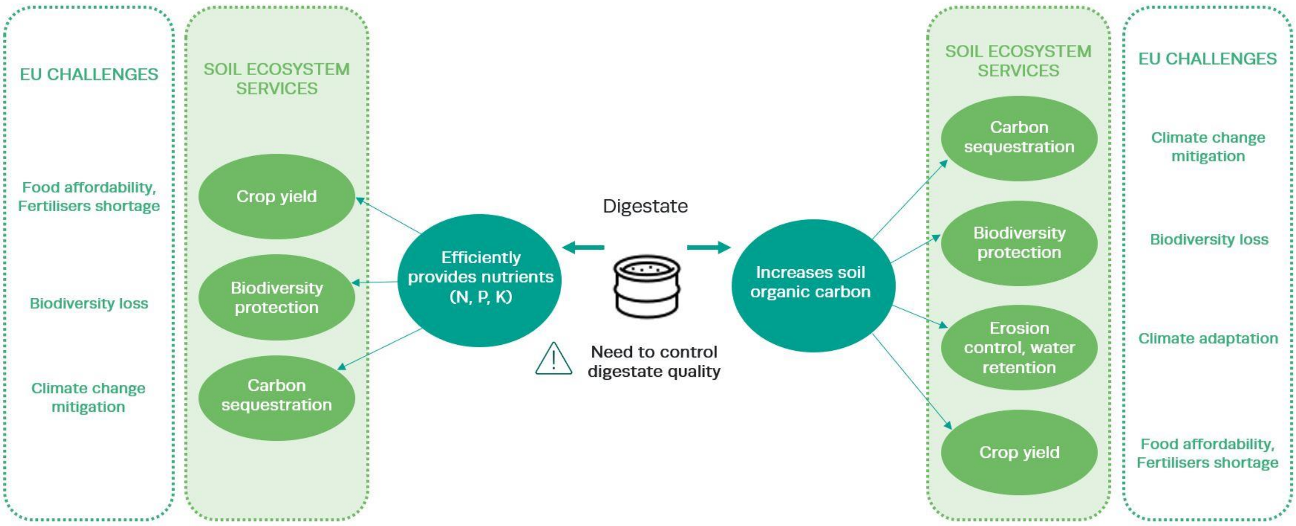
Returning digestate to the soil: a sustainable management practice contributing to soil health

INTRODUCTION

Soils are the foundation of our agri-food systems, they regulate the nutrient, carbon and water cycles and they provide a habitat for biodiversity. They also play an essential role in the circular economy and adaptation to climate change. Nevertheless, **today 60 to 70% of European soils are unhealthy**[1] due to climate change, extreme weather events, unsustainable soil management, intensification of agricultural practices, industrial activities, etc. These drivers of soil deterioration will not decline in the future unless a proper legislation is implemented.

An ambitious Soil Health Law is needed to ensure that EU soils are protected and that **all soils are in healthy condition by 2050** as envisioned in the EU Soil strategy in 2021. It is essential to define what is a healthy soil, to determine soil health indicators to monitor the condition of EU soils and soil threats and to promote the scaling-up of sustainable soil management practices able to restore soil health. To this end, the use of digestate – one of the co-products of biogas production – must be stimulated as it brings multiple health benefits to soils (see figure 1). **Digestate application to agricultural soils is a sustainable agronomic practice which has a positive impact on various soil ecosystem services and contributes to tackling multiple EU challenges**. By acting both as an excellent fertiliser which provides recycled available nutrients (cf. part 2.) and as a soil improver which builds up soil organic carbon (cf. part 3.), **digestate increases crop yield and biomass production, provides a habitat for biodiversity, enables greater carbon sequestration in the soil and helps to control erosion and retain water**. To maximise its benefits to the soil, digestate quality must be controlled (cf. part 4.).

Figure 1. Digestate benefits to soil ecosystem services and links with EU challenges



[1] Commission Staff Working Document accompanying the EU Soil strategy for 2030 of 17 November 2021 SWD(2021)323 final.

1. DIGESTATE BASICS

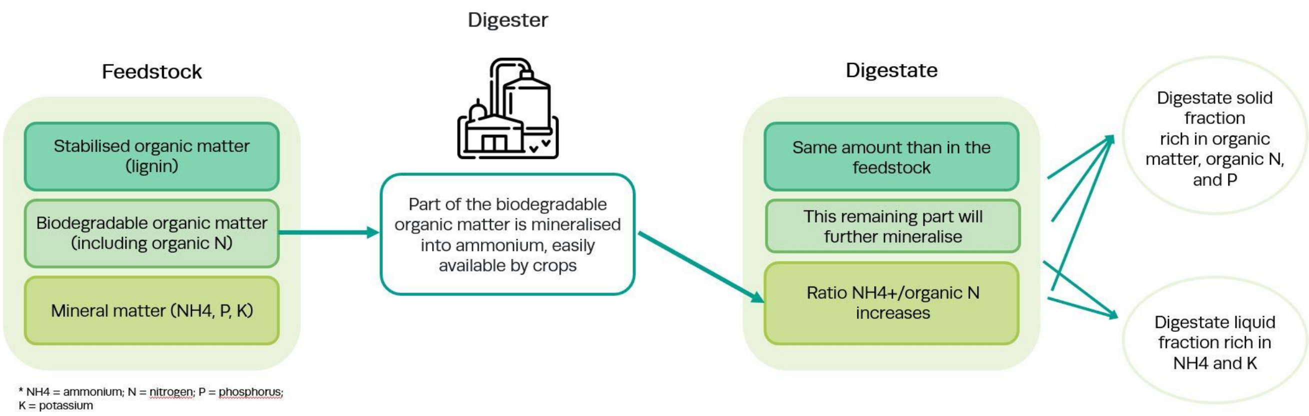
During anaerobic digestion, bio-chemical reactions take place in the digester which transform the organic compounds of the feedstock:

- A part of the organic nitrogen supplied by the **biodegradable organic matter** part of the feedstock is converted into **ammonium** which is a readily available source of nitrogen for plants (see figure 1). Thus, the **ammonium-organic nitrogen** ratio of the digestate increases compared to the raw feedstock. Even if the total content of nitrogen (both organic and mineralized) is the same, the percentage of readily available minerals in the form of **ammonium** will be higher in digestate than in the raw feedstock.
- The same amount of **stabilised organic matter** is present in the digestate than in the feedstock.

Before being applied to the soil, digestate is often mechanically separated (through sedimentation, belt press, screw press, centrifugation) between a **liquid fraction**, richer in nitrogen and potassium and a **solid fraction**, richer in **organic matter** and phosphorus. The dewatered solid fraction can then be more easily transported while the liquid fraction can be applied as fertiliser or undergo further processing.

When applied to the soil, the remaining part of the **biodegradable organic matter** (which has not yet converted into ammonium) will continue to mineralise.

Figure 2. What happens in the digester?



2. AN EXCELLENT FERTILISER WITH RECYCLED AVAILABLE NUTRIENTS

The relations between nutrients, crop nutrient uptake and soil functions are very intricate and are actively researched today. The fertilising properties of digestate, even more of the liquid fraction of digestate, are becoming increasingly popular in Europe. As showed in figure 2, at least 60 to 80% of the total nitrogen becomes directly available in the form of ammonium in the digestate[2].

[2] Makádi, M., Tomócsik, A., & Orosz, V. (2012). Digestate: a new nutrient source–review. *Biogas, 14*, 295-312.

Moreover, the biodegradable organic nitrogen in the digestate will continue to mineralise after being applied thus providing a valuable long-term fertilising effect. Evidence indicates that the **liquid fraction of digestate** or concentrates from liquid fractions (via membrane filtration or evaporation) **may substitute synthetic nitrogen fertilisers without crop yield losses**[3]. This is key since the need to **reduce dependency on nitrogen fertilisers** has gained urgency following Russia's war on Ukraine. The opportunity to substitute fossil-based synthetic fertilisers with alternative organic fertilisers based on recycled nutrients is also an opportunity **to achieve a circular economy and climate neutrality**[4]. Digestate has also interesting properties in terms of potassium (concentrated in the liquid fraction) and phosphorus (concentrated in the solid fraction) availability, the latter being even more relevant given its recent inclusion in the list of EU Critical Raw Materials.

Nevertheless, digestate application on soil needs to be carefully monitored during the whole crop growth cycle in order to ensure that digestate contributes positively to the nutrient balance and is not detrimental to soil health. To contribute to the Green Deal objective of reducing nutrients losses by 50% by 2030 while enhancing soil fertility, digestate application must be calibrated to the nitrogen need of the crop to ensure that:

- **The available ammonium must be taken up as efficiently as possible by the crop** as soon as digestate is applied. In order to avoid any risk of nitrate leaching, farmers must aim at the best **nitrogen use efficiency**[5]. To this end, farmers must adjust the digestate application to specific time periods and growth states of the fields. Another solution would be to favour the use of high efficient and precision fertilisation systems but research is only starting regarding precision fertilisation through digestate.
- **The biodegradable organic nitrogen part in the digestate which will continue to mineralise over time must also be controlled** to avoid nitrate leaching. To this end, monitoring can be implemented to ensure that further digestate inputs take into consideration the continuous nitrogen uptake by the crops. Nevertheless, evidence indicates that 90% of the nitrogen contained in digestate is short acting[6] so the long-term fertilising effect is more than manageable.

To avoid nitrogen leaching, digestate application can be coupled with the growth of catch crops able to retain nitrogen and other nutrients[7]. It must be recalled also that the Joint Research Centre has already provided **indicators for safety in terms of nutrients leaching** indicating that **RENURE products**, including the liquid fraction of digestate, would be safe to be used (even above the Nitrates directive limit of 170 kg per ha per year) if they have a mineral N:TN ratio ≥ 90% or a TOC:TN ratio ≤ 3[8].

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[3] Sigurnjak, I., Vaneeckhaute, C., Michels, E., Ryckaert, B., Ghekiere, G., Tack, F. M. G., & Meers, E. (2017). Fertilizer performance of liquid fraction of digestate as synthetic nitrogen substitute in silage maize cultivation for three consecutive years. *Science of the Total Environment, 599*, 1885–1894.

[4] The European Biogas Association 2022 statistical report calculated that, taking into consideration that 10-11% of the nitrogen synthetic fertiliser could be replaced with digestate by 2030, at least 21 Mt of CO2 equivalent could be saved per year.

[5] The nitrogen use efficiency is the *ratio of the crop nitrogen uptake to the total input of nitrogen in digestate.*

[6] Tambone, F., & Adani, F. (2017). Nitrogen mineralization from digestate in comparison to sewage sludge, compost and urea in a laboratory incubated soil experiment. *Journal of Plant Nutrition and Soil Science, 180*(3), 355–365.

[7] Riau, V., Burgos, L., Camps, F., Domingo, F., Torrellas, M., Antón, A., & Bonmatí, A. (2021). Closing nutrient loops in a maize rotation. Catch crops to reduce nutrient leaching and increase biogas production by anaerobic co-digestion with dairy manure. *Waste Management, 126*, 719–727.

[8] Huygens D, Orveillon G, Lugato E, Tavazzi S, Comero S, Jones A, Gawlik B, Saveyn HGM, Technical proposals for the safe use of processed manure above the threshold established for Nitrate Vulnerable Zones by the Nitrates Directive (91/676/EEC), EUR 30363 EN, Publications Office of the European Union.

In conclusion, it is important to highlight that **the risk of nitrate leaching has been proven to be equal or less important than with synthetic fertilisers**[9]. With the appropriate agronomic practices, it is possible to reach the proper nutrient balance when applying digestate with **positive impacts on crop yield and biomass production**. Nutrient balance provided by digestate can also affect positively the diversity of soil microorganisms, soil animals and plant species. Finally, a **higher nutrient status in digestate can increase carbon storage.**

3. A VALUABLE SOIL IMPROVER BUILDING UP SOIL ORGANIC CARBON

As indicated in figure 2, around 40 to 50% of digestate contains **stable organic matter** which is **particularly recalcitrant to biodegradation**[10]. It has a lower organic matter degradation rate after field application. This stable organic matter in the digestate contains **stable organic carbon** which, unlike synthetic fertilisers, contributes to restoring or increasing soil organic carbon (SOC)[11] when applied to the soil[12]. The stable organic matter in the digestate also contains strong **humus precursors** such as lignin which lead digestate to build up humus in the topsoil[13]. This stable organic matter part can be concentrated in the solid fraction of digestate and then further valorised as a **carbon rich fraction with the additional benefit of creating humus**. Thanks to its unique properties, digestate has a positive impact on almost all key soil ecosystems services, including biodiversity protection[14], carbon sequestration, soil aeration, water retention, erosion control and of course crop yield.

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[9] Zilio, M., Pigoli, A., Rizzi, B., Herrera, A., Tambone, F., Geromel, G., ... & 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.
Luo, H., Dewitte, K., Landschoot, S., Sigurnjak, I., Robles-Aguilar, A. A., Michels, E., ... & Meers, E. (2022). Benefits of biobased fertilizers as substitutes for synthetic nitrogen fertilizers: Field assessment combining minirhizotron and UAV-based spectrum sensing technologies. *Frontiers in Environmental Science, 10*, 2375.
Zilio, M., Pigoli, A., Rizzi, B., Geromel, G., Meers, E., Schoumans, O., ... & Adani, F. (2021). Measuring ammonia and odours emissions during full field digestate use in agriculture. *Science of the Total Environment, 782*, 146882.
Hendriks, C. M., Shrivastava, V., Sigurnjak, I., Lesschen, J. P., Meers, E., Noort, R. V., ... & Rietra, R. P. (2022). Replacing mineral fertilisers for bio-based fertilisers in potato growing on sandy soil: A case study. *Applied Sciences, 12*(1), 341.

[10] Esnouf, A., Brockmann, D., & Cresson, R. (2021). Analyse du Cycle de Vie du biométhane issu de ressources agricoles-Rapport d'ACV. INRAE Transfert, 50-62. Reinhold, G., Klimanek, E. M., & Breitschuh, G. (1991). Zum einfluss der biogaserzeugung auf veränderungen in der kohlenstoffdynamik von Gülle. *Archiv für Acker-und Pflanzenbau und Bodenkunde, 25*(2), 129-137.

[11] Soil organic carbon (SOC) refers only to the carbon component of organic compounds found in soil organic matter (SOM).

[12] Greenberg, I., Kaiser, M., Gunina, A., Ledesma, P., Polifka, S., Wiedner, K., ... & Ludwig, B. (2019). Substitution of mineral fertilizers with biogas digestate plus biochar increases physically stabilized soil carbon but not crop biomass in a field trial. *Science of the Total Environment, 680*, 181-189.
Slepetiene, A., Volungevicius, J., Jurgutis, L., Liaudanskiene, I., Amaleviciute-Volunge, K., Slepetys, J., & Ceseviciene, J. (2020). The potential of digestate as a biofertilizer in eroded soils of Lithuania. *Waste Management, 102*, 441-451.
Zilio, M., Pigoli, A., Rizzi, B., Herrera, A., Tambone, F., Geromel, G., ... & 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.
Bezzi, G., Maggioni, L., & Pieroni, C. Biogasdoneright® Model: Soil Carbon Sequestration and Efficiency in Agriculture.

[13] 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.
Gasser, A. A., Diel, J., Nielsen, K., Mewes, P., Engels, C., & Franko, U. (2022). A model ensemble approach to determine the humus building efficiency of organic amendments in incubation experiments. *Soil Use and Management, 38*(1), 179-190.

[14] Moinard, V., Redondi, C., Etievant, V., Savoie, A., Duchene, D., Pelosi, C., ... & Capowiez, Y. (2021). Short-and long-term impacts of anaerobic digestate spreading on earthworms in cropped soils. *Applied Soil Ecology, 168*, 104149.

Healthy soils are also crucial for climate change mitigation. Soils are the largest carbon terrestrial ecosystem sink. It is therefore also essential to support carbon farming practices which are able to sustainably enhance the storage of carbon in soils. This is why it is important to highlight that digestate application on soils is both a sustainable soil management practice and a **carbon farming practice**.

Even if the solid fraction digestate is more relevant as a soil improver, the Joint Research Centre has found no overall adverse effects on soil fertility and soil organic carbon sequestration from the application of liquid fraction of digestate on fields[15].

The EU project Nutri2Cycle, which is showcased in the EU Commission Results Pack on Fertilisers, aims at closing carbon, nitrogen and phosphorus loops by reconnecting nutrient carbon flows between conventional agro pillars through agro processing. As part of the project, one of the lighthouse demos was operated by the University of Milan at a full-scale anaerobic digestion facility in Northern Italy. This area is dedicated to cereal cultivation, mainly rice, and the demo plant produced mainly digestate (as well as ammonium sulphate) from sewage sludge to be used as an organic fertiliser. The biogas was converted into electricity and heat to be reused in the system. In addition to the application of digestate on field, minimum tillage and precision farming techniques were also integrated to improve health condition in the soil, particularly organic matter.

BETA Technological Center is actively engaged in multiple national and European initiatives focusing on assessing digestate as a viable fertilising product. The centre is involved in projects such as FERTIMANURE, FERTILWASTES, NOVAFERT or Vibrating RO, among others. These projects explore how digestate can be utilised effectively as a standalone soil amendment or through innovative techniques where the digestate undergoes further valorisation processes to recover and concentrate its nutrients.

4. DIGESTATE QUALITY CONTROL

Because it can originate from feedstocks as diverse as urban or industrial wastewaters, manure or biowaste, digestate has raised concerns in the scientific and political community. Organic pollutants, heavy metals, microplastics or pathogens potentially present in digestate might contaminate the soil. Nevertheless, a systematic sampling and analysis of each digestate before application is practically and economically unfeasible.

To prevent any negative impact of digestate application to soil, **certification/quality assurance systems are already implemented in several member states to ensure that operators comply with quality standards for digestate.** Depending on the feedstock used, operators from biogas

[15] Huygens D, Orveillon G, Lugato E, Tavazzi S, Comero S, Jones A, Gawlik B, Saveyn HGM, Technical proposals for the safe use of processed manure above the threshold established for Nitrate Vulnerable Zones by the Nitrates Directive (91/676/EEC), EUR 30363 EN, Publications Office of the European Union.

plant, urban wastewater treatment plants or waste treatment plants are the certified operators (complying with such certification systems might be more difficult for small biogas plants operators). These certification systems are voluntary or mandatory. These systems generally include several steps:

- Firstly, it is important to monitor potential pollution from the source. For instance, in Waste Treatment Plants or Wastewater Treatment plants, controls exist to guarantee the quality of the input material e.g. bio-waste or wastewaters.
- During the anaerobic digestion, temperature and management is controlled very closely. Evidence indicates that thermophilic digestion[16] or conventional hygienisation (1 hour at 70 °C) is very efficient to remove (micro)pollutants (e.g., antibiotics and antibiotic-resistant genes)[17,18] and some certain pathogens[19].
- Finally, a thorough monitoring of the quality of the end product is put in place with specific heavy metal and other pollutants limits. Regular samplings are carried out for product analysis.

In **Sweden**, the SPCR 120 **certification system** has been set to ensure that digestate is hygienised and meets the requirements for metal content and visible contaminants. SPCR 120 is now a trusted quality standard. The **KRAV certification** also exists that puts more stringent pollutants requirements allowing KRAV-certified digestate to be used in organic farming. Regarding digestate from sewage sludge, Sweden also implemented a specific certification called Revaq which sets quality requirements for digestate. Urban wastewater treatment plants which become Revaq-certified will work on the sources of heavy metals (especially cadmium) and other contaminants before they even reach the WWTPs to ensure a safe application of digestate to agricultural soil.

In **Flanders**, the Vlaco **quality assurance system** has been implemented to certify digestate from bio-waste or bio-waste and manure.

In **France**, also sets pathogens and pollutants limits in the a specific decree from 2020 approving **specifications for the marketing and use of digestates** from methanization of agricultural and/or agri-food inputs as fertilizing materials. The **standard NFU 44051** also certifies the use of digestate as an "organic amendment".

At the EU level, the **Fertilising Products Regulation** is also setting criteria for a number of pollutants. Any digestate-derived fertilising product compliant with the FPR will then be considered safe in terms of soil pollution.

[16] Pigoli, A., Zilio, M., Tambone, F., Mazzini, S., Schepis, M., Meers, E., ... & Adani, F. (2021). Thermophilic anaerobic digestion as suitable bioprocess producing organic and chemical renewable fertilizers: A full-scale approach. *Waste Management*, *124*, 356-367.
[17] Akyol, Ç., Turker, G., Ince, O., Ertekin, E., Üstüner, O., & Ince, B. (2016). Performance and microbial community variations in thermophilic anaerobic digesters treating OTC medicated cow manure under different operational conditions. *Bioresource Technology*, *205*, 191-198.
[18] Aziz, A., Sengar, A., Basheer, F., Farooqi, I.H., Isa, M.H., (2020). Anaerobic digestion in the elimination of antibiotics and antibiotic-resistant genes from the environment – A comprehensive review. *Journal of Environmental Chemical Engineering*, 10(1), 106423.
[19] Lloret, E., Pastor, L., Pradas, P., Pascual, J.A., (2013). Semi full-scale thermophilic anaerobic digestion (TAnD) for advanced treatment of sewage sludge: Stabilization process and pathogen reduction. *Chemical Engineering Journal*, 232, 42-50.

In general, it is important to clarify that anaerobic digestion is an efficient treatment method which already makes digestate a more stabilised material compared to the initial raw material[20]. Anaerobic digestion is also more efficient than composting for the removals of pollutants[21]. Moreover, in several studies conducted in recent years, **no significant accumulation of inorganic pollutants or heavy metals, were found in the soil after digestate application**[22]. Finally, it must be noted that research is also exploring further processing techniques to remove all contaminants in the digestate as well as the opportunity of directly extracting nutrients from digestate.

RECOMMENDATIONS

Taking into consideration the soil benefits and solutions to tackle potential soil threats summarised above, EBA proposes several recommendations to the European Commission in view of the adoption of the Soil Health Law:

- The **application of digestate on soil** must be recognised as a **sustainable soil management practice** in the Soil Health Law due to its outstanding benefits in terms of nutrients availability and SOC build-up. Digestate application should also be considered as a **carbon farming practice** supported in the Certification Framework on Carbon Removals. Finally, it must be further promoted in the framework of the Common Agricultural Policy as an additional **"good agricultural and environmental condition" (GAEC) or an eco-scheme.**
- Support must be directed at farmers to **monitor the level of SOC in their soils** and **implement sustainable soil management practices, such as digestate application on soil**, when soils do not comply with the desired levels of SOC. The build-up of SOC or SOM using digestate must be quantified and reported in the National Energy and Climate Plans.
- The **quality certification of digestate** at national level (through national assurance quality systems) or at EU level (through the Fertilising Products Regulation) must be incentivised.
- The Soil Health Law must be **aligned with other regulations setting limits related to soil organic carbon, nutrients or pollutants** such as the criteria set out in the Fertilising Products Regulation or in the SAFEMANURE report by the Joint Research Centre.
- Other sustainable soil management practices, such as the reduction of tillage or the growth of catch crops, must be promoted in the Soil Health Law.

[20] Moller, K., (2015). Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. *Agronomy for Sustainable Development*, 35, 1021–1041.
[21] COMMISSION STAFF WORKING DOCUMENT EVALUATION Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture {SWD(2023) 158 final}.
[22] Barłóg, P., Hlisnikovský, L., & Kunzová, E. (2020). Concentration of trace metals in winter wheat and spring barley as a result of digestate, cattle slurry, and mineral fertilizer application. *Environmental Science and Pollution Research*, *27*, 4769-4785.
Dragicevic, I., Sogn, T. A., & Eich-Greatorex, S. (2018). Recycling of biogas digestates in crop production—soil and plant trace metal content and variability. *Frontiers in Sustainable Food Systems*, *2*, 45.
Zilio, M., Pigoli, A., Rizzi, B., Herrera, A., Tambone, F., Geromel, G., ... & 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.
Koszel, M., & Lorencowicz, E. (2015). Agricultural use of biogas digestate as a replacement fertilizers. *Agriculture and Agricultural Science Procedia*, *7*, 119-124.

About EBA

The European Biogas Association is the voice of renewable gas in Europe since 2009. EBA advocates for the recognition of biomethane and other renewable gases as sustainable, on demand and flexible energy sources that provide multiple knock-on socio-economic and environmental benefits. Supported by its members, EBA is committed to work with European institutions, industry, agricultural partners, NGOs and academia to develop policies which can enable the large-scale deployment of renewable gases and organic fertilisers throughout Europe, supported by transparent, well-established sustainability certification bodies to ensure that sustainability remains at the core of the industry. The association counts today on a well-established network of over 200 national organisations, scientific institutes, and companies from Europe and beyond. EBA is a partner in the 4 per 1000 initiative and a signatory of the "Save Organics in Soil" manifesto and the Mission soil manifesto.

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