahl Nitrogen (TKN)		C/N	Ammonium Nitrogen (N-NH4+)		Phosphorous (P)		Potassium – (K)	
		(-)	(%)	(%TS)	(%TS)	(kg/t)	(%TS)	(-)	(kg/t)	(%TKN)	(kg/t)	(%TS)	(kg/t)	(%TS)
	Average	7,84	7,73	74,80	44,1	5,2	6,8	7,0	2,8	54	1,0	1,3	4,5	5,9
IT*	Std.Dev.	0,23	1,77	4,10	4,9	1,3	1,9	2,0	0,9	10	0,4	0,6	1,1	1,5

**CRPA - Centro Ricerche Produzioni Animali (2010-2023)*

1.3 Current use of untreated digestates

The N and P content of untreated whole digestate is usually lower than that of fossil-based mineral fertilisers (Möller & Müller, 2012) due to 90-95% water content that also results in additional storage and transport costs. Consequently, untreated digestate is primarily used locally. Figure 1 illustrates the impact of transport distance on the pricing point for digestate in the UK and compares it to the nutrient value against NPK fertilisers over different years. In three out of five years, the nutrient value of digestate would not support its sale beyond a 16 km radius. It should be noted that the only reason this was not the case for all 5 years is due to the conflict in Ukraine which caused a drop in European NPK production due to high gas prices. Because of this, digestates from agricultural biogas plants are usually returned to the farm which provided the feedstock or, in the case of manure fed plants, nearby farms with a 'feedstock in exchange for digestate' trade. Very effective leverage can be exerted by the mineral fertiliser prices, as could be seen with doubling and tripling prices at the beginning of 2022. As soon as mineral fertilisers become expensive or limited in availability, local digestate production automatically became more attractive.

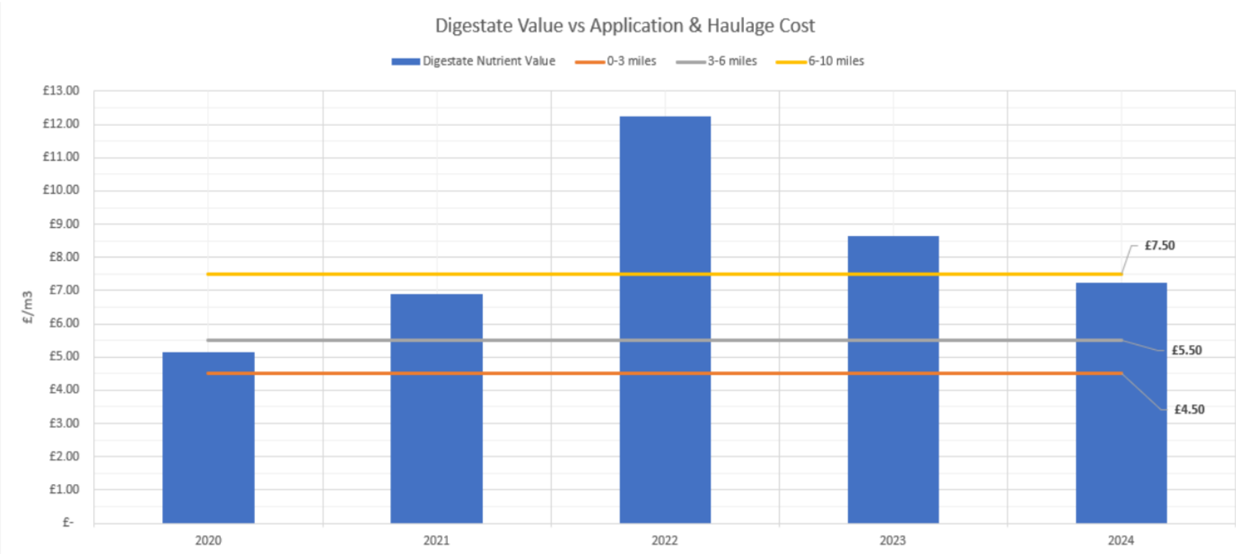

Figure 2 Digestate price according to haulage distance vs. nutrient value against equivalent fossil-based fertilisers (Source: Future Biogas, UK)

Despite its many benefits, the use of whole digestate for soil amendment and fertilisation also comes with potential economic drawbacks. These can, however, be mitigated by good management and the adoption of best practices. With the aim of bringing together economic, technical, environmental, and social aspects, the following chapters will provide evidence of how agricultural digestate generates positive effects both on crops (nutrient supply) and soil fertility (stable organic matter, soil conditioner), solutions for best practices utilisation, and examples of innovative technologies for digestate post-treatment.

2. European good practices and principles

for safe and effective direct use of digestates in agriculture

2 European good practices and principles for safe and effective direct use of digestates in agriculture

2.1 Reducing ammonia, methane emissions and nitrate leaching

Nitrogen, regardless of its origin (fossil produced or digestate), undergoes a variety of transformations in the soil; some of it is retained by plants, some is released into the atmosphere (volatilisation) or into water (percolation, leaching). Nitrogen fertilisation practices should maximise the amount of nitrogen used by crops and minimise/avoid losses into the atmosphere in the form of ammonia or into waterbodies in the form of nitrate. There is clear motivation for farmers to use digestate as efficiently as possible, as fossil-based fertiliser can account for a large proportion of operating costs. Therefore, digestate represents an opportunity.

Due to the anaerobic digestion process, the mineralised N content of digestate is higher than that of the initial feedstock[8], with a large part of this in the form of ammonium ($N\text{-}NH_4^+$) (WRAP 2016). The principal risk of using mineralised N, through digestate, biobased fertilisers or fossil fertilising products, is that all the nitrogen available may not be taken up by crops. Some of it may be lost, for example as ammonia gas[9] or through nitrate leaching[10]. Organic N, if not well stabilised, may also lead to uncontrolled nitrification[11], risking further nitrogen losses into the environment (Nkoa, 2014). However, the NPK concentration that are being digested remains similar through the process, anaerobic digestion only mineralised the nutrients. In addition, if the anaerobic digestion of organic matter was not complete, it will continue in the digestate, entailing methane emissions to air during storage if digestate is not covered or stored in gas-tight containers[12].

Ammonia emissions represent an agronomic loss of nitrogen, contribute to acid deposition and can cause eutrophication of ecosystems. Nitrates leaching can lead to eutrophication, indirect nitrogen oxides (Nox) emissions and nitrates pollution in waters, potentially damaging the suitability of water for drinking and stimulating excessive growth of algae. However, the amount and rate of ammonia and methane release during storage and after land spreading can be reduced as it depends on a range of factors including the organic material (e.g. pH, ammonium-N, dry matter), storage facilities and land spreading practices (e.g. application rate, method and timing), soil characteristics (e.g. moisture content) and environmental considerations (e.g. temperature, wind speed, rainfall). In European Member States, the Code of Good Agricultural Practices for digestate land spreading is required by the Nitrates Directive, especially in relation to distance from houses and surface waters, and harvest time for crops.

---

[8] Total N content of around 4-5 kg/m^3, compared with 2.6 kg/m^3 for 6% dry matter cattle slurry and 3.6 kg/m^3 for 4% dry matter pig slurry (AHDB, 2020).

[9] "Volatilisation" when ammonium reacts with air to form ammonia, during storage or use of digestates.

[10] As not all nitrates are absorbed by plants for their growth.

[11] Nitrification is the transformation of ammonium into nitrates, occurring in soil.

[12] See for example the report by the IEA Bioenergy Task 37, Methane Emissions from Biogas Plants by Liebtrau et al., 2017, available at: https://www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf

Key good practices to reduce the risks of ammonia and methane emissions, and nitrates leaching from the use of digestates for fertilisation and soil amendment, can be summarised as follows:

- **Digestate storage** is required at all biogas plants and sufficient storage should be built to store digestate during the periods that local farms do not need to fertilise the land. The creation of adequate digestate storage capacity, as well as the use of gas-tight covers for storage to avoid ammonia and methane emissions during storage and to prevent rain dilution of the digestate, are considered best practice. Italian best practices prescribe the use of tanks with a low surface to volume ratio with fixed or floating covers. Additionally, the Italian regulation for biomethane production[13,14] highlighted the importance of the storage tank to increase the environmental sustainability of the biomethane, making a gas-tight covered digestate storage tank with retention of at least 30 days mandatory. Residual methane emissions from digestate are greatly reduced and an additional quota of biogas is valorised for energy production, positively impacting the overall sustainability of biomethane. As Renewable Energy Directive (RED) III is adopted across the EU, the need to prove emission reductions will drive the adoption of gas-tight digestate storages across newly deployed and retrofitted AD plants.
- **Solid-liquid separation** provides a liquid fraction with a reduced total solids content, which concentrates soluble compounds, and a solid fraction. The separate management of these fractions leads to environmental and agronomical benefits. Further details are provided in sub-chapter 2.2 “Separating the liquid and solid fractions of digestate”. Solid-liquid separation also represents the first processing phase for subsequent more complex post-treatment of the solid fraction (i.e.: composting, drying and bio-drying) and the liquid fraction (i.e. stripping, evaporation, mechanical and membrane filtration).
- **Application method**: around 40% of the total N applied following conventional systems for applications of liquid digestate can be lost as ammonia (Nicholson et al., 2017). However, injecting the digestate into the soil at the time of spreading (e.g., at a 15cm depth) avoids or drastically reduces ammonia volatilisation and emissions (Riva et al., 2016), typically by 90%[15]. Consequently, injection is mandatory in several countries and splash-plate spreading often forbidden. The use of appropriate spreading equipment, typically equipped with trailing hose or shoe, or a shallow injector (see Figure 6, Figure 7, Figure 9), is strongly recommended for liquid or whole digestate. The use of spreading equipment without a slurry tanker also reduces the weight of the equipment and avoids soil compaction (Figure 11). In addition, the injection of digestate into the soil reduces odours by 82-88% compared to untreated biomass such as cattle slurry (Riva et al., 2016). See Section 2.3 “Application and storage of digestate liquid fraction” below for more details. Additional innovative methods employed to apply digestate can be evidenced, for

---

[13] Decree of 2 March 2018 “Promotion of the use of biomethane and other advanced biofuels in the transport sector” (19 March 2018).
[14] Decree of 15 September 2022 “Implementation of Articles 11(1) and 14(1)(b) of Legislative Decree No 199 of 8 November 2021, in order to support the production of biomethane injected into the natural gas grid, consistent with Mission 2, Component 2, Investment 1.4, of the RRNP” (26 October 2022).
[15] See “L’utilisation des digestates en agriculture, les bonnes pratiques à mettre en œuvre”, Ferti-Dig project, available at: https://fertiliser-avec-des-digestats.fr/

example, on farms in Italy which use digestate in simple fertigation systems, allowing slow release of nitrogen to the plant roots through the growing season.

- **Application timing** refers to two aspects:
    - Digestate should be spread at the time of the year when plants are starting their growth cycle and have the highest nutrient needs; supplying nitrogen close to high crop demands achieves greatest fertilisation efficiency. Outside of these times, digestate should be stored.
    - Weather at the time of application: in the EU spreading is forbidden on snowy, frozen or wet soil to reduce the risk of run-off to water courses (there are several other mandatory precautions[16]).
- **Balancing the nutrients brought to the soil with the nutrient needs of the crops** is an essential good practice, in line with the "rule of the 4Rs" for fertilisation (right time, right dose, right application method, right fertiliser). It requires N content profiling (organic N, N-NH_4^+, C/N ratio[17]) in the digestate before spreading and assessing how much of this N content will be available for plant growth as mineral N after spreading (which will depend on the season, weather, crop type and digestate type), and comparing this with the crop needs as well as the nutrients already available in soil. Determination of nitrogen concentration in digestate is essential for assessing amounts of digestate to be applied to land. Sequential and rotational cropping systems can help reduce leaching by increasing the yearly requirements for nitrates and reinforcing the presence of roots in soil (Beillouin et al., 2021). Considerable guidance is available in several European countries on balancing nutrients with digestate fertilisation. An example is the MANNER-NPK software tool (MANure Nitrogen Evaluation Routine)[18], aimed at guiding farmers in their use of manures for fertilisation. It can also be used for estimating the available nitrogen, phosphorous and potassium in digestates. Phosphorus and potassium remain in a stable form in the soil after digestate is spread, unlike nitrogen which is subject to potential volatilisation in air or leaching on soil when present as ammonium. Additionally, application of liquid digestate naturally provides water and this has a competitive advantage in dryer countries.
- **Drawing up a spreading/fertilising plan** considering all the above aspects.
- **Acidification of digestates**. Digestates have a high pH. Ammonia emissions from digestates are elevated when the pH of the material is >8 (e.g., Hoeksma et al., 2012). As a result, acidification of digestate to pH <6 (treatment during storage or spreading) is used as a method for the mitigation of ammonia emissions[19]. This method is particularly

---

[16] Under the EU Nitrates Directive. For example, minimum distances to waters, or a minimum band of non-fertilised soil around the fertilised field when close to waters, or the interdiction to spread digestate on soil not used for agricultural production.

[17] Total carbon/total nitrogen.

[18] Available free of charge at: https://www.planet4farmers.co.uk/Manner.aspx

[19] This method reduces the volatilisation process up to 50%, according to "L'utilisation des digestates en agriculture, les bonnes pratiques à mettre en œuvre", Ferti-Dig project, available at: https://fertiliser-avec-des-digestats.fr/

developed in Denmark[20] (e.g. BioCover[21]) where acidified digestate can be spread without injection e.g., on grassland. This practice is also used in Spain.

- **Nitrification inhibitors**. Land application of digestate represents an alternative to the use of mineral fertilisers but may lead to nitrate leaching and runoff, ammonia volatilisation, and nitrous and nitric oxide emissions. This occurs particularly in case of low nitrogen uptake by crops, and where the soil moisture is higher than the water-holding capacity (Giacometti et al., 2020). Nitrification inhibitors are able to maintain the nitrogen applied to the soil in the ammonium form through the biological immobilisation. Therefore, nitrification inhibitors can reduce the ammonium oxidation rate increasing nitrogen uptake for plants. This might suggest that nitrification inhibitor reduces nitrate leaching caused by rainfall and increase nitrogen retention in soil, providing environmental benefits (Piccoli et al., 2023).

2.2 Separating the liquid and solid fractions of digestate

A common good practice to help digestate management is to separate the liquid and solid phases (mechanical separation via screw pressing or centrifugation). This results in two fractions, solid digestate and liquid digestate. Advantages of doing so include the possibility of recirculating the liquid fraction, limitation of surface crust formation in storage tanks and better management of the two fractions during agronomic utilisation. As shown in Figure 3, the liquid phase will contain most of the soluble elements, making it most suitable for fertilising, while the solid phase contains most of the organic matter and phosphorous, making it most suitable for soil amendment.

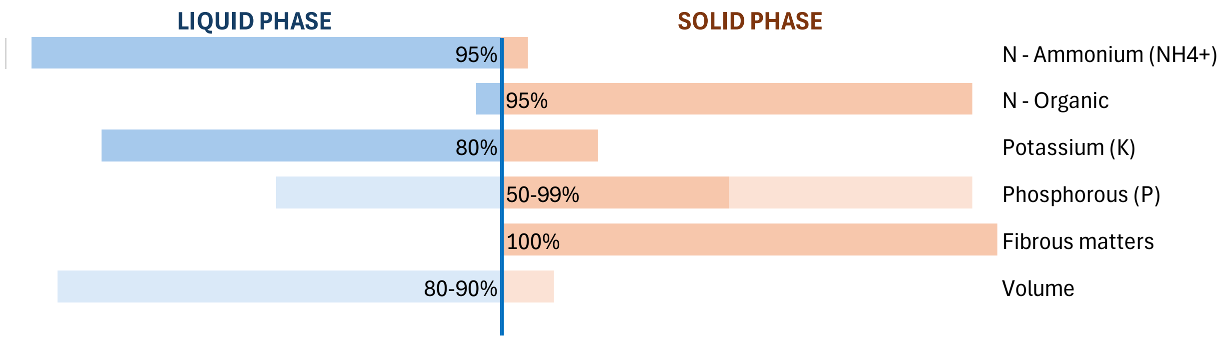

FIGURE 3 ORGANIC AND MINERAL REPARTITION IN THE LIQUID AND SOLID FRACTIONS OF THE DIGESTATE AFTER MECHANICAL SEPARATION (SOURCE: CARTON & BULCKE, 2021)

Solid-liquid separation is generally made with screw press, sieve drum press, centrifuges or belt presses. The solid and the liquid fractions obtained from whole digestate have the following characteristics:

[20] "Why is acidification only a success in Denmark", B.H. Jacobsen, Department of Food and Resource Economics, University of Copenhagen, Abstract from the ManuResource conference 2015.

[21] http://www.biocover.dk/uk/about-biocover.aspx

- Solid digestate (Table 3) comprises approximately 10-15% of the weight of the whole digestate. The dry matter (Total Solids) content is usually higher than ~20% and rarely higher than 30%. Organic matter (Volatile Solids), organic nitrogen and phosphorus are concentrated in the solid fraction, even if the nutrients separation efficiencies depend on the operational conditions (type of digestate, type and mode of use of the solid/liquid separation technologies used). Rich in organic matter and nutrients, the solid fraction is a good substitute for manure, helping maintain the soil's organic matter and gradually releasing nutrients. It can conveniently be used in pre-ploughing before renewal crops or autumn-winter crops.
- Liquid digestate (Table 4) represents at least 85-90% of the volume of the whole digestate. Liquid digestate has an average dry matter (Total Solids) content of between 3-7%. Water soluble compounds are concentrated in it, including ammoniacal nitrogen ($N\text{-}NH_4^+$), which can reach up to 60-70% of the total nitrogen concentration, providing a nutrient with high bioavailability for plants but with high risk of ammonia loss to air. Utilisation of high efficiency spreading technologies provide for the reduction of ammonia emissions into the atmosphere, as do soil injection techniques and equipment.

TABLE 3 CHEMICAL COMPOSITION OF SOLID DIGESTATE OBTAINED FROM ITALIAN AGRI-BASED AD PLANTS FOR ILLUSTRATION

		pH	Total Solids (TS)	Volatile Solids (VS)	Total Organic Carbon	Total Kjeldahl Nitrogen (TKN)		C/N	Ammonium Nitrogen (N-NH4+)		Phosphorous (P)		Potassium – (K)	
		(-)	(%)	(%TS)	(%TS)	(kg/t)	(%TS)	(-)	(kg/t)	(%TKN)	(kg/t)	(%TS)	(kg/t)	(%TS)
	Average	8,70	25,72	87,00	46,7	6,3	2,5	19,6	1,8	28	2,3	0,9	3,9	1,5
IT*	Std.Dev.	0,29	6,74	5,10	5,4	1,7	0,7	4,5	0,9	12	1,1	0,5	1,3	0,6

**CRPA - Centro Ricerche Produzioni Animali (2010-2023)*

Table 4 Chemical composition of liquid digestate obtained from Italian agri-based AD plants for illustration

		pH	Total Solids (TS)	Volatile Solids (VS)	Total Organic Carbon	Total Kjeldahl Nitrogen (TKN)		C/N	Ammonium Nitrogen (N-NH4+)		Phosphorous (P)		Potassium – (K)	
		(-)	(%)	(%TS)	(%TS)	(kg/t)	(%TS)	(-)	(kg/t)	(%TKN)	(kg/t)	(%TS)	(kg/t)	(%TS)
IT*	Average	7,93	4,79	66,03	39,9	3,01	8,3	5,4	2,3	57	0,7	1,4	3,6	7,5
	Std.Dev.	0,28	1,53	7,20	5,4	1,4	2,7	2,5	1,00	13	0,4	0,6	1,1	2,2

**CRPA - Centro Ricerche Produzioni Animali (2010-2023)*

Digestate distribution techniques and technology affect levels of nitrogen efficiency utilisation, environmental impacts and soil compaction. The choice of correct application equipment depends on the type of digestate (whole, liquid fraction, solid fraction), the timing of digestate distribution and the presence/absence of crops on the land.

2.3 Application and storage of digestate liquid fraction

If appropriate digestate spreading techniques are not used, then nitrogen emissions saved with covered digestate storage tanks could be lost in the field through ammonia emissions and risks of N_2O emissions.

Surface distribution of whole and liquid digestate fractions with conventional systems generate significant atmospheric emissions of ammonia and other volatile and odorous compounds as shown in (Figure 4) due to nebulisation during distribution and from the digestate remaining on the ground until tillage. Emissions primarily occur a few hours after application, while ammonia losses during distribution are more limited. Such systems should be avoided where possible. In addition, if the loading, transport and spreading of digestate is carried out with one single truck or machinery, it is necessary to enter fields with heavy trucks risking soil compaction.

Figure 4 Conventional digestate distribution equipment (Source: CIB – Consorzio Italiano Biogas)

With digestate managing systems, the separation of the transport and distribution phases leads to significant reductions in operational costs with optimisation of operating times. Additionally, the separation of the transport and land distribution allows for application during the most appropriate periods (i.e. close to sowing and/or when crops show the highest nitrogen efficiency uptake).

There are several innovative transport systems for liquid digestate. Atmospheric pressure wheeled tanks (up to 30-35m^3 capacity) for its transport from storage tanks (close to AD facility) to the distribution equipment or into farm-based decentralised storage tanks. Another transport solution involves the installation of underground pipelines, with sufficient diameter and feed pressure to avoid blockages and sedimentation. This dramatically reduces soil compaction which results from the loading, transport and spreading of digestate with one truck through conventional systems.

Figure 5 Low-pressure ground level digestate distribution (Source: CIB – Consorzio Italiano Biogas)

FIGURE 6 TRAILING HOSE EQUIPMENT WITHOUT A SLURRY TANKER ALLOWS TO REDUCE THE PRESSURE ON SOIL DURING SPREADING

Injection in soil significantly limits odour and ammonia emissions during distribution, allowing greater fertilising efficiency. It is well established that with injection, ammonia nitrogen losses are drastically reduced (no more than 10-15% of the total nitrogen input) and surface run-off is not formed. Injection devices can be installed on a tanker or, alternatively, they can be fed by roll-up pipes and towed by a tractor. An increasingly popular system for distribution on bare ground and grassland is the so-called umbilical system, in which the connection between the storage and the distribution device is made by a flexible, abrasion-resistant pipe of 100 m or more in length (Figure 7).

FIGURE 7 UMBILICAL DISTRIBUTION SYSTEMS. MINIMUM TILLAGE INJECTOR (SOURCE: CIB – CONSORZIO ITALIANO BIOGAS)

There are various types of soil injection but each fit into one of two categories:

- Open slot shallow injection (8a): the digestate is deposited into a furrow at a depth of no more than 5-6 cm. The ploughs, with single or double blades or discs, spaced 20-40 cm apart, cut the soil and leave an open furrow, which is then filled with digestate. This technique can be used with the crop in place, essentially on autumn-winter meadows and cereals, even when the vegetation is its development phase.
- Closed slot shallow injection (8b): digestate is injected to a maximum depth of 15 cm into a furrow created by tines or discs and then covered by discs or rollers downstream of the

injector. The complete covering of the digestate minimises emissions and odours; it is even more efficient than open furrow systems with reductions in ammonia losses of up to 80-90%. As the working depth and the processed section are greater, such systems allow for the distribution of a higher dosage. The type of tools (e.g. with wide or goose-foot blades) and the distance between them (from 25-35 cm up to 45-100 cm) allow for effective and efficient work on both bare soil and weeded crops.

FIGURE 8 A) DIGESTATE INJECTION SYSTEMS: OPEN SLOT SHALLOW INJECTION ON THE LEFT; B) CLOSED SLOT SHALLOW INJECTION ON THE RIGHT (SOURCE: CIB – CONSORZIO ITALIANO BIOGAS)

Depending on the type of operation to be carried out (e.g. minimum tillage, on a current crop or on a meadow), the furrow-opening devices have different shapes and sizes (e.g. discs, hoes, anchor coulters) and each is connected to the digestate supply pipes (Figure 9). The depth of injection is usually limited: no more than 15-20 cm for soil tillage and 5-10 cm when working on grassland.

FIGURE 9 DIFFERENT TYPES OF ELEMENTS FOR DIGESTATE DISTRIBUTION (SOURCE: CIB – CONSORZIO ITALIANO BIOGAS)

Through strip-till, digestate is injected to a maximum depth of 15 cm working only the portion of soil in which the crop will be sown, facilitated by the combined elements of tines, discs and rollers downstream of the injector. In addition to the complete cover of the digestate, and the resulting reduction in emissions and odours, this technique allows for the precise application of the digestate, better maintenance of soil moisture in relation to the smaller portion of soil worked, and a significant reduction in working time and energy consumption. However, this technique requires highly specialised equipment with a GPS system.

FIGURE 10 STRIP-TILL DIGESTATE DISTRIBUTION (SOURCE: CIB – CONSORZIO ITALIANO BIOGAS)

Low-pressure injection application of digestate can be performed with a roll-up pipe, by umbilical system, and tanker truck trucker. Recently, specialised, technologically advanced, tanker trucks have been developed, to minimise soil compaction (Figure 11). These tanker trucks (loading capacity of 5-21 m^3) allow precise and optimal distribution. This is due to low-pressure, wide lagging, flow controller, Variable Rate Technology with continuous analyser of nutrients concentration based on near-infrared spectroscopy or utilisation of prescription maps based on GPS and GIS technology.

FIGURE 11 INNOVATIVE TANKER TRUCKS FOR LOW-PRESSURE SURFACE APPLICATION AND INJECTION APPLICATION OF DIGESTATE (CIB)

Low pressure fertigation with drip wings is one of the most innovative digestate distribution systems. It allows for digestate application according to crop requirements during its entire growth cycle. In addition, it allows high efficiency in the use of irrigation water, enhancing the water content of the digestate itself and minimising additional water volumes and ammonia emissions.

Table 5 shows the efficiency and applicability of different liquid digestate distribution equipment in relation to crops.

Table 5 Efficiency and applicability of different digestate distribution equipment in relation to crops (CIB – Consorzio Italiano Biogas elaboration from of Options for Ammonia Mitigation Guidance from the UNECE Task Force on Reactive Nitrogen data)

Digestate distribution	NH3 emission reduction (%)	Distribution Period			
		Pre-sowing, non-cultivated land	On crop		
			Spring crops	Cereals	Meadows
Low pressure surface spreading (reference)	-	Possible	Possible	Possible	Possible
On ground band spreading	30-35	Possible	Recommended	Recommended	Recommended
On ground band spreading with diverter	30-60	Possible	Recommended	Recommended	Recommended
Injection					
- with disc *(open slot, < 5cm)*	70	Possible	Possible	Possible	Recommended
- with trailing hose *(closed slot, 5-10cm)*	80	Recommended	Recommended	N.A.	N.A.
Deep injection *(> 15 cm)*	90	Possible	N.A.	N.A.	N.A.
Incorporation of surface-applied digestate					
- immediately by ploughing	90	Recommended	N.A.	N.A.	N.A.
- within 4 hours by ploughing	45-60	Recommended	N.A.	N.A.	N.A.
- within 24 hours by ploughing	30	Possible	N.A.	N.A.	N.A.
- minimum tillage by non-inversion cultivation	70	Recommended	N.A.	N.A.	N.A.
Fertigation on surface *(pivot, ranger, drip)*	65-95	Not Recommended	Recommended	Recommended	Recommended

Sub-surface fertigation *(underground drip)*	95-100	Not Recommended	Recommended	Recommended	Recommended

2.4 Application and storage of digestate solid fraction

The distribution of the solid fraction of digestate is commonly carried out with spreaders:

- Rotaspreader: a side discharge spreader with a cylindrical body and a driven shaft fitted with flails running along the centre of the cylinder. As the rotor spins, the flails throw the solid digestate out to the side.
- Rear discharge spreader: a trailer body fitted with a moving floor or other mechanism which delivers solid digestate to the rear of the spreader. The spreading mechanism can have either vertical or horizontal beaters, plus, in some cases, spinning discs.

3.

From digestate to advanced digestate-based fertilisers

3 From digestate to advanced digestate-based fertilisers

As has been covered earlier in this report, the AD process produces renewable energy in the form of biomethane and a nutrient-rich organic product, called digestate. Even though it is usually preferable for digestate to be used directly for local agronomic use, a substantial share of EU biogas/biomethane production today is concentrated in areas with abundant feedstock, typically due to high livestock density. These areas are also typically characterised by an oversupply of nutrients, including nitrate and/or phosphorous vulnerable zones where the spreading of digestates (especially the liquid phase which contains most ammonium and phosphorous) is strictly limited or forbidden. Europe is thus facing an imbalance between regions where most of the biogas/biomethane production takes place but where opportunities to spread the digestate is limited, and areas where crops and soil could benefit from digestate application. Moreover, most anaerobic digestion in Europe is wet anaerobic digestion, resulting in digestate with a high-water content making it costly to transport over long distance.

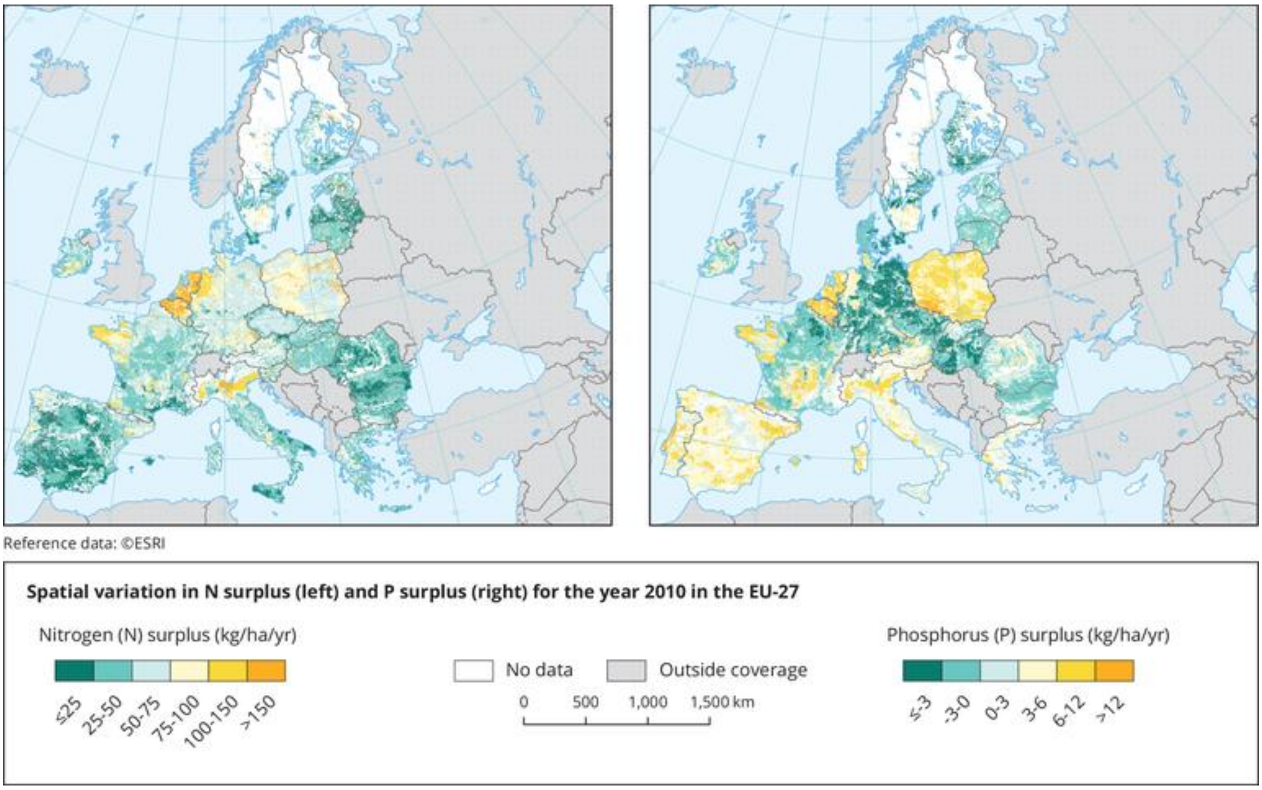

FIGURE 12 EUROPEAN ENVIRONMENT AGENCY (LAST UPDATE ON 20/09/2024)[22]

[22]https://www.eea.europa.eu/en/analysis/maps-and-charts/spatial-variation-in-n-surplus?activeTab=a7caf3b5-7254-4a24-8919-693d4115158b

Even where digestate is currently primarily managed in its whole/liquid/solid form, a number of biogas/biomethane producers located in regions with abundant feedstock and restricted digestate spreading are approaching innovative technologies as alternative approaches (Selvaraj et al., 2022) for digestate management, despite further processing requiring substantial investment and with the need to address technical and market challenges. Digestates contain valuable substances, including essential plant nutrients and trace elements, but also enzymes and extracellular polysaccharides, the benefits of which are still the object of study and research. These properties give AD produced digestate more application potential when combined with the appropriate treatments and valorisation processes to transform digestates into more advanced/processed fertilising products (for example: composts, liquid concentrates, pellets and granulates), which are also more suitable for storage and transportation. Typically, these processes aim to reduce the volume of digestates (and, consequently, transport and storage costs), while increasing the nutrient concentration. Available today are various Nutrient Recovery and Reuse Technologies (NRRTs) for post-treatment of digestate (Figure 13) which are able to increase the value of digestate as a nutrient source for agriculture.

Organic, organo-mineral and mineral fertilisers from digestates usually exhibit lower NPK values compared to equivalent conventional mineral fertiliser(s). However, academic research based on struvite or ammonia stripping examples, and experiences reported by BIP members described in this chapter, suggest that nutrient use efficiency and yields can be similar or higher, with positive end-user feedback. Other environmental benefits are also achieved, such as reduced footprint and limitation of GHGs emissions due to, inter alia, the production of renewable energy and increased organic carbon in soil.

3.1 Good practices of more advanced/processed digestate-based fertilising products

The implementation of sustainable agro-energy systems, that integrate crop, livestock, and biomethane production, boost resource recovery and advance circular economy principles. Several commercially available digestate processes and practical experience have been investigated (Figure 13) for the reduction of digestate volume, improving its manageability and reducing transportation costs, and for the recovery of nutrients.

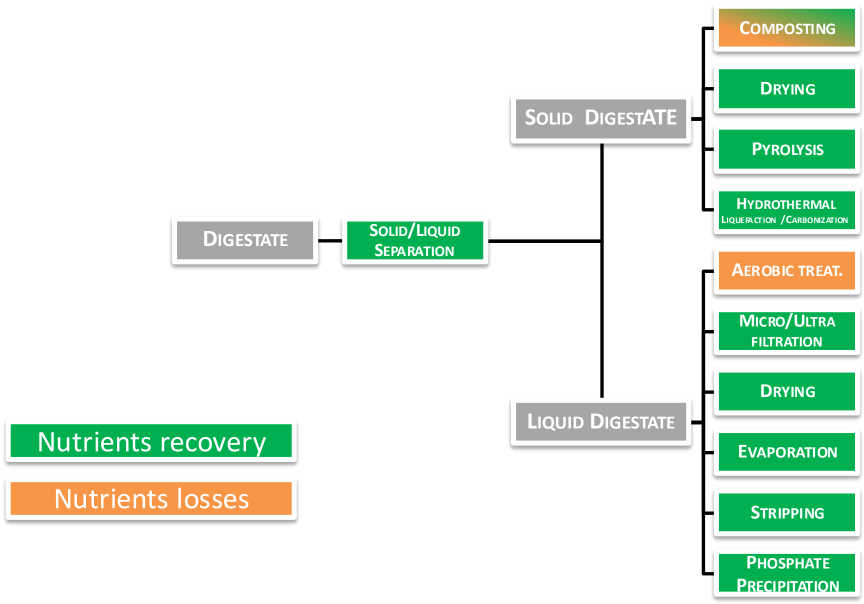

Figure 13 Most applied post-treatment technologies for whole digestate valorisation in fertilising products (Source: CRPA)

This chapter, based on contributions from Biomethane Industrial Partnership (BIP) members, focuses on commercially-ready technologies available in Europe, which are proven or emerging economic and operational models for advanced/processed digestate-based fertilising products. The BIP remains open to receiving feedback on such examples and to additional contributions from other companies or other case studies[23].

Thermal Drying

The drying process transforms the solid fraction of the digestate, or the digestate itself, into a dried end product with a very low water content (between 50% and 10%). This process is even more advantageous when low-cost thermal energy is available. For this reason, it is usually combined with AD, exploiting the surplus thermal energy from biogas-fuelled CHP units. These units produce electricity and thermal energy, only partially used to heat the anaerobic digesters.

The purposes of the drying process are the following: a) production of a stable, easy-to-transport and easy-to-spread commercial fertiliser; b) reduction in the volume and weight of the digestate, leading to reduced transport and management costs; c) concentration and following recovery of nutrients (mainly nitrogen, phosphorus and potassium) and organic matter.

Belt drying technologies housed inside a closed chamber and ventilated by a flow of hot air (70-110°C) are generally used for thermal drying. This solution requires the air expelled from the dryer

[23] Additional overview and reference plants are listed in "Digestate as fertilizer: application, upgrading and marketing", Fachverband Biogas e. V (2018).

to be treated with an acid scrubber to prevent emissions of ammonia and volatile compounds into the atmosphere and to recover the ammonia in the form of ammonium sulphate.

Agro-Energiek

Agro-Energiek is a family farming company from Zomergem (near Ghent, Belgium) operating a biogas plant since 2007 using feedstocks including manure and biowastes (agricultural residues and agri-food wastes). The plant includes two production lines, one with and one without manure. At the manure line, the digestate is dried on belt dryers and pelletised for export (stored and transported in large bags). At the line without manure, the digestate is first separated into a liquid and solid fraction via centrifugation. The solid, phosphorous-rich fraction is dried and pelletised for export and the liquid, nitrogen-rich fraction is spread onto Flemish arable land (via Trike or five-wheeler). Pellets are easily applied with classical spreading equipment. Agro-Energiek has not performed agronomical field trials for pellets; however anecdotal feedback from customers and others has ensured revenues from pellet sales outside Flanders. The drying process requires significant heat energy. The use of the heat from the CHP unit makes this process feasible for Agro-Energiek (CHP installations are supported in Flanders).

Composting

Compost is considered an important source of organic matter and nutrients for agriculture and plays an essential role in maintaining soil biodiversity and horticultural production when used as a component in the preparation of pot substrates. Composting is one post-treatment of the solid part of digestate to improve fertilisation properties and to fully stabilise the organic matter. Moreover, the microflora of compost has significant antagonistic effects against various soil-borne phytopathogenic microorganisms, which may play an important role in their control (Kovačić et al., 2022). From an environmental perspective the composting must be done in a closed system with exhaust air treatment.

Furthermore, combining anaerobic digestion and composting could enable better valorisation of biowastes (including food wastes, green wastes, food processing wastes) in Europe. Italy is a front-runner of biowaste separated collection, treatment and valorisation through combination of AD and composting. In 2023, Italy treated 5 Mt of food wastes, 1,9 Mt of garden wastes, 1,2 Mt of sludges and other organic waste from the food industry (0,6 Mt) according to the CIC (Consorzio Italiano Compostatori).

The agronomical benefits of composted digestates have been demonstrated by field trials, such as those carried out in Italy. The University of Bologna, on behalf of the CIC, conducted trials for five consecutive years in Northern Italy (at Fondazione per l'Agricoltura F.lli Navarra, Ferrara, region Emilia-Romagna, Italy), showing similar agronomic properties with biowaste composted digestate (BCD) and chemical fertilisation[24]. The trials also demonstrated significantly higher soil

[24] Similar values were found with chlorophyll content analysis in maize leaves, and no statistically significant differences were found in terms of fresh maize grain yields in ton/ha.

organic matter with BCD fertilisation, suggesting higher stability of organic matter having undergone both anaerobic digestion and composting. However, further trials are underway at the same site to confirm these findings. In addition, no statistically significant accumulation of tested metals (Cd, Cu, Cr, Fe, Mn, Ni, Pb, and Zn) was observed with compost fertilisation[25].

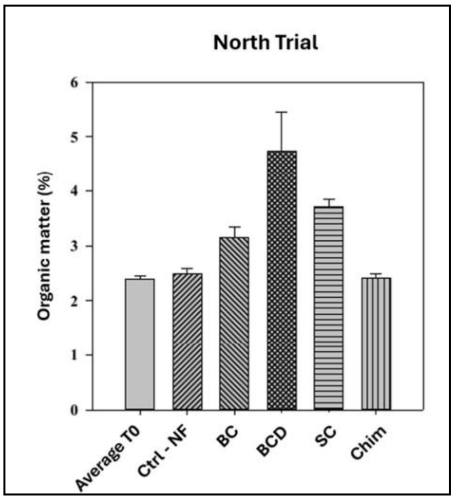

FIGURE 14 SOIL ORGANIC MATTER CONTENT WITH BIOWASTE COMPOSTED DIGESTATE AT THE END OF THE FIFTH YEAR (2023). SC = SLUDGE COMPOST, BC=BIOWASTE COMPOST, BCD= BIOWASTE COMPOSTED DIGESTATE, CTRL-NF = UNFERTILISED CONTROL, CHIM = CHEMICAL FERTILISATION. AVERAGE T0 IS THE VALUE AT THE BEGINNING OF THE TRIAL (OCTOBER 2018). TRIALS BY THE UNIVERSITY OF BOLOGNA AT FONDAZIONE PER L'AGRICOLTURA F.LLI NAVARRA (FERRARA, ITALY)

Despite all agronomical and environmental benefits of composting, most of the mineralised nitrogen (ammonia) is volatilised and potentially lost during the process. Ammonia emissions can be captured through scrubbers to recover the lost nutrients, requiring however additional investments and energy uses.

It also has to be noted that composting requires careful management of inputs: the optimal carbon to nitrogen ratio must be ensured, as are appropriate humidity levels and the use of texture-loosening agents to facilitate the process (Graves, 2000)[26].

Bioenergia de Almenar

Bioenergia de Almenar, SL is a company based in Lleida, Catalonia, which operates an anaerobic digestion plant and processes digestate into compost, osmosed water and a liquid fertiliser. After centrifugation, the solid phase is composted, and the liquid phase is treated through membranes

[25] A known challenge for the composting of digestate from biowastes is however the presence of non-compostable materials (such as plastics) in the collected biowaste, as described in the BIP Memo on 'Compostable plastics in biomethane plants.'

[26] As retrieved from the United States Department of Agriculture (USDA) in their Environmental Engineering National Engineering Handbook Part 637 Chapter 2 on composting.

(reverse osmosis and ultrafiltration), vacuum-evaporation and ammonia stripping-scrubbing, to obtain a liquid fertiliser and clean water (the water is reused at the biogas plant or for irrigation). The compost has 17-22% organic matter, 3% nitrogen content, and 1.5% sulphate and is certified and commercialised under the relevant Spanish rules. It is sanitised and free of pathogens, with reduced odours and higher biological stability than raw digestates and offers good soil amendment properties. The liquid organic fertiliser has typical NPK values 3-1-1, and 18% SO_2.

The business model of Bioenergia de Almenar relies on revenues from waste management (individual contracts signed with each waste producer for the management of agri-food wastes including sludges, meat processing solid waste, manures, and agricultural residues), the sales of compost and liquid fertiliser, and electricity sold to the grid[27].

Vermicompost by Algae LLDC

Algae LLDC has developed a unique vermicomposting to treat digestates. Algae LLDC's feedstocks for anaerobic digestion include manure/slurries, biowastes, food processing wastes (vegetables), green wastes from municipal collection, and sewage sludge. Feedstocks from animal by-products and sewage sludges are sanitised in a one-hour treatment at 70ºC. The liquid part is purified in a pond with hyacinths, while the solid part feeds earthworms (Figure 15).

FIGURE 15 EARTHWORM DIGESTING BENCH (SOURCE: ALGAE LLDC)

The output of this process includes a liquid fertiliser[28] and a granulated, organic vermicompost (soil improver) which can be applied during sowing with existing agricultural machinery (Figure 16).

[27] Surplus after the energy and heat needs of the biogas plant and digestate treatment process have been covered.
[28] For leaf spraying, certified against the applicable French standard AFNOR NF U42-003, exhibiting similar yields as the micro-starter DAP 18-46 (https://www.ldc-algae.com/essai-greencrops-lombricompost-liquide-special-mais/).

FIGURE 16 DIGESTATE-BASED GRANULATES OF DIFFERENT SIZES (SOURCE: ALGAE LLDC)

Vermicompost granules from agricultural and agri-food feedstocks (including green wastes) can be sold as organic soil improvers in France as they comply with the applicable French decree of 22 October 2020[29] and are tested and labelled against the applicable French standard[30]. They can be used for corn crops, where experience suggests a significant increase in soil organic matter[31] and a 20% increase of roots or an additional 1.5t/ha of vermicompost (Figure 17), also helping to increase the plant resilience to drought[32].

FIGURE 17 INCREASED ROOT GROWTH WITH ALGAE GRANULATES APPLIED DURING SOWING (SOURCE: ALGAE LLDC)

For vermicompost granules from other feedstocks (e.g. industrial or municipal wastewater), the applicable French standard[33] does not include vermicomposting in the composting processes allowed for return to soil, hence these granules currently do not achieve the end-of-waste status and cannot be commercialised.

The vermicomposting process has been gradually optimised since 2014, including by testing the edibility for worms of various batches of digestates (60% of batches are rejected by worms) and by developing an inoculum to help worms accept certain feedstocks. According to Algae LLDC's

[29] French Decree of 22 October 2020, available at: https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000042506471, which defines technical specifications for the use and selling of digestates from agricultural or agri-food feedstocks as fertilisers, including limit values on pathogens and contaminants, and marking requirements on organic matter, dry matter, NPK values or trace elements.

[30] AFNOR NF U44-051.

[31] 373 mgC/kg in the control sample vs. 435 mgC/kg in the soil treated with Algae granulates.

[32] Agronomical field trials are currently not available to confirm these results.

[33] AFNOR NF U44-095.

experience, acceptance by earthworms is a reliable (and cheap) indicator of digestate's suitability for return to soil. 90% of Algae LLDC products are sold to farmers directly (without an intermediary).

Ammonia stripping

Ammonia stripping is a mature technology for reducing ammonia in liquid digestate, with relatively low abatement costs. Ammonia stripping allows for the extraction of ammonia from liquid digestate and, in most examples, reacting it with sulphuric acid to produce dilute ammonium sulphate solution. Depending on the final objective, this process can be applied to all or part of the digestate, with or without a separation of the liquid and solid phases in association to other post-treatments (i.e. drying, evaporation).

Unless the recovered dilute ammonia salt solution can be used locally, then the key challenge is again energy, needed to concentrate the nitrogen from the digestate to produce a liquid fertiliser to reach the minimum threshold levels required by the EU Fertilising Products Regulation (PFC 1(C)(I)(b) (i.e. 5% N/wet weight).

MKR Cleanwater GmbH

MKR Cleanwater GmbH operates heat-driven digestate treatment by evaporation (Figure 18). In such as process of ammonia stripping, 80% of the ammonium nitrogen in the liquid digestate is converted to ammonium sulphate. Additional benefits[34] include discharge of the distillate to surface waters, accurate nutrient management, and reduced storage capacity (minus 70%).

[34] See at https://mkr-cleanwater.com/referenzen

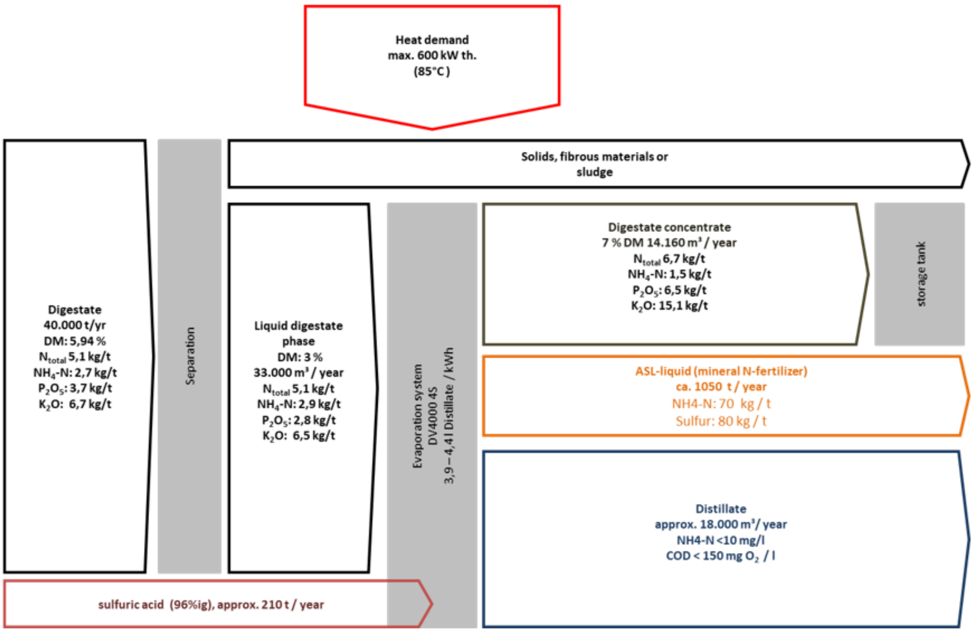

FIGURE 18 MASS BALANCE EXAMPLE FOR A HEAT-DRIVEN VACUUM EVAPORATOR DV 4-STAGE FOR DIGESTATE TREATMENT, SOURCE: MKR CLEANWATER GMBH

Acqua e Sole

Acqua e Sole[35] is a high solids anaerobic digestion co-generation plant (200-300 kW capacity) located in Northern Italy. The feedstock, a mix of sewage sludge and food waste (mainly domestic, but also agri-food), is co-digested in an AD plant under thermophilic conditions (55°c, min. 20 days). To prevent ammonia toxicity in the digester, a side-stream ammonia stripping unit is implemented (Di Capua et al., 2021) which removes up to 40% of the ammonia fed into this unit. The energy source is the biogas produced at the plant. Two fertilising products are thus produced:

1. The stripped ammonia, subsequently recovered as an inorganic ammonium sulphate (7.5% N), used as conventional N fertiliser and compliant with the quality requirements of the EU Fertilising Products Regulation.
2. The N-reduced digestate, pumpable (no separation of the solid and liquid phases), sanitised and highly stabilised in biological terms thanks to the thermophilic conditions (Pigoli et al., 2021). Microbiological analyses show, for example, the absence of salmonella and non-significant levels of faecal coliforms. Because the feedstock is classified as waste, the digestate output is also waste under the applicable Italian regulation, so it cannot be sold but can be provided to local farmers for free. This digestate has been used locally since 2016 as an organic fertiliser for cereal crops (rice, maize, wheat), allowing a reduction of the fossil-based N fertilisers needs by 75%. The digestate is injected into the top 15 cm of the soil (with specific equipment provided for free by Acqua e Sole to the farmers, Figure 19), which prevents odours, NH_3 emissions, nitrate leaching and runoff to surface and groundwaters and related N_2O emissions, while maximising agronomic benefits.

---

[35] https://neorisorse.net/

Figure 19 Example of Acqua e Sole equipment for injection of digestate in soil at pre-sowing (Source: Systemic Project, 2017)

The average compositions of ammonium sulphate and N-reduced digestate are reported in Table 6.

Table 6 Average composition of recovered products at Acqua e Sole (Source: Systemic Project, 2017)

	Ammonium Sulphate	Digestate
Total Solids (%)		10.5
Total Organic Carbon (%TS)		31.2
N-total (g/kgTS)		77.0
N-total (%wet weight)	~7.2	
P_2O_5-total (g/kgTS)		57.6
K_2O-total (g/kgTS)		8.3

Experimental research for three consecutive years on a maize crop (Zilio et al., 2022) showed the following benefits from the use of the Acqua e Sole fertilising products:

- Similar nutrient use efficiency when compared to synthetic ammonium sulphate and urea
- Increased soil organic carbon (SOC) after three years, because of the highly stabilised organic matter in the digestate
- No significant difference in terms of NH_3 and GHG emissions compared to synthetic mineral fertilisers
- No detected risks of N leaching (Zilio et al., 2023)

- Accumulation of inorganic and organic pollutants (POPs) did not occur after digestate application and ecotoxicology measurement indicate the absence of any adverse effect

Another study (Herrera et al., 2022) compared the environmental impacts of 1 ha of maize fertilised with the Acqua e Sole products versus mineral equivalents (urea, triple phosphate and potassium sulphate), using a cradle to grave lifecycle analysis covering production, transport and use phases. The research showed much lower environmental impacts from the use of Acqua e Sole products, because of the environmental benefits from the production of biogas and the substitution of mineral fertilisers, as well as the limited NH_3/N_2O emissions and nitrate leaching (due to digestate injection into the soil and to the high biological stability of the digestate).[36] This experimental research indicated that in well stabilised digestate, injected into the soil at the right time, only the efficient (mineral) N fraction contributed to N_2O emissions, while the organic N and C contained in the digestate did not mineralise in the short-medium term and did not additionally contribute to N_2O or CO_2 emissions. The research suggested that the N_2O and NH_3 could be further reduced using nitrification inhibitors and distribution equipment with flexible anchors.

Waste producers (e.g., municipal waste managers, agri-food companies) pay a fee to Acqua e Sole to cover the treatment costs of their waste. Further growth of this model would be possible if the digestate-based output could legally qualify as a fertilising product (even when the initial feedstock is waste) and would be replicable in other regions characterised by high waste generation (e.g., high population density) and sufficient local demand for fertilisers.

Cooperl

Cooperl, a co-operative of 3,000 pig farmers in French Britany specialising in primary meat production, estimated that biomethane production from manure can reduce the company's CO_2 emissions by 25%. The biomethane produced by Cooperl is currently injected to the grid, covering 75% of the gas needs of the Lamballe municipality (approx. 70,000 inhabitants). The digestate is not spread locally as Britany is a nitrate vulnerable zone but commercialised as fertilisers, after drying and granulation (using secondary energy from onsite incineration of meat processing wastes) and after blending with mineral nutrients to produce fertiliser products adapted to different crops' specific nutrient requirements, through the company's subsidiary Fertival[37], as liquids or granulates, thus allowing export outside Britany.

For collecting the feedstock, Cooperl has developed unique methods, including a patented V-scraping system (called TRAC[38]) which allows the separation of the liquids from the solid part of manure through a technology integrated in the buildings for animal husbandry. It allows for a reduction in odours, land pollution and greenhouse gas emissions. This system aims at reconciling respect for the environment and agricultural production. The liquid fraction, rich in ammonia, is usually spread at the farm, while the solid fraction, rich in nitrogen and phosphorous,

---

[36] An important distinguishing feature of this research is that air emissions, including NH3, N_2O, CH_4 and CO_2, were not assumed but measured in the field on randomly distributed soil plots. The full field tests showed no increased NH3 emissions compared to chemical fertilisation.

[37] https://www.fertival.fr/

[38] Video available at: https://youtu.be/wg7tc4GlG8U?si=ZpD7CCegchGlpFXT

is often pre-treated at the farm[39] and then fed into anaerobic digestion. The digestate is further processed in three steps: 1) centrifugation and further drying of the solid part for use into granulated fertilisers; 2) vaporising the liquid part to recover 100% phosphorous and produce ammonia water; and 3) ammonia stripping to obtain ammonium sulphate and clean water (the latter is reused in the meat production process). Heat is 100% from renewable energy[40] and the vaporisation energy is also recovered. Sanitisation is ensured through 120°c drying for 10 hours, combined with further heating during compacting and granulating. The final output undergoes bacteriological testing. The process, which entailed an initial investment of €15 million, is economically viable, with €20/t paid to farmers for their manure, revenues from sales of biomethane and fertilisers (including a price premium for high quality organic and organo-mineral fertilisers), and no treatment costs for industrial wastewaters. Fertival can thus be economically viable.

Struvite

Struvite (magnesium ammonium phosphate) can be precipitated from ammonia-phosphate-rich streams such as digestate from animal manures, food and food processing wastes and wastewaters, municipal wastewaters or sewage sludge. This method presents the two-fold advantages of producing an organo-mineral fertiliser and stabilising part of ammonia in the remaining digestate or sludge.

Struvite recovery is particularly relevant for wastewater treatment, where it allows the removal of orthophosphates from sludge (hence reducing the risk of phosphate runoff and related eutrophication), as well as the reduction of unwanted struvite precipitation which damages pipes and valves, hence reducing maintenance costs. The process requires substantial capital expenditures but can offer several economic benefits to a wastewater treatment plant by reducing maintenance costs, reducing disposal costs, bringing additional revenues from struvite and, if combined with anaerobic digestion, from renewable energy sales.

The struvite recovery process captures nitrogen, phosphorus and magnesium, turning them into a slow-release, high phosphate, starter fertiliser for crops (Thiessen Martens et al., 2022), thus reducing reliance on mineral alternatives. Studies have shown that struvite nutrient use efficiency is superior or comparable to most conventional P fertilisers for various plants such as ryegrass,

[39] Further separation between liquid (water recovered for irrigation) and solid matters (feedstock for anaerobic digestion).

[40] Wastewaters from the slaughterhouse and meat primary production are treated, the fats are recovered and used for heat generation and production of steam at 180°c. Some biomass recovered during the treatment of manure is also used for this heat generation, which covers all industrial heat needs of Cooperl. Besides, the unused heat from production processes is recovered and delivers water at 85°c across the industrial site.

maize, lettuce and cabbage[41]. Recent research (Erdal et al., 2024)[42] confirmed superior nutrient use efficiency (NUE) for powdered struvite recovered from digestates from poultry manure[43], delivering better yields with lower phosphate inputs. In addition, the slow-release properties of struvite offer several advantages:

- Mitigating the rapid fixation of phosphorus, thereby improving its uptake by plants
- Making it suitable for a variety of crops, particularly those with long growing seasons (Rahman et al., 2014)
- Delivering steady supply of nutrients to plants throughout the growth period, while minimising the need for frequent fertiliser application, thereby lowering labour and operational expenses for farmers[44]

Struvite recovery also mitigates eutrophication risks (Sylvester-Bradley et al., 2016) by reducing the release of P to waters.

The struvite market has economic risks and challenges. Substantial investment is required for struvite recovery technologies. To sell to downstream fertiliser companies, securing a long-term offtake contract can be challenging. However, producing a high-quality (in particular, not containing significant organic matter impurities), granular struvite, a standardised product, with consistent NPK levels, can mitigate this issue. Standardised products are more appealing to downstream farmers, as they can reliably predict performance in their local conditions; the reference price for these products will be linked to conventional mineral fertilisers like diammonium phosphate (DAP) or monoammonium phosphate (MAP).

The EU Fertilising Product Regulation (FPR) sets out a maximum limit of 3% C-org (organic carbon) in struvite, when this is used as a component in EU fertilising products, to exclude low-quality struvite "sludges", high in organic matter, so difficult to handle, not stable, susceptible to contain organic pollutants or pathogens.

Granular struvite can be applied without additional processing using standard fertilisers distribution equipment, making it convenient for farmers. The most common methods include broadcasting, banding and incorporation into the soil. The optimal timing for application depends on the crop cycle and nutrient demands even if the use of struvite at the beginning of the growing season is beneficial for many crops, as its slow-released properties ensure a steady supply of nutrients throughout the growth period. However, specific recommendations can vary based on crop type and local conditions).

[41] Plaza et al. 2007; Gell et al. 2011; Ryu et al. 2012; Hilt et al. 2016; Wen et al. 2019; Valle et al. 2022, cited in Erdal et al., 2024. See also Leon et al., 2023.

[42] Erdal, I., Yazici, H., Ekinci, K., Türkan, S. A., Yaylaci, C., Mejri, R., & Kumbul, B. S. (2024), "Comparison of Struvite as a P Source with Chemical Fertilisers and Evaluation of Additional Contribution to Growth and Mineral Nutrition of Lettuce Grown on Acidic and Calcareous Soils", Journal of Soil Science and Plant Nutrition.

[43] In this research, plants fertilised with struvite exhibited significantly higher fresh and dry weights than plants fertilised with DAP, MAP, TSP, and 20-20-20 NPK conventional fertilisers.

[44] https://www.ostara.com/benefits/maximize-yield/

Ostara

A prime example of this economic model is the Canadian company Ostara, relying on the sale of struvite reactors coupled with an offtake contract for the finished product (granular struvite[45]) with a guaranteed offtake price for the producer, and with anaerobic digestion offered as a possible 'value-add option'. The recovered struvite is sold by Ostara directly to farmers as Crystal Green Pearl®[46] fertiliser (CE-marked), one of the few examples of successful premium branding of recovered nutrients.

Struvite is covered by the scope of the EU Regulation for fertilising products (FPR). It may be covered by Component Material Category (CMC) 12, of Annex II to the FPR, setting out requirements for precipitated phosphate salts and derivates and if struvite is compliant with all relevant requirements, it can be used as a component in Compound Solid Inorganic Macronutrient Fertiliser (covered by Product Function Category 1(C)(I)(a)(ii), of Annex I to the FPR). Granular struvite can be applied with standard fertilisation equipment.

The sale of granular struvite as a fertiliser however encounters market barriers. It has a higher cost than conventional equivalent from mined P (e.g., DAP, MAP, TSP), due mainly to high CAPEX per mass of output. Pure struvite has an NPK sum of ~51% of the DAP[47] NPK sum (according to Recyfert). On June 7, 2024, the price for granular DAP (shiploads FCA Bulk Duty paid/free) port Ghent, Belgium was approximately 580 €/t, hence the theoretical price of granular struvite could be around 296 €/t (580*0.51). However, research (Muys et al., 2021)[48] indicated higher prices for granular struvite at €350/t (Phosphogreen) and up to €1,000/t for a high-purity, CE-marked product (Crystal Green Pearl), suggesting that in most cases struvite was sold at lower prices than the estimated market value of its macro nutrients (estimated at €250-412 /t in this research), except in cases where customers are willing to pay for a sustainability premium.

The CE-marking can also add significant costs per tons of output, due to the low tonnages per plant (cost reduction may be possible if a company operates the same struvite recovery process at multiple locations and all sites they should be considered as one factory).

Another market barrier is the lack of awareness by farmers. Standardisation of the quality and performance of granular struvite products, with low organic carbon, consistent granule size and characteristics, consistent NPK values, is important to mitigate these issues, as well as long-term offtake contracts to mitigate price volatility issues (as in the Ostara example).

The EU offers various supports for sustainable agricultural practices for using eco-friendly fertilisers like struvite. These supports can make struvite more attractive option for farmers seeking sustainable and economically viable fertilisation methods (Recyfert).

---

[45] Typically 1-2mm size.
[46] https://www.ostara.com/products/crystal-green/
[47] Diammonium phosphate.
[48] Maarten Muys, Rishav Phukan, Günter Brader, Abdul Samad, Michele Moretti, Barbara Haiden, Sylvain Pluchon, Kees Roest, Siegfried E. Vlaeminck, Marc Spiller, "A systematic comparison of commercially produced struvite: Quantities, qualities and soil-maize phosphorus availability", Science of The Total Environment, February 2021.

Biochar

Biochar is traditionally known as charcoal when produced from wood. It is produced via pyro-gasification, a thermal process whereby feedstock is heated in an oxygen-limited atmosphere, transforming it into a carbon-rich, highly porous substance primarily known for its soil-improving properties. Solid digestate can be used as feedstock for pyro-gasification even if distribution and physicochemical properties of the pyrolysis products depend on the applied thermal conditions and the properties of the original feedstock (Bardi et al., 2023). In addition to biochar's role in improving soil properties, it can remain in soil for centuries and act as carbon storage leading to recognise it as one of the few immediately accessible strategies for large-scale carbon sequestration and removal (Fuss et al., 2018).

Stiesdal SkyClean

The Stiesdal 20 MW pyro-gasification plant is located in Vra (Denmark). It processes 40.000 t of dried solid digestate per year. This pyrolysis plant was designed to use solid digestate from an existing local biogas plant. Since the solid digestate has significant humidity content, it needs to be dried to make pellets that can be used in the pyrolysis reactor. There is a synergetic relationship between the biogas plant and the pyrolysis plant. The former delivers feedstock to the pyrolysis plant, and the latter delivers additional renewable gas to the biogas plant for energy production. The biochar is applied to soil through standard farming machinery, and such practice is used for carbon capture and storage on farmland, generating additional revenues. The pyrolysis technology is being gradually scaled up into a fully automated commercial plant.

Hydrothermal Carbonisation (HTC) and Hydothermal Liquefaction (HTL)

HTC is described in some publications[49] as a process applicable to digestate, even if further research and development is needed to reach full commercial deployment. HTC can be installed at AD plants to dewater solid digestate and convert it (without further drying) into a dry, black powder or briquettes, called biochar or hydrochar. Biochar/hydrochar is chemically stable and storable, and can be used as a biofuel (e.g., replacing coal or wood pellets)[50] or soil improver. The HTC process works at 20-30 bar and 200-230 °C increasing C-content up to 60%. Various post-treatments can adjust the hydrochar to end applications, e.g. by modifying moisture content, density, content in nutrients or inorganic components (e.g., Ca, K, or P). The moisture from the feedstock condensates after the HTC process, and solubilises elements like N, P, and K, which can be recovered as liquid fertiliser[51] even if various valorisation pathways should be evaluated on the basis of characteristics of the recovered aqueous phase.

---

[49] For example, "Valorisation of Organic Wastes and Sludges for Hydrochar Production and Biofertilisers", IEA Bioenergy Task 36, Ciceri et al., 2021, or "Review: technologies to optimise the value of digestate", WRAP UK, 2020.

[50] See for example https://www.antaco.co.uk/technology/

[51] See for example https://ingelia.com/index.php/sostenibilidad-medioambiental/english-liquid-fertiliser

The HTL process yields a non-polar phase, mostly referred to as biocrude oil, a solid residue known as hydrochar, a gas phase mainly comprised of CO_2 and water-soluble compounds termed aqueous product (Klüpfel et al., 2025). The main product is the biocrude, an energy-dense and viscous, carbon-rich liquid, which is considered as a fuel precursor. In comparison with HTC, HTL does not require drying of the biomass but utilizes the properties of water at near-critical conditions and it could be applied directly to whole or liquid digestate.

Although technological improvements have been reported in the last years, its application at full-scale level is still not widespread.

Plasma Treatment

Plasma treatment is described as a process applicable to digestate in some publications[52], even though knowledge gaps need to be investigated before the technology can be deemed fit for wider practical application. The technology aims to reduce NH_3 emissions during storage and field application of treated slurries or digestates, limits CH_4 emissions, and increases available inorganic N. The plasma treatment fixes reactive nitrogen from the atmosphere to the slurries in NO_3^- and NO_2^- form. The fixation of NO_3^- and NO_2^- forms nitric acid (HNO_3) and nitrous acid (HNO_2), lowering the slurry pH and thereby reducing the risk of NH_3 emissions.

N2 Applied

N2 Applied has developed a plasma treatment (patented), using electricity to split N_2 and O_2 molecules from the air and produce a nitrogen oxides gas. This gas then reacts with and is absorbed by the digestate, lowering its pH (hence the rate of ammonia volatilisation) and increasing the nitrogen (as nitrates and nitrites) immediately available for plant growth, while organic matter remains stable. The process is being applied to digestates from manures, agricultural residues, agri-food waste, and co-digestates of these. Further drying and pelletising or granulating would be necessary to achieve the required nitrogen content for commercialising it as an ammonium nitrate fertiliser under EU or national rules. Currently, N2 Applied sells plasma-treatment units mainly for local farm usage and small biogas plants. The technology is currently being scaled up for use in larger biogas industry.

[52] For example: Nyang'au et al., "Effects of plasma treatment of digestates on pH, nitrification and nitrogen turnover during storage and after soil application", Environmental Technology & Innovation, Volume 34, 2024, 103578); Pedersen et al., "Effect of slurry separation and air-plasma treatment on NH3 and VOC emissions from field applied biogas digestate and pig slurry to grassland", Biosystems Engineering, Volume 247, 2024, Pages 257-266.

3.2 Technical barriers to the development of digestate-based fertilising products

An important technical constraint for producing digestate-based organic or organo-mineral fertilisers is reaching adequate nutrient content and conventional fertilising products characteristics (e.g, volumes, spreading technics, storability). Routes to achieve this are evaporation, drying, and other technologies such as membrane/reverse osmosis, but they require significant energy.

Possible solutions include the use of CHP engines as a heat source (see for example the case of Bioenergia de Almena). Where biogas is upgraded into biomethane for grid injection, other heat sources are needed, such as waste heat, heat generation from industrial wastewaters (see the example of Cooper) or heat pumps, or by using a part of the biomethane production for heat generation (however, given the premium price of biomethane, this could substantially inflate the thermal energy costs calculated for fertiliser production).

The use of natural gas for drying digestate adversely affects the carbon credits associated with biomethane production, limiting the added value of the final product as a low-carbon fertiliser when marketed. Given the premium price of biomethane, thermal energy costs become a significant portion of the overall production cost.

Another innovative method could be to use renewable electricity (e.g., solar or wind) for heat generation and store excess heat into on-site thermal batteries for release during peak hours[53]. Thermal batteries, capable of charging up to 1800°C, can store this energy and release it during peak hours when electricity prices are higher. This method assists renewable energy companies in managing grid flow but necessitates a robust connection from the refinery to the grid.

[53] Such large thermal batteries are commercialised in Europe for example by Siemens Gamesa, Energynest or Rondo.

4.

Bringing more advanced digestate-based fertilisers

onto the European market

4 Bringing more advanced/processed digestate-based fertilisers onto the European market

As illustrated in Chapter 3, several processes are developed at industrial and commercial scale to transform digestates into more advanced/processed fertilising products and soil amendments from organic origin. As shown in Table 7, the solid fraction of digestate is mostly used for amendments purposes (dewatered solid fraction, compost, biochar), whereas the liquid fraction enables the recovery of ammonium, phosphorus and potassium (N, P, K) that could replace conventional fertilisers with recovered materials (Table 6). It should be mentioned that digestate is the only fertilising product from organic source containing nitrogen in a mineralised form (ammonium) through the process of digestion (Riva et al., 2016). Organic nitrogen contained in most pure organic fertilisers and soil amendment has a long-term effect, mineralised nitrogen is readily available for plant uptake, promoting rapid growth and higher yields, especially in the short term.

Table 7 Nutrient component concentration after digestate separation into liquid and solid fraction (EAWAG (2009) and (Carton & Bulcke, 2021)

Component	Liquid phase	Solid phase
N - Ammonium	95%	5%
N - Organic	5%	95%
Potassium (K)	90%	10%
Phosphorus (P)	50-10%*	50-90%
Fibrous Matter	0%	>95%**
Volume	80-90%	<20%

**Depends on the use of coagulants/flocculants for the separation of the solid phase **Depends on the state of methods for the elimination or transformation of nitrogen for small/medium-sized agricultural biogas plants.*

However, transforming digestate into fertilising products through post-processes technologies necessitate significant investments and operational costs. Digestate-based organic and organo-mineral fertilisers typically have higher production costs compared to their fossil-based equivalent, notably due to higher energy and processing costs for nutrient recovery. These higher costs make organic and organo-mineral fertilisers less resilient to high price volatility on the fertilisers market, and to the related downward pressure on end-market prices[54].

4.1 Business models for biogas plants with digestates

Add value by reducing operational costs for AD plants

In the seven cases investigated by the EU-funded SYSTEMIC project[55] (2017-2022) (all of which processed digestates into various digestate-based fertilising products), the business case analysis demonstrated the nutrient recovery and recycling added value and improving the financial result of the enterprise due to the reduced operational costs.

The cases investigated were typically situated in "regions with elevated livestock density and corresponding limitations to the use/disposal of digestate, or other constraints like nitrate vulnerable zones or climatic conditions limiting the use of digestate", where it is too costly to store, handle and transport digestate (with >90% water). Hence, it is more profitable to invest in NRR[56] technologies than coping with the corresponding high operational costs."

As a result, in all investigated cases, nutrient recycling was not subsidised, but a net cash contributor for the biogas/biomethane plant. The project also concluded that "a biogas plant located in an area with low livestock density, large cropping/pasture areas, mild climate (allowing longer and possibly more than one agricultural cycle(s)) and low nitrate sensitivity (no nitrate vulnerable zone), may not need to have its digestate treated to make good use of it", and therefore may not be willing to invest in NRR technology, especially if the business is profitable without, and despite the potential for removing pollutants or pathogens.

However, the SYSTEMIC project identified significant untapped potential in the development of "upcycled", branded digestate-based fertilisers, which would require a favourable framework and risk capital, as "examples show that 3-5 years of continuous efforts including a dedicated and experienced team are needed until a product brand can be established".

Realistically, many digester operators are too small to set up their own fertiliser marketing department and work better through existing fertiliser distributors and waste brokers. Other larger companies, such as large waste management companies or biogas/energy companies, may have the critical mass to themselves becomes a fertiliser company, or may purchase organic fertiliser companies to bring such competence into their group.

---

[54] Downstream fertilisers companies (dealers/retailers) retailers aim to negotiate offtake prices below market value, to mitigate their own risks related to price volatility.

[55] Horizon 2020 Framework Programme for Research and Innovation, grant n° 730400, available at: https://systemicproject.eu/plants/. The seven investigated cases included 5 demonstration and two outreach plants.

[56] Nutrient Recycling and Recovery systems (NRR).

Valorising digestate-based fertilisers in the conventional market: a market struggling to emerge

A 2023 report by WRAP for the UK Department of Energy Security and Net Zero[57] investigated scenarios for the valorisation of digestates from food wastes and from manures/slurries mixed with crop residues. The report found that the valorisation depends on the nutrient content of the digestate and the fertiliser market prices.

Conventional fertilisers are market commodities with price indicators (e.g., S&P Fertecon), which are correlated to the gas price (used to the production of ammonia and urea). Marketing digestate can thus be challenging due to the high price volatility of synthetic fertilisers; as for other organic fertilisers, the demand for digestates increases with the price of synthetic fertilisers. When the price of fossil gas is low, the price of conventional fossil-based fertilisers is also low, lowering the desirability of organic fertilisers such as digestate-based fertilisers.

Thus, downstream fertiliser retailers negotiate the digestate-based fertilisers (DBF) prices below market value to hedge against potential risks. Beside the primary challenge for most digestate post-processing projects remaining to secure long-term offtake contracts, the price levels negotiated barely cover the investments and operational costs of post-process facilities.

Furthermore, fossil fertilisers have shaped the market for decades, and therefore, farmers are used to the formulations described in Figure 20. Farmers choose fertilisers depending on the cost, expected crop yield (based on standardised NPK values), ease of application, as well as the medium-long term benefits for soil health. For example, farmers are usually willing to pay more for round granules than pellets because pellets create more dust during spreading, and granules flow better through spreaders and thus more accurate application is possible.

However, the price formulation does not reflect their environmental positive externalities like organic carbon storage, lower carbon footprint, impact on soil microbiology and health, or superior nutrient use efficiency, which are typically not valorised.

[57] Identifying Impacts from Food and Farm Digestates, available at: https://assets.publishing.service.gov.uk/media/641c471aba5ac90013b1a737/identifying-impacts-from-food-and-farm-digestates.pdf

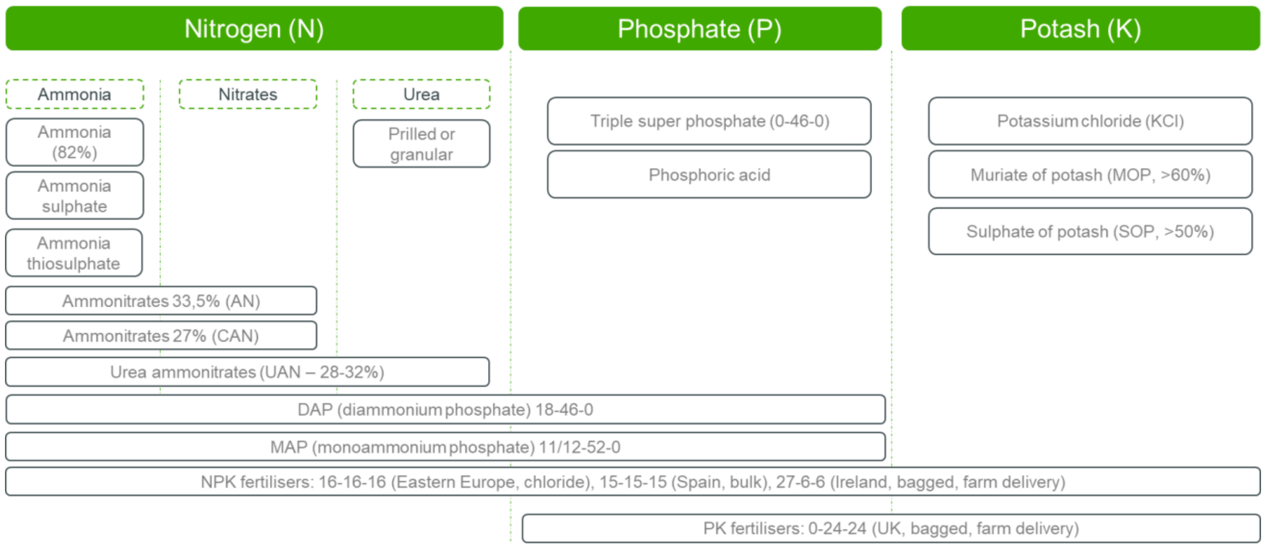

FIGURE 20 NPK FORMULATION OF CONVENTIONAL FOSSIL-BASED FERTILISING PRODUCTS[58]

Adapting digestate-based fertilisers to agricultural practices and needs for European independence

Organic fertilisation is key in European food independence[59] and soil health, by recycling the nutrients that are available without importing gas and conventional fertilisers from third countries, i.e., Russia. A recent study for the European Commission on SMEs and open strategy autonomy[60] stated that "SMEs play a central role in strategies aimed at reducing dependence, particularly in the production of alternative sources of fertilisers such as organic fertilisers" and plant biostimulants. The study concluded that organic, bio-based fertilisers is one of the sectors "where the EU can still build a solid competitive position and where SMEs play a significant role".

Given farmers' lack of awareness and training on the benefits and application methods of organic fertilisers can hinder market growth, adapting DBFs to their needs could enable the development of the market. DBF are low-volumes and very specific (e.g., an organo-mineral 10-5-5 with 35% organic matter or an organic 3-3-3 with 60% organic matter). They can thus be modulated and formulated with other organic materials given the needs of specific agricultural needs and practices, based on the local characteristics of fertilising products being used, as shown in Table 8. The global market for nutrients needs is about 110 million t/y for nitrogen, 45-50 Mt/y for phosphorous, 40 Mt/y for potash (International Fertiliser Industry Association internal data), from which organic fertilisers containing mineralised nutrients could gain market shares.

---

58 Claire-Lise Speisser (2024).

59 European Commission (2022), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, "Ensuring availability and affordability of fertilisers" (COM(2022) 590 final).

60 "SMEs and Open Strategy Autonomy", Final report by CSIL, IDEA Consult, PPMI and LSE for DG GROW, 3 July 2024, available at: https://single-market-economy.ec.europa.eu/document/download/27773867-479e-464e-af2f-b548b76ffb13_en

Table 8 Nitrogen fertilising products consumption in the European Union in % by types of products (average values from 2016 to 2020) based on IFA data (2023) and (Hu & Schmidhalter, 2024)

	CAN	NP+NPK	U	AN	UAN	AS
France	16	8.7	19.60	24	30.2	1.1
Germany	58.2	8	18.5	0	10	5.2
Poland	12.3	15.8	26	37.3	6.2	2.3
Spain	24	24.5	29.6	4	9	7.2
UK	10.8	10.5	14.9	44.1	16.6	2.1
Romania	12.1	27.6	21.8	33	3	2.3
Italy	14	15.1	60.3	5	1.3	3.6
Bulgaria	3.5	14.4	23.1	50.8	7.1	1
Hungary	54.3	15.3	9.1	6.4	14.2	0.7
Ireland	47	36	14.2	2.2	0	0.1
Estonia	0	38.5	61.4	0	0	0
Czechia	45	5.8	23	1.1	21.8	3.2
Denmark	58.8	22.3	0.3	2.2	11.3	3.7
Sweden	62.9	33.1	0.4	2.1	1.1	0.1
Netherlands	73.5	8.1	3.9	0	11.2	1.1
Belgium & Lux	53.2	4.8	5.9	0	33.9	1.6
Greece	19.2	40.9	22	11.9	0	5.4
Lithuania	4	14.8	7	30	21.4	22.7
Finland	30.3	69.7	0	0	0	0
Slovakia	43.3	11.8	28.8	2.3	11.1	1.6
Croatia	34.7	21.7	42.2	0.4	0.4	0.6
Latvia	8	37.1	7.1	32.3	6.9	8.6
Austria	63.5	19.1	12.2	0	0.8	4.2
Portugal	44.1	33.2	8.7	0	7.6	5.1

Slovenia	67.8	30.1	0	0	0	1.9
Cyprus	2.8	64.1	20.4	11.1	0	0.3

Notes - CAN: Calcium Ammonium Nitrate; NP + NPK: Nitrates and Phosphorous + Nitrates, Phosphorous and Potassium based-fertilising products used; U: Urea; AN: Ammonium Nitrate; UAN: Urea Ammonium Nitrate; AS: Ammonia Sulfate

Alternative paths

However, a share of economic actors of the agri-food sector might be willing to pay a premium for organic or organo-mineral fertilisers, if this fits into their corporate sustainability strategy or contribute to higher product value for the end customer. This may be especially the case for crops with higher economic value per hectare, such as wines, fruit or vegetables, as certified organic farming production.

Looking forward, the global market for organic and organo-mineral fertilisers, driven by increasing demand for sustainable agricultural practices, including from food companies, is expected to grow as of 2023 at an annual growth rate of 7.3% projected over the next five years (Market Research Future, 2023). Organo-mineral fertilisers, combining organic materials with mineral nutrients for enhanced efficiency, are expected to grow at a slightly higher rate of 8.2% (Grand View Research, 2023).

In addition to the benefits of processing technologies, positive impacts on the environment, climate and soil health are observed[61].

4.2 The role of regulation and political support for the emergence of the organic fertilisation in Europe

WRAP's report for the UK Department of Energy Security and Net Zero[62] observed that "regulatory barriers currently prevent the use of digestate concentrates or soil improvers for landscaping / amenity purposes as products" and therefore, "the financial status of several valorisation approaches would be very significantly improved if end of waste positions could be developed or clarified for the supply of nutrient concentrates and separated fibre digestates to amenity/landscape markets".

---

[61] "Exploring digestate's contribution to healthy soils", available at: https://www.europeanbiogas.eu/wp-content/uploads/2024/03/Exploring-digestate-contribution-to-health-soils_EBA-Report.pdf; ISWA Working Group Biological Treatment of Waste, available at: https://www.iswa.org/biological-treatment-of-waste/?v=d3dcf429c679

[62] "Identifying impacts from food and farm digestates", available at: https://assets.publishing.service.gov.uk/media/641c471aba5ac90013b1a737/identifying-impacts-from-food-and-farm-digestates.pdf

Also, the study on SME and open strategy autonomy[63] already mentioned, suggested supporting the emergence of the European organic fertilisers industry by "investing in infrastructure for the collection, treatment, and processing of biowaste", "promoting the separate collection of bio waste and supporting composting facilities", "promoting the use of sustainable farming practices" and "easing some regulatory barriers, such as the clarification on the use of animal by-products, and the elaboration of standards across the EU".

Therefore, both regulation and political support are key in the emergence of a European organic fertilisation industry.

The regulatory framework for organic fertilisation from digestate

Digestates' return to soil is highly regulated by a myriad of diverse mechanisms, at different governance levels (local, national, regional). EBA's reports (European Biogas Association, 2024a, 2024b) provide a detailed review of the European-level and Member States's regulation regarding digestate production, management and use.

The EU FPR is not the only way to market products and national legislations cover similar products. Regarding the very specific regulation of the use of raw or untreated digestate and digestate-based fertilisers (DBF), both European and Member States rules apply.

The EU regulatory framework aims to favour organic fertilisation

The Fertilising Product Regulation (FPR) 2019/1009 offers the opportunity to CE-Mark organic and organo-mineral fertilising products across all Europe. This regulation sets out requirements for digestate-based fertilising products (DBF) to be placed on the European market, covered by the rules of different categories such as the Product Function Categories (PFC) 1(A) "Organic fertiliser" and 1 (B) "Organo-mineral fertiliser", and the PFC 3(B) "Inorganic Soil Improvers". All CE-marked products must comply with quality and innocuity requirements which are set out at component material level e.g. digestate, but also at product level e.g. fertiliser, such as organic matter content, nutrients content, pH, heavy metals or pathogens content.

EU fertilising products may only contain materials covered by a Component Material Categories (CMC) and should comply with all relevant requirements. For DBFs, the digestate used should meet CMC 4 (energy crops), or CMC 5 (other feedstocks) requirements, and additionally comply with all relevant requirements the FPR (requirements for the PFCs and labelling requirements). In case animal by-products were used for the production of these materials, they must have undergone specific processes to ensure compliance with the Animal By-Product Regulation (ABP) 1069/2009[64]. More specifically, digestates produced from animal by-products must have reached

---

[63] "SMEs and Open Strategy Autonomy", Final report by CSIL, IDEA Consult, PPMI and LSE for DG GROW, 3 July 2024, available at: https://single-market-economy.ec.europa.eu/document/download/27773867-479e-464e-af2f-b548b76ffb13_en

[64] Delegated Regulation (EU) 2023/1605.

an end point in the manufacturing chain according to the criteria set in the aforementioned Regulation (EC) 1069/2009 and Delegated Regulation (EU) 2023/1605.

Additionally, some feedstocks such as agri-food sludges are not (yet) recognised input materials to digestate covered by CMC5. However, many digesters take a mixture of different feedstocks, which can often include materials from, e.g., food processing or animal feed processing. As a result, methanisation units may refuse these wastes in order to comply FPR rules and operate under their FPR certification for the production of EU fertilising products – despite the environmental and economic benefits from the valorisation of agri-food sludges.

The Fertilising Products Regulation (FPR) represents a significant regulatory instrument capable of recognising, at the European level, the fertilising and soil-amending potential of digestates. However, the FPR does not currently allow the recognition of unprocessed digestates as fertilisers under PFC 1(A). This is because the minimum nutrient concentrations are expressed on a fresh matter basis, whereas unprocessed digestates are predominantly composed of water. To allow for the recognition of unprocessed digestates as fertilizers, the BIP considers that nutrient values would need to be calculated on a dry matter basis, reflecting their true capacity. This regulatory gap hampers the development and implementation of circular economy loops across European territories.

The use of digestate in organic production

Organic production should not be confused with *organic fertilisation*. Organic production describes agricultural practices aimed in particular at reducing the use of convention pesticides and fertilising products, whereas organic fertilisation is an alternative to fossil-based fertilisers originating from organic matter that have been processed and may originate from various sources - including conventional farming.

Digestate is authorised for use in organic agriculture under the Commission Implementing Regulation (EU) 2021/1165. Annex II of this Regulation lists the fertilisers, soil conditioners and nutrients authorised for use in organic agriculture and includes “biogas digestates containing animal by-products co-digested with material of plant or animal origin”. This is solely applicable to digestate from animal by-products, and the animal by-products shall not be from “factory farming origin”.

Besides, Article 31 of the Regulation (EU) 2018/848 on organic production and labelling of organic products provides the possibility for fertilisers that have been authorised in accordance with Articles 9 and 24 of the Regulation to bear a reference indicating that those fertilisers have been authorised for use in organic production.

Within the certified organic production, digestates-based fertilisers (DBF) can be used provided they respect the description, specific conditions and limits set in Regulation (EU) 2021/1165, along with farmyard manure and “raw digestates”. Under Regulation 2021/1165[65], composted digestates or fermented biowaste, or composted or fermented mixture of vegetable matter, vermicompost,

[65] European Commission Implementing Regulation 2021/1165, Annex II.

and recovered struvite and precipitated phosphate salts are authorised fertilisers for organic production, under certain conditions. In Member States, there are other examples of digestate-based fertilisers suitable for organic farming (see Chapter 3 on good practice examples). However, the production costs gap cannot always be covered by the selling price of the DBF, whereas in California, for example, the labelling stating that a fertiliser can be used in organic farming justifies a market price enabling to cover the gap.

National regulations do not always favour digestate-based fertilisation

Member states implement different regulations on digestates. While the Fertilising Product Regulation (FPR) addresses the placing on the EU market, the high level of heterogeneity between national regulations and associated lack of regulatory transparency is a market barrier to the development of digestate-based organic fertilisation. Investors face uncertainty regarding their ability to market processed digestates as fertilisers because national legislation varies in how it classifies these materials—sometimes as waste, sometimes as product. This inconsistency increases risk and discourages investment in circular economy solutions. As with all circular EU single markets—such as recycled steel—regulatory visibility and a sufficient level playing field are essential for developing a robust EU-wide market for recovered organic fertilisers.

In particular, depending on the country, the “waste” or “product” status determines in different ways how digestates and DBF can be used and spread. When digestates are considered wastes, the spreading of digestates – regardless of their post-processing from untreated to separated to transformed into DBF, is either prohibited, or requires specific permitting procedures that increase the administrative burden for producers and users of digestate.

National regulations favouring the use of digestate

Denmark

In Denmark, digestate produced from a minimum of 75% livestock manure (dry matter) can be spread without permit, using injection and/or nitrification inhibitors. For digestate generated from more than 25% of waste, digestate uses and spreading must be declared to the authorities, but no permits are required. In any case, the digestate must comply with quality and safety criteria set by the Danish regulation.

The Netherlands

Given high concentration of N and P nutrients, digestates are mostly being post-processed for export. Digestate produced from at least 50% of livestock manure and co-digestion feedstocks authorised in the Fertilisers Act can be used as a product, mostly for organic farming.

Conservative national regulations towards the treatment of wastes by AD

Italy

In Italy the biogas-biomethane supply chain has developed along two lines: biogas/biomethane from waste (such as source-separated organic fraction from municipal solid waste and sewage sludge) and biogas/biomethane from "non-waste biomass", such as livestock effluents, crops, crop residues and food residues managed as "by-products" in accordance with environmental legislation.

Digestate from non-waste biomass (“agricultural digestate”) is, in most cases, intended for agronomic use as "by-product" considered to be fertilising products, as either agrozootechnical digestate or agro-industrial digestate (in presence of one or more food by-products from the agro-industry). They must comply with quality limits and safety standards (Table 9).

TABLE 9 SPECIFICATIONS FOR AGRICULTURAL DIGESTATES TO BE CONSIDERED AS PRODUCTS IN ITALY

Parameter	Value	U.M.
Pb	≤ 140	mg/kg TS
Cd	≤ 1.5	mg/kg TS
Ni	≤ 100	mg/kg TS
Zn	≤ 600	mg/kg TS
Cu	≤ 230	mg/kg TS
Hg	≤ 1.5	mg/kg TS
Cr^{VI}	≤ 0.5	mg/kg TS
Salmonella spp.	Absence in 25 g in 5 of 5 samples	

The waste-based digestate remains a waste under the national regulation, and its application to soil must be regulated by local authorities. On the other hand, if digestate is composted and compost complies with the national law on fertilisers, it reaches the end of waste status.

The national law on fertilisers (Legislative Decree 75/2010) also defines dried solid digestate from non-waste biomass as organic fertiliser.

Poland

Agricultural feedstocks used to produce digestates enable the producer to seek for a product status under a new procedure implemented in 2023. However, for other feedstocks such as industrial wastewater or animal by-products other than manure, they need to apply for a spreading permit at local level.

France

Digestates produced in France are automatically considered as waste, and users must apply for a spreading permit at local level. Post-composting under certain conditions enables the end-of-waste status for digestate, if a marketing authorisation is granted by the French Agency for Food, Environmental and Occupational Health and Safety. However, for agricultural AD plants owned by a majority of agricultural shareholders using more than 55% of agricultural feedstocks, dedicated specifications enable digestate producers to get a product status.

Political support schemes for the emergence of digestate-based organic fertilisation in Europe

The EU offers various supports, including subsidies and grants to encourage the use of sustainable fertilisers and practices.

Price stability tools

Even though the demand for organic and organo-mineral fertilisers is expecting to grow, a market for digestates-based fertilisers struggles to develop. Fertilisers prices are referenced by major fertiliser platforms publications such as S&P Fertecon. Establishing a similar price indication platform for standard organic and organo-mineral fertilisers (e.g. an organo-mineral 10-5-5 with 35% organic matter or an organic 3-3-3 with 60% organic matter) would assist the market in determining a price point for these products. This would provide investors with a reliable knowledge base.

Carbon farming incentives

As for other organic fertilisers, the economic model could improve if the avoided carbon emissions from the use of digestates and digestates-based fertilizers (DBFs) in substitution of fossil-based fertilizers could be recognised and incentivised, e.g. under carbon farming frameworks. This measure could contribute to the integration of the environmental benefits from the use of digestate and DBFs, instead of fossil fertilisers, in their market price.

Nitrates directive

The Nitrate Directive of 1991 promotes the reuse of manure and processed manure, including digestates, as fertiliser. However, in parts of Europe affected by pollution by nitrates from agriculture, it limits the application of digestates and other manure-derived fertilisers. In fact, limiting the nitrogen from livestock manure application, including processed manure-derived digestates, at 170 kg/ha/y level is imposed for the environment preservation and human health. In certain regions, this limits the reuse of digestates at local level – conversely, it might encourage further processing of digestates into exportable digestates-based fertilizers.

RENURE criteria as proposed by the Joint Research Centre (European Commission. Joint Research Centre., 2020) would allow certain forms of manure to be spread beyond the 170 kg of total nitrogen/ha/y in substitution of fossil-based fertilisers. A revision of the Nitrates Directive introducing this possibility has already been proposed in a draft comitology act in 2024, allowing products from three manure and digestate post-process technologies to be used as substitute for fossil-based nitrogen fertilisers and applied above the limit.

Recommendations

BIP members point to the value of consolidated existing good practice guidelines and principles to facilitate the proper return to soil of digestate, based on the experience of EU countries such as Germany, France, Italy, Belgium, Denmark, Spain and the Netherlands.

The BIP recommends complementary research among universities, research centers, and companies to foster digestate-based fertilisers to further confirm their benefits for crops, soil health and GHG emissions reduction and to assess both technical practicality and economic viability.

At farm and AD plant level

- Take a holistic approach to digestate to maximise its environmental, agronomical and social benefits.
- Install sufficient storage so digestate is made available for the field when it is needed by the plant, this will ensure digestate is valued.
- Perform routine characterisation of the digestate to measure the concentration of nitrogen (N), phosphorus (P), potassium (K), and organic matter complying with the relevant quality standards.
- Increase the use of low emission/high efficiency digestate spreading systems, such as direct incorporation into the soil and fertigation.
- Spread the right digestate (solid, liquid) with right dose and right application method during the right time.

At local level

- From the beginning of the operation of the anaerobic digestion plant, engage the local community to raise awareness and to promote the understanding of the role of biogas/biomethane in the ecological transition.
- Raise awareness of digestate's potential as a technical resource able to replace chemical fertilisers and increase soil fertility due to the organic matter it provides.
- Verify compliance with the requirements that the AD plant must guarantee and the adoption of best management practices in all phases of the production process and use of digestate.

At national and international level

- Foster regenerative farming practices by recognising the role of organic recovered fertilisers and soil amendments.
- Incentivise the use of organic fertilisers and digestates-based fertilisers. A blending obligation would offer regulatory support and visibility as well as creating a sufficient level playing field.
- Offer support schemes to produce digestates-based fertilisers (e.g.: centralised digestate processing plants, technologies and systems for digestate post-treatment).
- Design the circular criteria for public procurement to foster the use of recovered organic fertilisers in public gardening and public services.
- Remove barriers for digestate deployment to farmland.
- Review advanced technologies and systems for post-processing digestates and their use as fertilising products, including evolutions related to market conditions, technology, quality control and innovation.
- Enhance and simplify fertiliser regulatory framework related to digestate.
- Develop and require implementation of Quality Management System for digestates and digestates-based fertilising products.
- Develop programmes that specifically support phosphorus recovery and micro/macro nutrients recyclin

References

Al Seadi, T., Baxter, D., Lukehurst, C. T., & Frost, P. (2012). *Quality management of digestate from biogas plants used as fertiliser*. IEA Bioenergy. https://www.ieabioenergy.com/blog/publications/quality-management-of-digestate-from-biogas-plants-used-as-fertiliser/

Álvarez-Fraga, L., Capson-Tojo, G., Sanglier, M., Hamelin, J., Escudié, R., Wéry, N., García-Bernet, D., Battimelli, A., & Guilayn, F. (2025). A meta-analysis of pathogen reduction data in anaerobic digestion. *Renewable and Sustainable Energy Reviews*, *207*, 114982. https://doi.org/10.1016/j.rser.2024.114982

Angst, G., Mueller, K. E., Castellano, M. J., Vogel, C., Wiesmeier, M., & Mueller, C. W. (2023). Unlocking complex soil systems as carbon sinks : Multi-pool management as the key. *Nature Communications*, *14*(1), 2967. https://doi.org/10.1038/s41467-023-38700-5

ARPAE Emilia-Romagna. (2016). *Monitoraggio della composizione analitica del digestato prodotto da impianti a biogas" Esiti delle attività di monitoraggio. Anno di riferimento 2015"*. ARPAE Emilia-Romagna.

ARPAE Emilia-Romagna Sez. Bologna. (2014). *Monitoraggio conoscitivo della composizione chimico-fisica e microbiologica del digestato prodotto da impianti a biogas*. ARPAE Emilia-Romagna Sez. Bologna.

ARPAV Regione Veneto. (2013). *Caratteristiche del digestato da impianti di digestione anaerobica. Campagna di monitoraggio maggio-settembre 2013*. ARPAV Regione Veneto.

Bardi, M. J., Mutunga, J. M., Ndiritu, H., & Koch, K. (2023). Effect of pyrolysis temperature on the physiochemical properties of biochar and its potential use in anaerobic digestion : A critical review. *Environmental Technology & Innovation*, *32*, 103349. https://doi.org/10.1016/j.eti.2023.103349

Béghin-Tanneau, R., Guérin, F., Guiresse, M., Kleiber, D., & Scheiner, J. D. (2019). Carbon sequestration in soil amended with anaerobic digested matter. *Soil and Tillage Research*, *192*, 87-94. https://doi.org/10.1016/j.still.2019.04.024

Beillouin, D., Pelzer, E., Baranger, E., Carrouée, B., Cernay, C., De Chezelles, E., Schneider, A., & Jeuffroy, M.-H. (2021). Diversifying cropping sequence reduces nitrogen leaching risks. *Field Crops Research*, *272*, 108268. https://doi.org/10.1016/j.fcr.2021.108268

Bünemann, E. K., Reimer, M., Smolders, E., Smith, S. R., Bigalke, M., Palmqvist, A., Brandt, K. K., Möller, K., Harder, R., Hermann, L., Speiser, B., Oudshoorn, F., Løes, A. K., & Magid, J. (2024). Do contaminants compromise the use of recycled nutrients in organic agriculture? A review and synthesis of current knowledge on contaminant concentrations, fate in the environment and risk assessment. *The Science of the Total Environment*, *912*, 168901. https://doi.org/10.1016/j.scitotenv.2023.168901

Carton, S., & Bulcke, Q. (2021). *L'utilisation des digestats en agriculture : Les bonnes pratiques à mettre en œuvre* (p. 48). AgroParisTech.

Chojnacka, K., & Moustakas, K. (2024). Anaerobic digestate management for carbon neutrality and fertilizer use : A review of current practices and future opportunities. *Biomass and Bioenergy*, *180*, 106991. https://doi.org/10.1016/j.biombioe.2023.106991

Cooke, J., Girault, R., Busnot, S., Morvan, T., & Menasseri-Aubry, S. (2023). Characterising the Effect of Raw and Post-Treated Digestates on Soil Aggregate Stability. *Waste and Biomass Valorization*, *14*(9), 2977-2995. https://doi.org/10.1007/s12649-023-02045-3

Côté, C., Villeneuve, A., Lessard, L., & Quessy, S. (2006). Fate of pathogenic and nonpathogenic microorganisms during storage of liquid hog manure in Québec. *Livestock Science*, *102*(3), 204-210. https://doi.org/10.1016/j.livsci.2006.03.018

Di Capua, F., Adani, F., Pirozzi, F., Esposito, G., & Giordano, A. (2021). Air side-stream ammonia stripping in a thin film evaporator coupled to high-solid anaerobic digestion of sewage sludge : Process performance and interactions. *Journal of Environmental Management*, *295*, 113075. https://doi.org/10.1016/j.jenvman.2021.113075

Erdal, İ., Yazici, H., Ekinci, K., Türkan, Ş. A., Yaylaci, C., Mejri, R., & Kumbul, B. S. (2024). Comparison of Struvite as a P Source with Chemical Fertilizers and Evaluation of Additional Contribution to Growth and Mineral Nutrition of Lettuce Grown on Acidic and Calcareous Soils. *Journal of Soil Science and Plant Nutrition*, *24*(2), 3315-3328. https://doi.org/10.1007/s42729-024-01755-4

European Biogas Association. (2024a). Exploring digestate's contribution to healthy soils.

European Biogas Association. (2024b). Regulatory framework for digestate. Country analysis.

European Commission, Joint Research Centre. (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). Publications Office. https://data.europa.eu/doi/10.2760/373351

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., De Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., Del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions—Part 2 : Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

Giacometti, C., Mazzon, M., Cavani, L., Ciavatta, C., & Marzadori, C. (2020). A Nitrification Inhibitor, Nitrapyrin, Reduces Potential Nitrate Leaching through Soil Columns Treated with Animal Slurries and Anaerobic Digestate. *Agronomy*, *10*(6), 865. https://doi.org/10.3390/agronomy10060865

Goberna, M., Podmirseg, S. M., Waldhuber, S., Knapp, B. A., García, C., & Insam, H. (2011). Pathogenic bacteria and mineral N in soils following the land spreading of biogas digestates and fresh manure. *Applied Soil Ecology*, *49*, 18-25. https://doi.org/10.1016/j.apsoil.2011.07.007

Govasmark, E., Stäb, J., Holen, B., Hoornstra, D., Nesbakk, T., & Salkinoja-Salonen, M. (2011). Chemical and microbiological hazards associated with recycling of anaerobic digested residue intended for agricultural use. *Waste Management*, *31*(12), 2577-2583. https://doi.org/10.1016/j.wasman.2011.07.025

Graves, R. E. (2000). *Part 637Environmental Engineering National Engineering Handbook*. https://irrigationtoolbox.com/NEH/Part%20637/NEHPart637ch02.pdf

Herrera, A., D'Imporzano, G., Zilio, M., Pigoli, A., Rizzi, B., Meers, E., Schouman, O., Schepis, M., Barone, F., Giordano, A., & Adani, F. (2022). Environmental Performance in the Production and Use of Recovered Fertilizers from Organic Wastes Treated by Anaerobic Digestion vs Synthetic Mineral Fertilizers. *ACS Sustainable Chemistry & Engineering*, *10*(2), 986-997. https://doi.org/10.1021/acssuschemeng.1c07028

Hoeksma, P., Losada, J. M., & Melse, R. W. (2012). *Monitoring methane and nitrous oxide reduction by manure treatment*. https://research.wur.nl/en/publications/monitoring-methane-and-nitrous-oxide-reduction-by-manure-treatmen

Hu, Y., & Schmidhalter, U. (2024). Annual consumption and types of synthetic nitrogen fertilizers : Ammonia emission indicators for mitigation strategies in the European Union. *Environmental and Sustainability Indicators*, *22*, 100365. https://doi.org/10.1016/j.indic.2024.100365

Karimi, B., Sadet-Bourgeteau, S., Cannavacciuolo, M., Chauvin, C., Flamin, C., Haumont, A., Jean-Baptiste, V., Reibel, A., Vrignaud, G., & Ranjard, L. (2023). Review of the impact of biogas digestates on the microbiological quality of agricultural soils. *Étude et Gestion Des Sols*, *30*, 169.

Klüpfel, C., Yuan, B., Biller, P., & Herklotz, B. (2025). Hydrothermal liquefaction as a treatment technology for anaerobic digestate : A review. *Renewable and Sustainable Energy Reviews*, *210*, 115156. https://doi.org/10.1016/j.rser.2024.115156

Kovačić, Đ., Lončarić, Z., Jović, J., Samac, D., Popović, B., & Tišma, M. (2022). Digestate Management and Processing Practices : A Review. *Applied Sciences*, *12*(18), 9216. https://doi.org/10.3390/app12189216

Lemes, Y. M., Nyord, T., Feilberg, A., Hafner, S. D., & Pedersen, J. (2023). Effect of anaerobic digestion on odor and ammonia emission from land-applied cattle manure. *Journal of Environmental Management*, *338*, 117815. https://doi.org/10.1016/j.jenvman.2023.117815

Möller, K., & Müller, T. (2012). Effects of anaerobic digestion on digestate nutrient availability and crop growth : A review. *Engineering in Life Sciences*, *12*(3), 242-257. https://doi.org/10.1002/elsc.201100085

Muys, M., Phukan, R., Brader, G., Samad, A., Moretti, M., Haiden, B., Pluchon, S., Roest, K., Vlaeminck, S. E., & Spiller, M. (2021). A systematic comparison of commercially produced struvite : Quantities, qualities and soil-maize phosphorus availability. *Science of The Total Environment*, *756*, 143726. https://doi.org/10.1016/j.scitotenv.2020.143726

Nicholson, F., Bhogal, A., Cardenas, L., Chadwick, D., Misselbrook, T., Rollett, A., Taylor, M., Thorman, R., & Williams, J. (2017). Nitrogen losses to the environment following food-based digestate and compost applications to agricultural land. *Environmental Pollution*, *228*, 504-516. https://doi.org/10.1016/j.envpol.2017.05.023

Nkoa, R. (2014). Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates : A review. *Agronomy for Sustainable Development*, *34*(2), 473-492. https://doi.org/10.1007/s13593-013-0196-z

O'Connor, J., Mickan, B. S., Rinklebe, J., Song, H., Siddique, K. H. M., Wang, H., Kirkham, M. B., & Bolan, N. S. (2022). Environmental implications, potential value, and future of food-waste anaerobic digestate management : A review. *Journal of Environmental Management*, *318*, 115519. https://doi.org/10.1016/j.jenvman.2022.115519

Orzi, V., Riva, C., Scaglia, B., D'Imporzano, G., Tambone, F., & Adani, F. (2018). Anaerobic digestion coupled with digestate injection reduced odour emissions from soil during manure distribution. *Science of The Total Environment*, *621*, 168-176. https://doi.org/10.1016/j.scitotenv.2017.11.249

Page, L. H., Ni, J.-Q., Zhang, H., Heber, A. J., Mosier, N. S., Liu, X., Joo, H.-S., Ndegwa, P. M., & Harrison, J. H. (2015). Reduction of volatile fatty acids and odor offensiveness by anaerobic digestion and solid separation of dairy manure during manure storage. *Journal of Environmental Management*, *152*, 91-98. https://doi.org/10.1016/j.jenvman.2015.01.024

Piccoli, I., Grillo, F., Longo, M., Furlanetto, I., Ragazzi, F., Obber, S., Bonato, T., Meneghetti, F., Ferlito, J., Saccardo, L., & Morari, F. (2023). A farm-scale sustainability assessment of the anaerobic digestate application methods. *European Journal of Agronomy*, *146*, 126811. https://doi.org/10.1016/j.eja.2023.126811

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

Rahman, Md. M., Salleh, M. A. Mohd., Rashid, U., Ahsan, A., Hossain, M. M., & Ra, C. S. (2014). Production of slow release crystal fertilizer from wastewaters through struvite crystallization – A review. *Arabian Journal of Chemistry*, *7*(1), 139-155. https://doi.org/10.1016/j.arabjc.2013.10.007

Riva, C., Orzi, V., Carozzi, M., Acutis, M., Boccasile, G., Lonati, S., Tambone, F., D’Imporzano, G., & Adani, F. (2016). Short-term experiments in using digestate products as substitutes for mineral (N) fertilizer : Agronomic performance, odours, and ammonia emission impacts. *Science of The Total Environment*, *547*, 206-214. https://doi.org/10.1016/j.scitotenv.2015.12.156

Selvaraj, P. S., Periasamy, K., Suganya, K., Ramadass, K., Muthusamy, S., Ramesh, P., Bush, R., Vincent, S. G. T., & Palanisami, T. (2022). Novel resources recovery from anaerobic digestates : Current trends and future perspectives. *Critical Reviews in Environmental Science and Technology*, *52*(11), 1915-1999. https://doi.org/10.1080/10643389.2020.1864957

Smith, S. R., Lang, N. L., Cheung, K. H. M., & Spanoudaki, K. (2005). Factors controlling pathogen destruction during anaerobic digestion of biowastes. *Waste Management*, *25*(4), 417-425. https://doi.org/10.1016/j.wasman.2005.02.010

Sylvester-Bradley, R., Withers, P., Rollett, A., Talboys, P., Walker, R., Edwards, T., Payvandi, S., Heppel, J., Roose, T., & Jones, D. (2016). *Improving the sustainability of phosphorus use in arable farming – ‘Targeted P’* (Sustainable Arable LINK Project LK09136 No. 2017/2). Agriculture and Horticulture Development Board. https://www.researchgate.net/publication/317488276_Improving_the_sustainability_of_phosphorus_use_in_arable_farming_-_'Targeted_P'

Tambone, F., Scaglia, B., D’Imporzano, G., Schievano, A., Orzi, V., Salati, S., & Adani, F. (2010). Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost. *Chemosphere*, *81*(5), 577-583. https://doi.org/10.1016/j.chemosphere.2010.08.034

Tampio, E., Laaksonen, I., Rimhanen, K., Honkala, N., Laakso, J., Soinne, H., & Rasa, K. (2024). Effect of manure co-digestion on methane production, carbon retention, and fertilizer value of digestate. *The Science of the Total Environment*, *927*, 172083. https://doi.org/10.1016/j.scitotenv.2024.172083

Thiessen Martens, J. R., Entz, M. H., Schneider, K. D., Zvomuya, F., & Wilson, H. F. (2022). Response of organic grain and forage crops to struvite application in an alkaline soil. *Agronomy Journal*, *114*(1), 795-810. https://doi.org/10.1002/agj2.20943

Van Midden, C., Harris, J., Shaw, L., Sizmur, T., & Pawlett, M. (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

Zilio, M., Pigoli, A., Rizzi, B., Goglio, A., Tambone, F., Giordano, A., Maretto, L., Squartini, A., Stevanato, P., Meers, E., Schoumans, O., & Adani, F. (2023). Nitrogen dynamics in soils fertilized with digestate and mineral fertilizers : A full field approach. *Science of The Total Environment*, *868*, 161500. https://doi.org/10.1016/j.scitotenv.2023.161500

Zilio, M., Pigoli, A., Rizzi, B., Herrera, A., Tambone, F., Geromel, G., Meers, E., Schoumans, O., Giordano, A., & Adani, F. (2022). Using highly stabilized digestate and digestate-derived ammonium sulphate to replace synthetic fertilizers : The effects on soil, environment, and crop production. *Science of The Total Environment*, *815*, 152919. https://doi.org/10.1016/j.scitotenv.2022.152919

BIOMETHANE INDUSTRIAL PARTNERSHIP

BIP Europe
Biomethane Industrial Partnership