BIP Europe
Biomethane Industrial Partnership



BIOMETHANE INDUSTRIAL PARTNERSHIP

IMPROVING DIGESTATE VALORISATION: NOVEL TECHNOLOGIES & RESEARCH NEEDS

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Improving digestate valorisation: novel technologies and research needs

Executive Summary

This report by the Biomethane Industrial Partnership highlights the crucial role of digestate valorisation in reaching the EU's target of 35 bcm of biomethane production by 2030. As a by-product of anaerobic digestion (AD), digestate contains valuable nutrients, such as nitrogen, phosphorus, and potassium, making it a key component in sustainable fertilisation practices. The report provides an in-depth analysis of current technologies, regulatory frameworks, and potential future innovations, all aimed at enhancing the economic and environmental value of digestate within the circular economy.

Digestate is currently produced in large quantities across the EU, with annual production estimated at 222 to 258 million tonnes. Primarily used as a biofertiliser, digestate plays a significant role in promoting soil health, enhancing organic carbon levels, and supporting sustainable agriculture. However, its application varies by region, depending on local agricultural practices and legislation. The report emphasises the importance of advancing digestate processing technologies to maximise its potential. Techniques such as solid-liquid separation, ammonia stripping, and membrane filtration are highlighted as effective methods for improving nutrient recovery. Furthermore, innovations like biochar production and hydrothermal carbonisation (HTC) offer promising solutions for enhancing soil quality and mitigating climate change through carbon sequestration.

The policy landscape surrounding digestate is also critical in shaping its role in the EU's green transition. The report examines key regulations, including the Fertilising Products Regulation (FPR) and the Nitrates Directive, which govern the production and use of digestate as a biofertiliser. These policies not only facilitate the substitution of synthetic fertilisers with digestate but also promote the circular economy by encouraging the use of waste-based products.

In terms of environmental impact, the report underscores the positive role digestate can play in reducing greenhouse gas emissions and minimising nutrient pollution. By replacing synthetic fertilisers, digestate contributes to energy security and helps mitigate the effects of climate change. Looking ahead, the report identifies several technological gaps and opportunities for further research. These include the development of advanced nutrient recovery methods, microbial valorisation processes, and precision agriculture techniques. The integration of digestate with other bioprocesses, such as bioplastic and biofuel production, offers additional pathways for maximising its value.

The report concludes that while significant progress has been made, continued innovation and supportive policy frameworks will be essential to fully realise the potential of digestate in driving both biomethane production and sustainable agricultural practices.

In conclusion, this report emphasises the strategic importance of digestate valorisation in the EU's efforts to transition towards a more sustainable and circular economy. By leveraging advanced technologies and fostering a more adaptive regulatory environment, digestate can play a pivotal role in reducing environmental impact, enhancing energy security, and supporting long-term agricultural sustainability.

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Glossary

AD	Anaerobic digestion
AMR	Antimicrobial resistance
ABP	Animal by-product
ABPR	Animal By-Product Regulation
CMC	Component material categories
FPR	Fertilising Products Regulation
HRT	Hydraulic retention time
HTC	Hydrothermal carbonisation
LF	Liquid fraction
MMCs	Mixed microbial cultures
NG	Natural gas
OFMSW	Organic fraction of municipal solid waste
PAHs	Polycyclic aromatic hydrocarbons
RENURE	Recovered nitrogen from manure
SF	Solid fraction
SOC	Soil organic carbon
TDS	Total dissolved solids
TE(s)	Trace element(s)
TS	Total solids
TSS	Total suspended solids
VFA	Volatile fatty acids
VS	Volatile solids
WFD	Waste framework directive
WWT	Waste water treatment

Introduction

In recent decades, significant progress has been made in exploiting the anaerobic digestion (AD) process as a valuable biotechnology enabling the transformation of various waste-based substrates and biomasses into renewable energy on one hand and digestate on the other. Whereas in the past digestate was considered rather as a mere byproduct of the renewable energy generation, recent attention has shifted towards also valorising this digestate. This in turn allows recovery of plant-available minerals (N, P, K and other nutrients) from said digestate, in addition to other value-added products with broad applications in a variety of industrial sectors. This has improved the overall added economic value balance of the AD plant [1] and positioned it as a biorefinery producing a wider range of products than 'merely' biogas. In general, either via recovery and valorisation in the form of raw digestate or through more advanced digestate refineries, the valorisation of digestate has earned its reputation in terms of economic and environmental added value.

Figure 1 illustrates a comprehensive plan for sustainable organic waste management and energy/material recovery [2]. It highlights the benefits of various transformation stages: initial stages have lower costs (CAPEX and OPEX) but yield products of lower economic value, whereas later stages offer increased commercial opportunities, revenue generation, and environmental advantages. Despite higher costs, these stages prevent economic losses caused by issues such as nutrient pollution. However, due to early development, the costs (CAPEX and OPEX) are significantly higher, with uncertain economic benefits [2]. In Europe, the cost-benefit of progressive costs for advanced refining compared with the use of digestate in its raw form depends very much on the local context. For example, in regions characterised by high nutrient pressure on arable land induced by high densities of animal production, local legislation may stimulate or impose more advanced digestate treatment for export, upcycling into chemical fertiliser replacement or even removal rather than recovery of nutrients (e.g. by nitrification-denitrification for excess N removal in analogy with WWT).

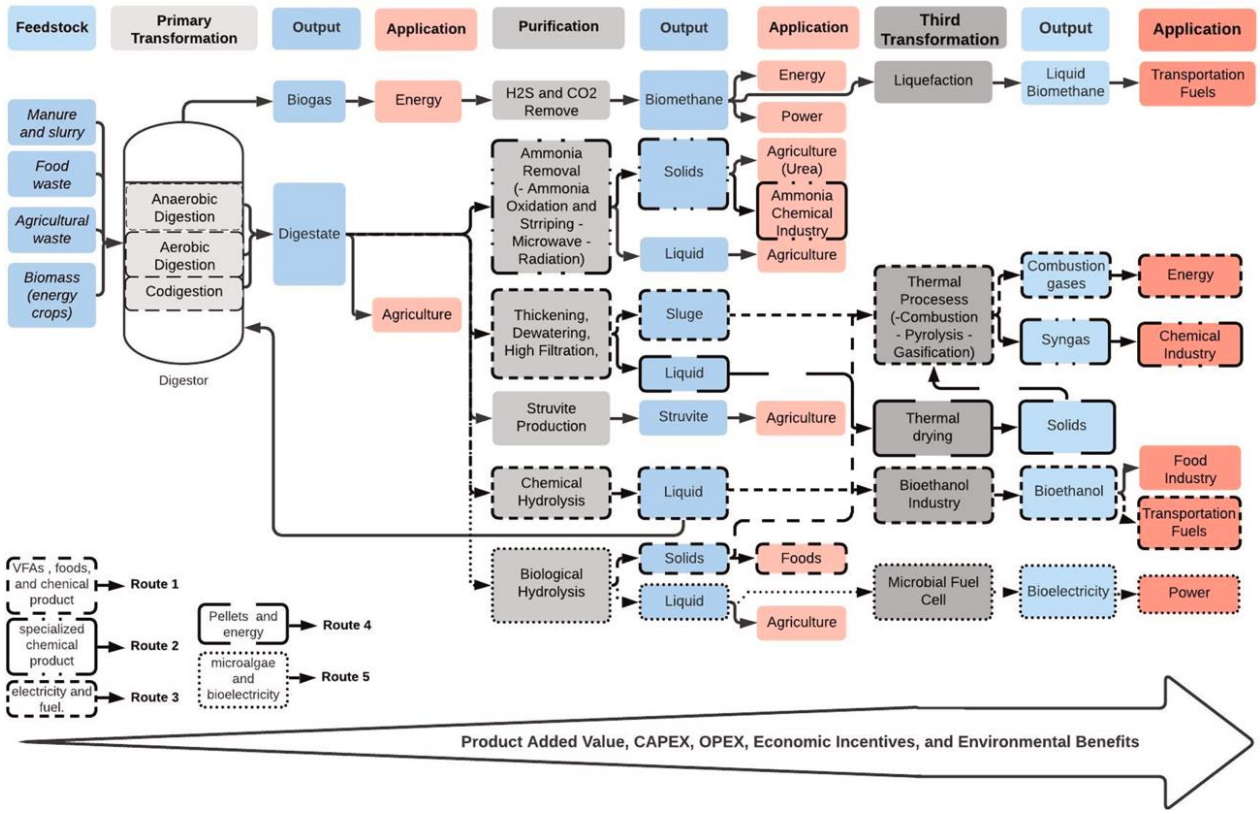

FIGURE 1 A DIVERSION MAP FOR THE SUSTAINABLE MANAGEMENT OF ORGANIC WASTE AND THE RECOVERY OF ENERGY AND VALUE-ADDED MATERIALS (ADAPTED FROM [2])

Figure 2 provides an infographic illustration by the US-EPA, adapted for some notable added value products that can be derived from the AD process, namely (I) at the gas phase when purifying biogas into biomethane, purified CO2 becomes available as a commodity (not a waste) and (II) at the digestate phase, in addition to organic fertiliser also inorganic fertilisers (in purified mineral form) as well as biostimulants and soil enhancers can be produced. These are separate categories of products (also within the framework of the EU Fertilising Product Regulation) and therefore merit a separate mention.

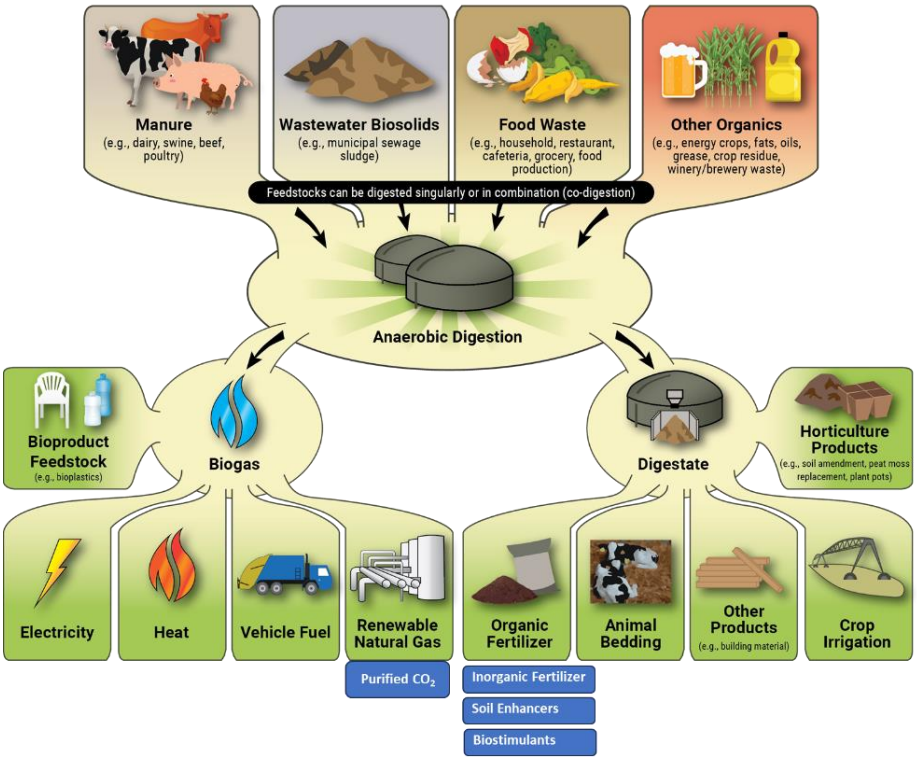

FIGURE 2 ADAPTED FROM US-EPA VIEW ON AD BIOREFINERIES [3]

1.

Review of the current state-of-the-art

of digestate in the EU



1 Review of the current state-of-the-art

This chapter reviews the current state of the art of various approaches to digestate treatment, areas of technological application, novel strategies including upgrading techniques and opportunities to use and valorise digestate.

In addition to biogas, digestate is a parallel product of anaerobic digestion of biodegradable feedstocks. It contains nearly all the nutrients of the original feedstock and the poorly degradable or stable organic fraction. Digestate is therefore a very valuable organic fertiliser, which delivers not only nutrients for plant growth but is additionally a soil improver through its valuable organic carbon content. Depending on the feedstock used and the fermentation process applied, digestate can occur in liquid, semi-liquid or solid form.

1.1 Overview of digestate in the EU

The current annual EU production of digestate ranges from 222 to 258 million tonnes of fresh matter, equivalent to 31 million tonnes of dry matter, corresponding to 193-253 tonnes of digestate (dm)perGWh of biogas and biomethane production. Given the significant growth of the biogas and biomethane market, there is an aim to reach 35 bcm of biomethane production by 2030 (as targeted under REPowerEU) [4], [5]. Germany, Denmark, the UK, Italy and France are the largest digestate producers in Europe and are expected to remain the frontrunners for the years to come, with almost half of all digestate produced in Germany.

The majority of digestate produced in the EU is derived from agricultural feedstock (manure, agricultural residues, energy crops), while less than 30% derives from biowaste including sludges from municipal WWT. As part of the urgent measures to overcome the difficulties of the energy crisis and the inflation tensions resulting from the Russian-Ukrainian conflict, as the sanctions have been affecting imports to the EU, the range of by-products to produce digestate fertiliser from AD is expected to be further expanded to include residues from food production and agro-industrial activity, municipal waste management, and biomass from sequential cropping (i.e. rotations which respect food production and residual biomass within the same field) and phytoremediation biomass from marginal or contaminated lands unsuitable for food production.

Currently, over 70% of the digestate in the EU is directly applied to the soil as biofertiliser and amendment, whereas 16% is applied to soils after first being upgraded. The remainder is used for other applications such as horticulture, soil production, landfill coverage or biological processing, or is exported.

In this context, nutrient recycling through waste and residue, AD creates additional value, moving towards replacing synthetic fertiliser based on natural gas (NG). This is a development which itself does not go against conventional fertiliser production in Europe, but can go hand-in-hand with greening the existing fertiliser-producing sector by substituting the raw fossil resources with biobased counterparts facilitated through AD.

According to recent estimations based on the nitrogen (N) and phosphorus (P) consumed in the 27 EU countries, digestate can already replace 15% of N-based fertilisers and about 11% of P-based fertilisers and 6% of K-based fertilisers [6], [7]. By 2050, the potential replacement of N and P

fertilisers is expected to be around 26-31% and 86%, respectively. However, a cautionary note: these values are to be considered as broad estimations and the NH4 content is not to be regarded 1:1 as a synthetic fertiliser equivalent, as the capacity of crops to assimilate the nitrogen influences the efficiency of digestates. Fertilisation with digestate requires targeted use in line with soil and plant characteristics and requires assessment of potential on a case-by-case basis.

In this context, recent studies have shown that an average of 2 bcm of NG consumption could already have been avoided if digestate had been used to replace synthetic nitrogen fertilisers, delivering an important positive impact both in terms of energy security in the EU and of climate change mitigation (10 Mt of CO2eq reduction) by preventing GHG emissions by utilising the closed and controlled environment of AD and thus avoiding emissions from the open decomposition of organic matter.

1.2 Relevant legislation at the EU level

At European level, digestate is affected by several important laws which may be, but are not necessarily, related to each other. If feedstock for AD comes from animal by-products or waste, digestate falls under the Animal By-Product Regulation (ABPR) [8], [9] (2019/1069/EU) and/or the Waste Framework Directive (WFD)(2008/98/EC) [10]. The amount of nitrogen which can be applied for for plant nutrition from livestock manure, including its processed forms in Nitrogen Vulnerable Zones is limited to 170kg per hectare through the Nitrates Directive (91/676/EEC) [11]. The last and maybe most important EU legislation for the development of digestate as an organic fertiliser is the Fertilising Product Regulation (FPR; 2019/1009/EU) [12].

Fertilising Product Regulation (2019/1009/EU)

This regulation sets important rules on the requirements for digestate destined to become an EU fertilising product. When a manufacturer of a digestate-derived fertilising product seeks to market their product nationally, they must demonstrate compliance with relevant national legislation, which could pertain to waste or fertilisers depending on the legal framework in place. Alternatively, the manufacturer can choose to demonstrate compliance with the rules outlined in the Fertilising Products Regulation (EU) 2019/1009 (FPR), which aims to harmonise requirements for EU fertilising products bearing a CE mark.

According to Article 19 of the FPR, component materials of fertilising products are no longer considered to be waste the moment the manufacturer signs the EU declaration of conformity of the EU fertilising product containing such a material. At EU level, the end-point in the manufacturing chain for digestate derived from animal by-products to be used in fertilising products has been determined in Delegated Regulation (EU) 2023/1605.

Within the FPR, all raw materials possibly used are categorised into 11 component material categories (CMC) [13]. Within these categories, requirements for their use are laid down (possible feedstocks, possible additives, requirements on pasteurisation, requirements on impurities etc.). There is a category included for digestate from crops and one for digestate from other feedstocks.

The EU fertilising products themselves are then categorised into 7 product functioning categories (PFC). Each category has its own requirements for the products, such as minimum nutrient content, upper limit of heavy metals and other relevant fertilising properties for plants or even soil etc.

From the 11 possible component material categories to be used in Fertilising Products, 2 are mainly of interest for digestate: CMC4 and CMC5; for more technical details, we refer to the abovementioned FPR and indicated reference [12].

CMC 4: Fresh crop digestate

CMC 4 refers to fresh crop digestate in the context of the EU fertilising product regulation. It is a material that can be included in EU fertilisers obtained through anaerobic digestion of specific input materials. The regulation aims to harmonise conditions for making fertilisers available on the internal market, promoting the use of recycled nutrients and supporting the circular economy.

Permitted components are:

- Energy crops
- Max. 5% required additives (has to be registered under REACH) relative to feedstock used

Other requirements:

- No contact between feedstock and digestate
- Residual biogas potential: max. 0.25 L biogas g-1 VS

CMC 5: Digestate other than fresh crop digestate

CMC 5 refers to digestate from waste materials in the context of the FPR. When used in organic fertilisers, soil improvers, or growing media, it requires external conformity assessment by a notified body. The regulation aims to harmonise conditions for making EU fertilising products available on the market, promoting the use of recycled nutrients and supporting the circular economy.

Allowed components are:

- Biowaste (2009/98/EG) [14] from separate biowaste collection
- Products derived from ABPR for which the end point in the manufacturing chain has been determined in accordance with ABPR
- Living or dead organisms or parts thereof, which are unprocessed or processed only by manual, mechanical or gravitational means, by dissolution in water, by flotation, by extraction with water, by steam distillation or by heating solely to remove water, or which are extracted from air by any means, except organic fraction of municipal waste, sewage sludge, ABP category 1)
- Max. 5 % required additives (has to be registered under REACH) relative to feedstock used

Other requirements:

- No contact between feedstock and digestate
- Residual biogas potential: max. 0.25 L biogas g-1 VS
- Compost + digestate < 6 mg kg-1 PAH (based on dry matter)

Product functioning categories

If digestate reaches the above-mentioned criteria laid down in the CMCs, it is possible to create EU fertilising products from it, provided it meets the requirements of one of 7 possible product functioning categories. The possible PFCs are:

TABLE 1 THE SEVEN PRODUCT FUNCTIONING CATEGORIES OF THE FERTILISING PRODUCT REGULATION

1: Fertilizer		
	a: Organic fertilizer	**I: Solid organic fertilizer** **II: Liquid organic fertilizer**
	b: organo mineral fertilizer	**I: Solid organo mineral fertilizer** **II: Liquid organo mineral fertilizer**
	c: Inorganic fertilizer	**I: Inorganic macro nutrient fertilizer** **II: Inorganic micro nutrient fertilizer**
2. Liming material		
3: Soil improver		
	a: Organic soil improver	
	b: Inorganic soil improver	
4: Growing media		
5: Inhibitor		
	a: Inhibitor, b: Nitrification inhibitor, c: Urease inhibitor	
6: Plant biostimulants		
	a: Microbial plant biostimulant	
	b: non microbial plant biostimulant	
7: Fertilizing product blend		

If digestate fulfils requested nutrient, heavy metal and other requirements it can be registered under the EU fertiliser regulation via a so-called Notified Body [15]. The application has to be made to the responsible national authority.

Animal By-Products Regulation (2019/1009/ EU)

Digestate produced from animal by-products (ABPs) falls under the ABPR. Animal by-products (ABPs) are materials of animal origin that are not intended for human consumption. The regulation of these by-products is crucial to ensure they are handled safely and do not pose a risk to public or animal health. European Union Regulation (EC) No. 1069/2009 classifies ABPs into three categories based on their risk levels [16]:

- **Category 1 (High Risk):**

Includes materials that pose the highest risk, such as carcasses of animals infected with transmissible spongiform encephalopathy (TSE), specified risk materials (e.g. brain, spinal cord), and international catering waste. These materials must be disposed of by incineration or other approved methods to prevent any risk of disease transmission.

- **Category 2 (Intermediate Risk):**

Comprises materials that are not suitable for animal feed but do not pose as high a risk as Category 1. This includes manure, digestive tract content, and animals that die other than by being slaughtered for human consumption. These materials can be used for purposes such as biogas production or as fertilisers, but strict processing standards must be followed.

- **Category 3 (Low Risk):**

Consists of materials that pose the least risk and can be used in animal feed. Examples include parts of animals that were fit for human consumption but are not intended for it, such as hides, skins, and certain by-products from food production. These materials can be safely processed and used in pet food, animal feed, or for other industrial purposes.

This classification helps ensure that ABPs are managed in a way that minimises health risks while allowing for their safe and efficient use in various industries. Category I are ABP materials which are not allowed to be used in biogas plants, whereas category 3 materials such as kitchen waste etc. are allowed to be treated within biogas plants, but have to be hygienised:

- Particle size < 12 mm
- Time temperature profile: 1 h ≥ 70 °C, or an equivalent time-temperature regime achieving the same level of hygienisation

The table below shows possible time-temperature profiles.

TABLE 2 TIME–TEMPERATURE PROFILES FOR ABP MATERIALS

Temperature	Hydraulic retention t	pasteurisation	postcomposting
55 °C, > 24 h	+ x °C + 20 d		
55 °C		+ 70 °C, >1h	
> 37 °C		+ 70 °C, >1h	
> 37 or 55 °C			70 °C + 3 days
> 37 or 55 °C			60 °C + 7 days
> 37 or 55 °C			55 °C + 14 days

Waste Framework Directive (2008/98/EC)

If digestate is produced from waste, the waste framework directive stipulates that digestate is considered as a waste. 'End of waste' (EoW) criteria by the EC applies at the moment digestate is commercialised as an EU fertilising product (Article 19 of the fertiliser regulation) and is included in the EU Fertiliser Regulation. The principles of EoW criteria include quality testing. The table below summarises the main policy framework in 10 selected EU countries and the UK and quality controls of AD digestate.

TABLE 3 SUMMARY OF THE MAIN POLICY FRAMEWORKS ON AD DIGESTATE

Country	Description of Regulation
Austria	• Digestate is accepted as a product if it is composted based on the Austrian Compost Ordinance and the Austrian Fertiliser Ordinance. • Digestate from agricultural residues falls under the national fertiliser regulation and has to be registered under the national fertiliser regulation. • Cross-border-traded digestate has to be registered under the EU fertiliser regulation. • The application of digestate has to fulfill requirements of the national water rights act law.
Denmark	• The digestate is considered as a product only if it originates from animal husbandry and complies with the fertiliser application legislations. • A maximum of 0.7 ton TS/ha is accounted for application.
Germany	RAL quality assurance system (RAL-GZ 245 for biowaste and RAL-GZ 246 for renewable energy crops) specifies process requirements and suitable input materials, independent analysis and declaration of the product quality and documentation and application requirements
Greece	The digestate is not considered as a product. However, if it is composted and matured under adequate aerobic conditions, it can be considered as such under CMD 114218/1997.
Italy	• The digestate originating from wastes is not considered as a product unless and until it is composted. If the digestate is from liquid slurry/agricultural by-products/plant biomass then composting is not required and it can be applied directly onto agricultural land. • Permits are needed based on the EU Nitrate Directive, with a max of 170 kg N/ha if it originates from a liquid slurry.
Norway	• The Ordinance for Organic Fertiliser uses three classes 0–3. • In the case of heavy metal content, the raw material must comply with class 3.
Portugal	The digestate originating from wastes is not considered as a product unless it is composted.
Sweden	Regulates the feedstock, pretreatment additives and their quantity Monitoring the hygienization of the animal by-products as the feedstock material. Deals the digestate quality and certification.

UK	• BSI PAS 100 (for compost) and BSI PAS 110 (for biofertiliser) covers anaerobic digesters that accept source segregated biowaste and controls input materials, management systems for processes and minimum digestate quality. • Without blending with any other materials like composts or additives, the digestate must comply with the standards and the certification process is done by a third party accredited by the UK Accreditation Services.

Nitrates Directive (2008/1137/EU)

With the Nitrates Directive, the EU intends to reduce and prevent water pollution caused or induced by nitrates from agricultural sources. The Directive requires that Member States identify waters affected by pollution, i.e. waters containing more than 50mg of nitrates per litre, thus designating Nitrogen Vulnerable Zones (NVZs). In NVZs application of nitrogen from manure is limited to 170 kg per hectare per year. This includes the processed forms of manure, such as digestate, which maintains its status as being “animal manure” and is thereby automatically subject to the limitations of the Nitrates Directive in terms of how much you can use per ha per year.

Over recent years, much research work has looked at the techno-economic as well as environmental aspects of so-called RENURE products. These are Recovered Nitrogen from Manure-type of products, a novel term for a category of products coined by the European Commission. In April 2024, the European Commission, while awaiting the outcome of the Nitrates Directive Evaluation [17], prepared and made available for public consultation, a draft Directive amending the Nitrates Directive, as regards the use of fertilising materials from livestock manure [18], for which the regulatory procedure is on-going.

In essence, RENURE products are upcycled nitrogen fertilisers with the potential to substitute natural gas-derived chemical fertilisers. Research on RENURE products has focused on agronomic, economic, technical and environmental aspects in comparison with conventional fertilisation regimes that use animal manure and/or chemical fertilisers [19], [20]. Although a considerable body of evidence has already been accumulated throughout Europe, further scientific support of the Nitrates Directive, in terms of the monitored use of novel biobased fertilisers entering the market and the observed effects thereof, needs to be shared with European and local policy makers. Over the next decade, the EU finds itself in a phased transition towards reduced overall fertiliser use, progressive substitution of finite fossil resources by biobased alternatives and a more optimal synergy of agricultural practices with our environment.

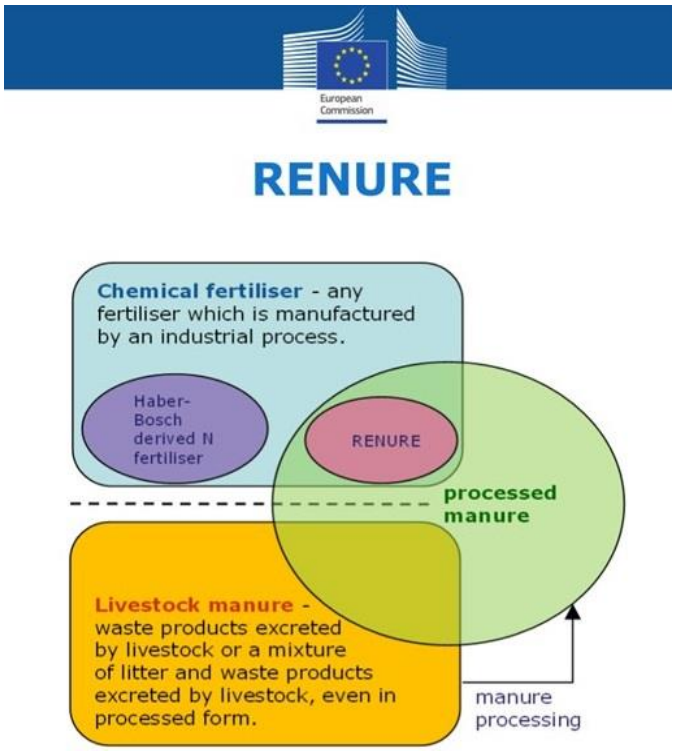

FIGURE 3 CONCEPT OF CREATING RENURE PRODUCTS DERIVED FROM MANURE WITHIN THE FRAMEWORK OF THE EU NITRATES DIRECTIVE [21]

1.3 Digestate processing

Various forms of digestate treatment facilitate efficient storage, transport, processing, handling, and management.

The physical, chemical, biological and thermal techniques for value enhancement of AD digestate are summarised in Table 2 [22].

TABLE 4 DIGESTATE ENHANCEMENT TECHNIQUES AND THEIR POTENTIAL APPLICATION

S. No.	Valorization	Applications
I	**Physical**	
1	Thickening; gravity settling; filtration; air flotation; centrifugation	Separation of digestate in liquid and solid fractions
2	Dewatering; filtration (belt filter press, chamber filter press, vacuum filtration); centrifugation	Elimination of water and concentration of suspended solids in solid portion.
3	Membrane filtration; microfiltration (MF); ultrafiltration (UF); nanofiltration (NF); reverse osmosis (RO); forward osmosis (FO)	Removal of suspended solids, microorganisms, macromolecules and small organic molecules and ions from the liquid fraction. Permeates are rich in K and N and can be used as green fertilizers.
II	**Chemical valorization**	
1	Struvite precipitation; magnesium ammonium; phosphate precipitation	Recovery of primary plant nutrients (nitrogen and phosphorus) from liquid fraction.
2	Ammonia recovery; air stripping; steam stripping; scrubbing	Removal of ammonia from liquid fraction. The stripping can be applied directly to digesters, reducing costs of removal and recovery of ammonia.
3	Ammonia recovery; membrane contactor; ion exchange	Removal of ammonia from liquid fraction.
4	Ammonia oxidation; ozonation; peroxone oxidation; photocatalytic oxidation; electrochemical; bioelectrochemical	Removal of ammonia from liquid fraction.
5	Microwave (MW) radiation; MW stripping	Removal of ammonia from liquid fraction.
6	pH adjustment; acid addition; alkaline stabilization	Stabilization of solid fraction by acidification or alkalinization.
7	Chemical hydrolysis; ozonation; alkaline hydrolysis	Breakage of cells and macromolecules to increase biodegradability of suspended solids and dewaterability of solid fraction.
III	**Biological valorization**	
1	Composting	Biostabilized material for land application
2	Reed beds	Removal of nutrients
3	Biological oxidation	Removal of nutrients
4	Biofuel production (Algae)	Production of biofuels and biogas
5	Biofuel production (hydrolysis of fiber to bioethanol)	Production of biofuels and biogas
6	Microbial fuel cell	Production of energy
IV	**Thermal valorization**	
1	Drying (rotary drying, belt driver, J-vap, solar)	Elimination of water from the dewatered solid fraction; Using forced convection of heated air.
2	Evaporation (scraped surface heat exchangers)	Removal of water from the dewatered solid fraction; Using forced convection of heated air.
6	Combustion	Production of syngas which can be valorized as hydrogen for energy or chemical purposes or to produce chemical block molecules.
7	Pyrolysis; dry pyrolysis; wet pyrolysis: hydrothermal carbonization (HTC); MW-HTC	Production of energy products from thermally; decomposed biomass: bio-oil, char, and syngas. These three products can be valorized differently: bio-oil to extract chemical block molecules (organic acids, aromatics, etc.), char as a soil the amendment, and syngas to synthesize chemical. Block molecules (alcohols, alkanes, etc.).
8	Conversion (incineration)	Production of energy
9	Conversion (gasification)	Production of syngas which can be valorized as hydrogen for energy or chemical purposes or to produce chemical block molecules.
10	Conversion (wet air oxidation)	Production of energy
11	Ultrasound	Treatment to solubilize organic matter and to increase dewaterability of solid fraction.

Monfet et al. (2018); Frischmann (2012).

Solid-liquid separation processes

The application of whole digestate as fertiliser on fields is an easy management solution for biogas plants where distances to the fields are low, nutrient demand is present and application costs are lower than further treatment costs. The first process is solid/liquid phase separation to reduce the volume to be treated for each fraction. Usually, the total solid content in the digestate is around 8 to 10% depending on the AD system and feedstock. After the separation process, the solid phase has a solid content of between 25 and 30% and the liquid phase between 2 and 5%. The technologies used for separation are well developed, easy to operate and low-cost [23]. In addition, to an overall mass separation and distribution of the water over both fractions, K, N, P and organic Carbon also have different tendencies towards either the liquid or solid fractions. K and mineral N, for instance, tend to remain predominantly in the dissolved (liquid) phase, whereas P and organic carbon have a stronger tendency towards the solid fraction. Each of the various mechanical separation systems have a further effect on the distribution of nutrients over both resulting fractions. Moreover, this distribution can be further influenced by the use of coagulants and flocculants. All this implies that with mechanical separation, the ratio of nutrients can be manipulated as well as the mineral over total nitrogen (which itself is a proxy for direct plant availability and nutrient use efficiency of N).

The method most commonly used in European biogas plants is generally carried out using screw presses, screening/sieve belt drum presses (vibrating screen), or decanter centrifuges. To improve solid removal, the use of precipitating agents (e.g. flocculants, coagulants, polymeric lime $Ca(OH)_2$) is applied depending on local regulations.

TABLE 5 COMPARISON OF DIFFERENT SEPARATION TECHNIQUES

Digestate fraction		Screw press	Belt press	Centrifuge
Liquid digestate	DM (%)	5.6	5.4	4.5
	Weight (tonnes)	106,000	88,000	93,000
Solid digestate	DM (%)	26	16.7	21
	Weight (tonnes)	18,700	36,000	31,000
Energy consumption		0.4–0.5 kWh/m³	1.5–2 kWh/m³	3–5 kWh/m³
Separation efficiency		0.936	0.938	0.948

TABLE 6 DISTRIBUTION OF THE PRINCIPAL CONSTITUENTS AFTER SEPARATION

Parameter	General range		Screw press		Centrifuge	
Mass	Liquid (%)	Solid (%)	Liquid (%)	Solid (%)	Liquid (%)	Solid (%)
Total Solids (TS)	14–52	48–86	52	48	14	86
Volatile solids (VS)	35–45	55–65	–	–	–	–
Ash	50–60	40–50	–	–	–	–
Total nitrogen (TN)	65–83	17–35	83	17	75	25
Ammonia-nitrogen (NH_4^+-N)	70–93	7–30	82	9.2	92.5	7.5
Phosphorus (P)	22–45	55–78	–	–	22	78
Potassium (K)	70–93	7–30	90	10	93	7
Carbon I	30–40	60–70	–	–	–	–

Screw presses or belt filters are mechanical devices able to squeeze the digestate against a screen or filter to separate the liquid and the solid. The separated liquid is collected using gravity. Both technologies are continuous processes where in the case of the screw press, the digestate is conveyed by continuous screw to the press head. For the belt filter, the digestate is pushed between two moving porous belts. The belts are then passed through rollers to extract the liquid. These technologies are able to handle a complex matrix and are easy to use and cost effective.

Centrifuges are another technology used to efficiently extract the liquid phase from the digestate. The principle is to employ rotational speed to separate elements of differing density. The decanter centrifuge is the main device used in AD as it allows continuous action with the solid part being collected at the bottom. The rotational speed is between 1,000 and 4,000g. The process is efficient, but the higher energy consumption is one of the main limitations [24], as is the need for polymer addition.

In addition to influencing the distribution of nutrients over the various fractions using different types of equipment, potentially assisted by the use of coagulants and/or flocculants, there is also growing interest in acid-leaching P from the solid fraction. There are a number of benefits for doing so, first and foremost the potential to precipitate the leached P into purer mineral products (vivianite, struvite, etc.). A second potential benefit is associated with the leached solid fraction itself, which then becomes reduced in mineral nutrients but at a ratio that enjoys a higher organic carbon content over P. This facilitates its use as a soil enhancer promoting soil organic carbon (SOC) restoration, which in turn has soil quality benefits as well as SOC sequestration benefits and thereby contributes to climate change abatement.

Liquid phase treatment

Liquid digestate is a nutrient-rich solution that can be used as a fertiliser or be processed further for upgrading. Among its novel uses (discussed in section 2.3) is the use of the fraction as a low-cost medium for the growth of microalgae.

Several technological options have been developed for nutrient extraction from the liquid fraction to produce biobased fertilisers.

Pressure-driven membrane technology is used to push the water (permeate) through the pores and retain the solid and other compounds (retentate). A wide range of membrane processes (micro, ultra, nano-filtration and reverse osmosis) are used depending on the treatment need and membranes are often set up in series for higher efficiency [25]. The main advantages of membrane technology are the ease of installation and the low energy consumption (especially at low pressure).

Finally, ammonia stripping and scrubbing is a chemical-physical process commonly used to recover nitrogen from the N-rich liquid stream of digestate. The principle is the evaporation of ammonia in contact with air flowing in the opposite direction of the liquid. The ammonia can be recovered using an acid solution and the formation of an ammonium salt. As one of the key factors of efficiency is the pH, alkali solution is often added to the liquid to obtain a pH above 9.

This technology is robust and low-cost even if the large addition of chemical can increase the operating cost.

An alternative technology for dealing with the liquid fraction is nitrification-denitrification. In this process, the liquid fraction is aerated to allow microbial conversion of ammonium nitrogen into nitrate. In a subsequent denitrification step, the produced nitrates are converted into nitrogen gas (N2) by respiration, and then harmlessly released into the atmosphere (considering N2 is an inert gas that makes up 80% of the earth's atmosphere). This process is used to convert (and thereby destroy) mineral nitrogen forms in regions where it is considered to be surplus to local requirements. Although sound from a techno-economic point of view, processing in this manner requires large amounts of energy associated with the aeration step and furthermore destroys rather than recycles the nitrogen.

TABLE 7 MAIN EXAMPLES / SHOWCASE / ONGOING RESEARCH AND PILOT INITIATIVES IN EUROPE RELATED TO RECOVERY OF NUTRIENTS FROM DIGESTATE

	Country	Company Name Tech/Project	Process Description Yield	Technical Development TRL
Nitrogen recovery	Italy	BTS Biogas Srl /GmbH NITROStrip [26]	NH3 Stripping 70% w/w/ removal	8-9
		H2ORO	Filtration and reverse osmosis membrane	8-9
	Belgium	Detricon [27]	Scrubbing w/ HNO_3	8-9
		Biogas Bree [28]	600 t/yr ammonium sulfate	8-9
		Waterleau New Energy [29]	1500 t/yr 15% ammonium	8-9
	Netherlands	AMFER (Colsen) [30]	50% w/w , 1 -500 ton /h	8-9
	Germany	Benas farm [31]	57% of ammonium nitrogen as NH_4 sulphate (22%)	8-9
Phosphorous recovery	Spain	SCEPPHAR pilot plant [32]	45-60% recovery as P-struvite from wastewater	5-7
		REVAWASTE	95.4%	7
	Belgium	NuReSys [33]	Struvite pellet at 12.6% w/w/ P	8-9
		Aquafin		8-9

	Germany	AirPrex™	90% w/w precipitation	8-9
	Netherlands	Phosphaq paired™	76% w/w Combined with Anammox system	

Solid phase treatment

The main use of solid digestate is as a fertiliser spread on land. It may be incinerated if no other option is available or the digestate does not reach the correct quality standards. However, new solutions have been developed and employed to valorise the solid digestate, which may be treated further, e.g. by drying or composting.

A wide range of digestate conditioning and treatment technologies have been explored in several studies, and AD plant developers successfully advanced various ways to recover value-added products and nutrients essential to producing new biobased fertilisers that are easy to use and/or be transported, for example by converting it into products such as pellets to be used as a source of energy and carbon [34].

Drying helps digestate stabilisation and reduces the overall volume. Several drying systems have been developed, often using the thermal heat produced by the AD plant to reduce the energy demand. Drying digestate with industrial residual heat is also a viable alternative if the CHP engine produces no or insufficient residual heat. Belt or rotary drum dryers use mechanical movement to bring the solid into contact with the heated gas for higher efficiency. An exhaust gas cleaning system needs to be implemented to remove dust particles and volatile compounds extracted during the drying process. The other possibility is to use solar energy to dry the digestate. It has the advantage of requiring no energy and reduces the production of dust and volatiles as the temperature is around 50-70°C. However, this technology requires a large area to spread the digestate.

After drying the digestate (65-80°C) to reduce water to below 15% ww/w, one option for solid digestates is further thermochemical conversion by pyrolysis or gasification.

Besides generating oil and syngas, enhancing the energy balance and the viability of the process, these endothermic processes, carried out at a high temperature (400-600°C) [35] and in an anaerobic atmosphere, produce chars, which have applications as a long term C sink as they are highly resistant to microbial degradation and stable for long periods when applied in soils, also enhancing water retention capacity and nutrients.

Biochars can also be reused after activation for treatment of wastewater and drinking water, thus being integrated within the biogas production cleaning and upgrading during the purification steps as adsorbents for hydrogen sulphide and carbon dioxide, thanks to their intrinsic physicochemical properties such as aromaticity, porosity, alkalinity and hydrophobicity.

In the hydrothermal carbonisation (HTC) technique, which does not require pre-drying, the solid is treated at moderate temperatures (180-280°C) and low residence times (5-120 min). Water in the feedstock acts as a solvent, solubilising N and P in the liquid phase while hydrochar as the final product can be applied not only as a soil improver but also as an adsorber matrix capable of removing pollutants such as heavy metals.

Digestate valorisation by HTC is emerging in Europe on a commercial scale, with examples of plants integrating AD with thermal processes such as the novel industrial-scale continuous system known as C700 [36] in which the aqueous residues can be recirculated into the AD system of the waste management system, further increasing biogas production.

Hydrochars and biochars from AD-derived digestate have been studied for a number of benefits as soil enhancers. For one, the chemothermic process consolidates the organic carbon in a more stable, recalcitrant form, resisting biodegradation in the soil and thereby contributing more and longer to soil quality in terms of soil organic carbon, cation exchange capacity, overall porosity, water holding capacity and physical aggregation.



2.

Novel Technologies & Gaps in Technology

2 Analysis of novel technologies and identification of gaps in technology

2.1 Agronomic use of digestate

The digestates arising from biogas and biomethane production have a high nutrient content for plants, particularly in the form of mineral and organic nitrogen [37] and phosphorus [38]. Additionally, they also represent, along with crop residues, a source of organic carbon that can be stored in the soil by exploiting the ability of the fine fraction of the soil (silt and clay) to protect organic matter from microbial degradation [39], [40].

Given the growing interest in "carbon farming" and the development of the carbon credit market in agriculture, which aims to promote the removal of carbon from the atmosphere and achieve the climate neutrality target by 2050, as established by the European Climate Law and other environmental objectives of the European Green Deal [41], the incorporation of digestates into the soil at variable rates to maximise the accumulation of carbon in the soil as stabilised organic matter is of increasing interest. Assessment of effective organic carbon remaining in the soil over extended periods of time, as well as the influence of digestate and other fertilising products on greenhouse gas (GHG) emissions from agricultural soils, are important current and future research topics [42]. Not only is the GHG exchange of CO2 compared with chemical fertilisers and manure of consequence here (e.g. distinction of anthropogenic CO2 from NG-derived urea vs biogenic CO2 from digestate), but also the impact on the soil of N dynamics and losses to the atmosphere in the form of the potent GHG N2O. In addition to experimental validation, there is also a need for a better understanding of the mechanistic processes taking place as well as a need to model and forecast expected impacts over longer time periods, in terms of carbon build-up and gas exchange.

Today, there are advanced techniques and technologies in precision agriculture (PA) to characterise soil at low cost, and to monitor crops, with high spatial and temporal resolution and with rapid timing. Such techniques can effectively support site-specific and variable-rate application of organic residues and mineral fertilisers. These solutions are interesting for supporting the management of livestock effluents and derivates in the development of site-specific fertilisation and carbon storage methods (i.e. at the sub-parcel scale), in order to further increase nitrogen use efficiency, increase the farm's economic margin and improve the environmental impact of agricultural activities [43], [44].

The typical framework for optimising the distribution of digestates with precision agricultural tools in a cereal-livestock context consists of the following steps [45]:

1. High-resolution mapping of the spatial variability of soils and vegetation within fields. Variables of interest can be measured directly (soil analysis and direct mapping of crop yield) or estimated through the measurement of proxies such as soil electrical resistivity and vegetation indices measured by drone or satellite.

2. Integration of soil and vegetation maps and/or production maps to formulate fertilisation advice and create distribution maps for organic fertilising products and chemical mineral fertiliser either before sow or after establishment of crop vegetation
3. Application of nitrogen through site-specific variable-rate distribution machines.

Within this framework, rapid systems can be developed for mapping soil particle size and organic matter based on the use of geoelectrical sensors and NIR analysis of soil organic matter. Based on these rapid analysis methodologies, a procedure has been developed for mapping soil carbon deficit, i.e. the capacity of the soil to protect organic matter for a long time [46]. An organic residue management criterion based on this property has been proposed with the aim of increasing carbon storage in the soil as a function of field variability. The maximum amount of carbon that a soil can fix in a stable form depends on multiple factors, including the physical and chemical characteristics of the soil, the climate and vegetation. Estimating this storage capacity can be proposed as a guiding criterion for variable rate distribution of digestates, considering them not only as a source of nitrogen and other mineral nutrients but also as a tool to increase carbon storage in the soil.

Soil carbon deficit mapping at field scale can be partially automated with the development of a prototype rover for geoelectric mapping and automatic sampling of soil. A decision support system (DSS) can manage nitrogen fertilisation in maize based on a spatialised mass balance, which integrates the use of livestock effluents and mineral fertiliser.

Digestates are also rich in phosphorus, both in mineral form as phosphates and in organic form (phytates and phytic acid) derived from the excretions of monogastric animals. In order to be assimilated by plants, phosphorus must be solubilised as orthophosphate. In the case of phytates this occurs through exoradical enzymes (phytases) produced by microorganisms or by the plants themselves. Studies on the expression capacity of exoradical phytase by ecotypes and cultivars of fodder crops such as alfalfa and maize have been carried out. The genetic selection of varieties that produce greater quantities of exoradical phytase can in fact favour a better agronomic use of by-products from biogas production plants and reduce the use of phosphate fertilisers.

2.2 Mineral nutrient extraction and valorisation

Biogas operations lend themselves perfectly to dual valorisation whereby biogas plants can serve both the societal function of renewable energy production as well as fertilising product production. Potential pathways for producing added-value products are varied and diverse [47].

Nitrogen, phosphorus and potassium (N, P, & K) exist in various forms in the liquid and solid fraction of AD digestate. Digestate can vary significantly in composition of total solids (TS), total suspended solids (TSS), total dissolved solids (TDS), N, P, K, organics, inorganics, recoverable resources and impurities. For the purpose of this review, raw digestate (RD) is considered as the untreated product leaving the AD reactor at 5-10% TS. The liquid fraction (LF) is the centrate, filtrate or permeate of the digestate after having been processed by a dewatering unit operation such

as a centrifuge or filter press typically with <5% TSS. The solid fraction (SF) is the sludge cake produced during the same unit operation with >15% TS.

Organic N, P and K can be recovered as organic matter through dewatering, drying and or pelletising of the SF with a wide variety of technologies available from other industries. These pellets will include a variety of other compounds, including contaminants, depending on the feedstock material [48]. Minimising the energy required and residual biomethane potential of the SF final product requires full scale demonstration and independently verified energy balances. Continuous hydrothermal carbonisation processes for RD also show potential for improving dewaterability and changing the N, P and K concentrations of the LF which can improve the efficiency of downstream valorisation; these processes have not been effectively demonstrated at full scale [49]. Organic matter can also be produced from the LF by growing algal biomass and other microorganisms in raceways and ponds. This has been demonstrated at larger scale for wastewaters but limited to mostly pilot scale for recovery from digestate. Again, other compounds are recovered in the biomass. For N, P and K recovery alone, algae production processes are likely too costly due to hydraulic retention times and growth rates [50].

Recovery of mineral forms of nitrogen and phosphorus has gained more momentum than recovery of potassium. This is due to phosphorus being on the EU critical raw material list, the fossil fuel intensity of nitrogen fertiliser production and the eutrophication caused by both entering aquatic environments [51], [52], [53].

Ammonia stripping is becoming a key recovery technology, which can be applied to all forms of digestate (RD, LF, and SF). Thermal energy is applied, pH is increased, and a carrier gas is used to transfer the ammonia to a scrubbing solution and the final product can be ammonium sulphate, ammonium nitrate or ammonia water. The use of phosphoric acid to produce ammonium phosphate is not widely reported. A variety of processing technologies are available on the market today [54], [55].

Economic feasibility, primarily due to the concentration of ammoniacal nitrogen in the feedstock, seems to be the greatest challenge the technology faces, with 1,000 – 2,000 mg L-1 NH4-N being mentioned as minimum concentrations while maximum concentrations to avoid inhibition of the AD process are 2,000 – 3,000 mg L-1 NH4-N. This suggests an intermediary concentration step may be beneficial but the feasibility of this has not been reported [56], [57]. Ammonium carbonate production processes are reported to be cheaper and can make use of CO2 produced at an AD facility. However, the stability of the final product relies on additives, some of which are patented, indicating that more research could provide pathways to more efficient processes [58].

Some of the advanced technologies for nitrogen removal are summarised in Table 8 [59].

TABLE 8 OVERVIEW OF SOME OF THE ADVANCED TECHNOLOGIES FOR NITROGEN REMOVAL

Process	Description	References
Nitritation-denitrification		
SHARON	Stable reactor system for high-activity ammonia removal over nitrite	Mulder et al. (2001)
SBR	Sequential batch reactor	Fux and Siegrist (2004)
Nitritation-ANAMMOX		
CANON	Completely autotrophic nitrogen removal over nitrite	Valverde-Perez et al. (2015)
OLAND	Oxygen-limited autotrophic nitrification-denitrification	Valverde-Perez et al. (2015)
DEMON	Deammonification sequential batch reactor	Valverde-Perez et al. (2015)
ANAMMOX	Nitrification reactor + ANAMMOX reactor	en.paques.nl/products/featured/anammox
DEAMOX	Denitrifying ammonium oxidation	Kalyuzhnyi et al. (2006)
ANITATMmox	Moving bed biofilm reactor	http://technomaps.veoliawatertechnologies.com/anita/en/anitaçmox.html
CleargreenTM	SBR with three stages	www.degremont.com/en/know-how/municipal-water-treatment/wastewater/wastewater-biological-purification-cleargreen
DeAmmon	Nitritation + anammox	aditera-cms.se/lackebywater/industri/the-deammon-process
SNAP	Single-stage nitrogen removal using ANAMMOX and partial nitritation	Furukawa et al. (2006)
SNAD	Simultaneous partial nitrification, ANAMMOX and denitrification	Daverey et al. (2012)
SHARON coupled with anammox	A stable reactor system for high-activity ammonia removal over nitrite + ANAMMOX	Magri et al. (2013)
Bioaugmentation		
MAUREEN	Mainstream autotrophic recycle enabling enhanced N removal	Katehis et al. (2006)
BABE	Biological augmentation batch enhancement	Furukawa et al. (2006)
InNitri	Supplemental nitrifiers (nitrification – northern climate)	http://www.m2ttech.com/innitri.html

Adapted from Monfet et al. (2018).

Precipitation is a key phosphorus recovery technology for wastewaters and by extension (in context of biogas) also applicable to Liquid Fraction. It can also apply to Solid Fraction if this was first pre-treated with a leaching or solubilisation technology (e.g. acid leaching, bio-acidification, HTC…). Struvite precipitation is the most popular P recovery technology. Struvite is a crystalline mineral composed of magnesium, ammonium and phosphate. Struvite processes are installed globally and are proven to be effective, but life cycle assessment has shown it may not be the most environmentally beneficial P recovery method in all situations. Other precipitation processes are being developed, producing, for example, magnesium potassium phosphate, brushite, calcium phosphate, potassium struvite, vivianite and others. These have not yet been scaled up and commercialised to the same extent [60], [61].

Ion exchange and adsorption show some promise for N and K recovery from LF. The use of zeolites and, more recently, geopolymers have shown promising results for adsorption capacities and regeneration but have not been deployed at full scale [62], [63], [64].

Membrane concentration of the LF is currently used at full scale to produce end products with high concentrations of N, P and K. Several subsequent high-pressure stages of ultrafiltration, nanofiltration and reverse osmosis are required to achieve clean water for discharge or reuse and a concentrated nutrient solution. Forward osmosis membrane distillation and electrodialysis have recently shown promising results for nutrient recovery [65], [66], [67], [68].

High recovery rates of >98% can be achieved with membranes, but fouling presents a challenge, which makes membrane concentration less economically feasible. It was reported in one study that ozone could reduce fouling and increase flux but more research is needed to optimise the ancillary processes in a full-scale membrane concentration plant. Hydrophobic membranes can be utilised in transmembrane chemical absorption or TransMembrane ChemiSorption (TCMS) to allow ammonia to pass from the feed side to the acid side in a low-pressure process. A limited number of pilot and full-scale studies have been reported and knowledge gaps include reducing water vapour transport, optimal operational conditions, fouling and cleaning cycles.40 Osmotic membrane bioreactor processes can use flat-sheet cellulose triacetate membranes. Hybrid systems are also being researched and there is potential to reduce the effect of fouling through draw solutions, biomass and selection of other operational parameters, but again research is limited [69].

Freeze concentration (FC) is used in food and chemical manufacturing. It takes advantage of the variety of freezing points of the required nutrients and the fact that the energy requirement to freeze water is 13.4% of that required to evaporate it. Theoretically, it has the potential to remove water more efficiently than membranes and evaporation. It can concentrate nutrients to levels that make downstream processes more viable. However, capital and energy costs are a limiting factor for use with digestate and need further research [70].

Ammonium and phosphate ions can also be concentrated in the cathode chamber of a Bioelectrochemical System (BES). BES are innovative technologies that combine biological and electrochemical processes to achieve various environmental and energy-related goals. BES can be used for wastewater treatment, bioenergy production, and resource recovery. They offer a sustainable way to treat waste while generating useful byproducts [71]. Mechanism: BES typically consist of two electrodes (anode and cathode) connected by an external circuit. Microbes at the anode oxidize organic substrates, releasing electrons and protons. The electrons flow through the circuit to the cathode, where they participate in reduction reactions [72]. These systems are gaining attention for their potential to address environmental challenges and contribute to sustainable energy solutions.

A Microbial Recovery Cell (MRC) is a type of BES that utilises microorganisms to recover valuable resources from waste. These cells leverage the metabolic processes of microbes to convert waste materials into useful products, such as electricity, hydrogen, or other chemicals. The microbes act as biocatalysts, facilitating the transfer of electrons in the system.

Stripping, precipitation and forward osmosis (FO) have been reported as the next stages of N and P recovery from an MRC. Ammonium bicarbonate is mentioned as a promising draw solution due to ease of recovery. Other research focuses on a concentrated ammonia solution with a notable lack of contamination which could be used for microbial protein production or other valorisation processes [73]. Flow-electrode capacitive deionisation (FCDI) cells are another BES which could have applications for digestate, but the limited research seems to point towards its use with low-ammonia LF, with feed concentrations of ~30 mgL -1 N and final concentrations of ~300 mgL-1 N [74]. Microbial electrolysis cells (MECs) have also been shown to upgrade biogas at the same

time as recovering ammonium at bench scale, suggesting that N, P and K recovery should not be researched in isolation from other valorisation processes at an AD site [75], [76]. Further research into BES and chemical-free electroconcentration for N, P, and K recovery is required to increase the number of pilot and full-scale processes.

Thermal treatments for the SF or RD can offer mitigation against contamination of recovered N, P and K products by destroying pathogens and many micropollutants, depending on the temperature. The lowest temperature process is hydrothermal carbonisation (HTC), which can avoid gaseous nitrogen emissions, while incineration, gasification and pyrolysis are mostly used for the recovery of phosphorus and potassium as biochar and ash [77]. Further P and K recovery can be achieved by solvent extraction. Nitrogen recovery is most cost effective as stripping/scrubbing steps for the thermal drying fume condensate when combined with LF [78]. Incineration, gasification and pyrolysis are available at full scale but optimising the operating parameters and ancillary processes requires further research. There is also a need to independently verify energy balances and N, P, K mass balances with particular attention paid to N2O and NOx emissions.

2.3 Extraction of other valuable compounds

Biostimulants

Limited studies have explored the bio-stimulant properties of digestate, but some research has shown that specific biochemical fractions of digestate have auxin-like effects and promote plant and root growth including positive effects on germination rates, enhancing nutrient mobilisation, photosynthesis efficiency, improving concentration of carotenoids, phenols, flavonoids, and NPK, also mitigating the negative effects of drought stress.

Typically, while the labile fractions of organic matter are transformed into biogas, the digestate contains stabilised organic matter resulting from formation of stable compounds, such as aromatics and long aliphatic chains. The AD strategies for enhancing the stabilised organic matter in the digestate can be found in an excellent review by Guilayn et al. [79], which highlights the impact of the technology and process parameters used in AD on the soil, amending the value of digestates, and on the residual organic matter.

The biostimulant properties of such biochemicals within the digestates are highly dependent on the feedstock used as substrate during the AD, therefore the chemical composition of the feedstock likely plays a central role in determining the biostimulant effect.

Sewage sludge/manure digestates have been found to exhibit auxin-like properties on maize plants, demonstrating that these specific fractions of digestate may possess bioactive properties that promote plant growth. Scaglia et al. [80] recently conducted research on the presence of hormone-like molecules and growth-promoting substances such as auxin and gibberellin-like activity in pig slurry digestate. By testing the increase in the growth of lettuce (Lactuca sativa L.) the study found no gibberellin-like activities in digestate. However, digestate exhibited auxin-like

properties, primarily attributed to auxin derived from AD of aromatic amino acids (both phenyl acetic acids and auxin). The auxin-like activity was found to be predominantly associated with water extract and thus the neutral hydrophobic dissolved organic matter (DOM) fractions of the digestate.

Possible promising outcomes in terms of biostimulants come from projects such as ALG-AD, developed by Interreg NWE [81], which have investigated algal biomass grown on digestate and their ability to use the nutrients to produce useful bioactive elements and biostimulatory compounds [82].

Volatile fatty acids (VFA)

During a typical AD process, the consortia of microbes generate, as intermediates and co-products in the methane formation pathway, short-chain volatile fatty acids (VFA), which include, for example, acetic, butyric and propionic valeric acids [83], [84]. At low hydraulic retention time (HRT), not all organic acids are completely converted to biogas and they remain in the digestate.

Interest in VFAs has recently increased as they are acknowledged to have higher value and varying possibilities for their end uses compared with methane [85]. In particular, they can be used as renewable and bio-based building block chemicals in various sectors and feedstocks in the production of bioplastics since they are direct metabolic precursors [86], [87].

Recent studies proposed a circular approach that involves the recovery of VFAs, produced during AD of the organic fraction of municipal solid waste (OFMSW), to be used as a cheaply available carbon substrate for biopolymer production such as polyhydroxyalkanoates (PHAs)51 through pure or mixed microbial cultures (MMCs) of PHA-accumulating microorganisms [88], [89].

Previous research [90], [91] explored the valorisation of OFMSW and investigated the recovery of VFA in digestate for production of PHAs to integrate and maximise the overall process within the AD-based biorefinery approach. The studies evaluated the effects of various AD configurations on the yield of both biogas and VFAs. The potential for retaining a good conversion into methane while producing a VFA-rich digestate feedstock, which was subsequently used as a “building block” to produce PHAs by employing a microbial mixed community (MMCs), has been evaluated. The VFA concentration found in the range of 100 (g kg-1 TS) never achieved values which could cause instability of the AD process by lowering methane production, i.e. 11 to 16 g TS L-1 d [92] or even AD process inhibition, i.e. 16.5–18.0 g L-1 [93].

Further approaches explored the enhancement of VFA production from solid digestate by fungal pretreatment. The VFA obtained from the lignin degradation enzymes such as laccase and manganese peroxidase from P. sajor-caju/T versicolor has been reported by Fang et al. [94].

Trace elements

The bioavailability of nutrients is a key factor which may influence process performance, since nutrients are necessary for microbial activity. Deficiency in even a single nutrient may limit microbial activity and, consequently, digester performance. Trace element (TE) is a term used to include a wide range of micronutrients essential for the microbial community underpinning AD. TEs mostly include elements from the metal groups (e.g. cobalt, nickel, zinc and tungsten) but also other elemental groups, such as metalloids (e.g. selenium). These TEs can be anionic or cationic which induce a different (opposite) chemical behaviour.

Unlike organic compounds, TEs introduced in the reactor are not degraded during AD, and their content in the feedstock is highly dependent on anthropogenic sources. Among the main origins of the TEs are animal feed additives, food processing residues, flotation sludge, fat residues and domestic sewage. In order to avoid risks with TE supplementation, it is very important to develop an appropriate dosing strategy, ensuring that each TE concentration is comprised between the two inhibition zones (deficiency and toxicity). Overdosing of at least one TE may result not only in toxicity effects inside the bioreactor, with a decrease in the reactor performance, but can also lead to an environmental risk once the digestate is discharged.

The publicly available specification BSI PAS 110:2014 specifies upper limits for Cd, Cr, Cu, Pb, Hg, Ni and Zn in digestate, but the safe upper limits for other TEs are not determined. Several studies have reported lower levels in digestates relative to the standards set by German, British and Spanish legislations, but the long-term application of TEs and their accumulation in soil over repeated application is not known and needs to be investigated in the future.

The recovery of trace elements from the digestate can be an advantageous solution to allow the discharge of heavily charged digestate and contribute to the production of valuable compounds. The main bottleneck is the extraction of trace elements from the organic material as they are present in the solid phase as precipitate. The acidification of the solid phase could be a possibility to solubilise the trace elements, but it will not be environmentally friendly and economically viable. One of the suitable options would be to use the chemical and physical properties of each element to extract them separately. As an example, the magnetic property of iron means it could be recovered as vivianite (plus recovery of phosphate) [95]. For the other elements, a change to the digestate condition (pH, redox, ligands) will affect their chemical speciation and potentially allow their recovery.

2.4 Microbial valorisation of the digestate

Filamentous fungi naturally produce and secrete a wide range of metabolites and enzymes, so they can be employed as a biocatalyst in fungal biorefineries. A biorefinery is a multiproduct system that utilises biomass obtained from a plethora of untreated sources, e.g. oil crops, starchy plants, forest and agriculture residue, organic wastes, wet feedstocks, grass and green crops as inputs, and transformed with the aid of microbes into multiple, environmentally adaptable products such as fuels (bioethanol, biogas and biodiesel) and other value-added chemicals.

The production of hydrolytic enzymes (e.g. xylanase, chitinase, cellulase) is an example of biorefinery based on agro-industrial wastes as raw substrates. Fungi also produce a variety of secondary metabolites that are involved in their development, defence, and host-interaction. These metabolites have been an historical treasure for drug discovery; only recently, microbial value-added products have found broad applications in food (organic acids as acidulants) and agrochemical (biopesticide and biostimulant production) industries. Establishment of an integrated biorefinery that is competent in utilising organic wastes for commercial product biosynthesis is a sustainable alternative for waste management along with resource recovery addressing the circular economy in the framework of industrial symbiosis [96]. Development of integrated biorefineries can fulfil unmet needs of the bioeconomy to produce value added compounds [97]. In conventional refineries, resources are not recycled after the primary process that is eventually excluded from the process loop.

The application of digestate as a biomass in biorefinery remains poorly explored. Only a couple of methods for the valorisation of digestate as a substrate for solid-state fermentation (SSF) have been reported up to now: as a biopesticide, with the inoculum of Bacillus thuringiensis (Bt) or for Trichoderma spp. biomass production [98]. The whole digestate (liquid and solid fraction) has been recently applied as biomass in a fungal biorefinery to produce enzymes, organic acids and phytohormone-like molecules [99]. Also, enrichment with microbial consortia via dedicated inocula could enhance digestate fertilising potential by favouring nutrient mobilisation, organic matter degradation and plant biostimulation [100].

2.5 Trans-sectoral use of digestate

Insect cultivation

Insects grown on digestate for protein production is a strategy gaining research interest. In the VALUEWASTE project [101], the pilot plant located in the waste management facilities in Murcia (Spain) successfully demonstrated the valorisation of biowaste into food and feed ingredients through insects that feed on the solid digestate. Once treated, the solid digestate is taken to a pilot black soldier fly-rearing unit designed and installed by Entomo Agroindustrial, which produces dried larvae. Later, these are transformed into flour with a high protein content. The whole digestate (liquid and solid fraction) has been recently applied as biomass in a fungal biorefinery to produce enzymes, organic acids and phytohormone-like molecules [102].

Electrochemical methods

Ammonium and phosphate ions can also be concentrated in the cathode chamber of a bioelectrochemical system (BES), microbial recovery cells (MRC). The liquid fraction of digestate can be used as the feeding substrate for a microbial fuel cell (MFC) and a microbial electrolysis cell (MEC) to produce electricity and H2, promoting P removal (as struvite: $MgNH_4PO_4 \cdot 6H_2O$) as a consequence of the pH increase at the cathode level. The effluent from METs was treated to reduce P content by promoting struvite precipitation in a crystallisation device, by adding either pure Mg salt ($MgCl_2$) or an Mg by-product (seawater bittern).

Digestate as denitrification source

When digestate is applied to the soil, it promotes the growth of denitrifying bacteria and provides a source of nitrates that can be used by these bacteria for the denitrification process. This can be advantageous for managing and closing the nitrogen cycle in the soil, as denitrification helps prevent the excessive loss of nitrogen to groundwater or the atmosphere.

Fibers for bedding material, peat replacement or biomaterials

For the solid fraction, alternative use of the fibrous dried product towards fibre production (biobased building materials) or as peat replacement has also been developed at pilot-scale (TRL 5) in several leading companies and institutes across Europe. For instance, fibre board production was integrated in the digestate post-treatment of the BENAS installation within the EU SYSTEMIC project [103], [104]. Other research investigated the potential use of dried solid fraction of digestate as bedding material in animal housing [105], the potential for peat replacement [106], [107], or even in biomaterials for buildings such as insulation panels. The GRASSIFICATION project [108], for example, investigated a biorefinery-based valued chain for roadside grass and found that AD-digested grass fibres were superior to undigested ones for production of biopolymers for biomaterials [109]. All these applications are in their initial stages of development and targeted further research will be needed to advance this promising cross-connection between renewable energy production and bioeconomy via biogas as a bridging technology.

2.6 Economic optimisation and social acceptance

One of the key challenges that biogas operations have been struggling with over recent decades, was their high (initial) dependence on public support schemes such as feed-in tariffs and green heat/power certificate-based incentives for business viability. Support mechanisms for biogas-derived renewable energy are nationally or even regionally organised, resulting in a patch work of different support systems and levels which also vary in time with changing political administrators. This has resulted in a drive towards higher value operations in which renewable energy production is combined either with reduced costs associated with digestate handling or even (more and more) achieving added value from the digestate on top of the energy production. A growing body of research is dedicated to multi-functional biogas biorefineries [110], [111], as well as other targeted economic optimisations in digestate management. Non-limitative examples (in addition to above-mentioned mineral fertilisers through biorefineries) include (i) solar drying to optimise energy requirements for digestate drying [112], (ii) placing an effective value on soil organic carbon stocking (carbon farming) making use of the stable nature of OC in digestate [113] or even optimisation of single unit steps such as (iii) the potential use of shear viscosity to monitor polymer conditioning of sewage sludge digestates [114] or (iv) reducing fugitive emissions of biogas from digestate storage. The latter are but a handful of a growing body of researched strategies to increase value and reduce costs, thereby progressively further improving the business proposition posed by biogas systems as whole.

2.7 Environmental impact

Thanks to its versatility, anaerobic digestate has become a highly regarded resource with a wide range of applications. Nonetheless, it is critical to conduct an evaluation of the environmental associated with its utilisation. This paragraph aims to present an overview of the potential risks, advantages, and most frequent measures to mitigate the impacts related to the use of anaerobic digestate, as well as the further research and innovation needs.

Anaerobic digestion provides a sustainable solution for managing organic waste by diverting it from landfill, thereby reducing associated environmental concerns. This process aligns with the principles of the circular economy by converting organic waste into biogas and digestate. Biogas serves as a renewable energy source, while digestate acts as a valuable nutrient resource. This closed-loop system promotes waste valorisation and reduces reliance on raw resources, leading to a significant reduction in environmental pollution.

Moreover, anaerobic digestate serves as a source of organic matter and vital nutrients, including nitrogen (N), phosphorus (P), and potassium (K).

Further research should be conducted to map the benefits of various digestates towards soil quality, soil health, soil biodiversity and soil organic matter, depending on the soil type and other parameters. The European Biogas Association drafted a dedicated explorative report, providing interesting handles and guidelines for further research follow-up [115].

Poorly managed application of digestate, particularly when excessive nutrients are brought to soil, can lead to imbalances in soil nutrients and potentially contaminate water sources. The surplus nitrogen and phosphorus have the potential to infiltrate groundwater or runoff into surface water bodies, causing eutrophication and compromising water quality (a 'caveat' that applies to all other existing categories of fertilising products).

Developing thorough nutrient management plans that account for crop nutrient needs, soil fertility, and digestate composition is a frequent practice to mitigate these risks, as well as, increasingly, precision agriculture techniques, such as variable rate application, to align nutrient supply with crop demand. Soil testing and advanced nutrient modeling tools can also optimize digestate application rates, together with precise nutrient application rates and appropriate timing.

Anaerobic digestate may potentially harbour various microorganisms, including potential pathogens, which could pose health risks if not treated or handled properly. Pathogens can survive and spread through inadequate storage, insufficient treatment, or incorrect application methods. To ensure safe digestate utilisation and avert potential health hazards, rigorous pathogen monitoring, well-defined treatment protocols, and strict adherence to safety guidelines are crucial. Further research should be conducted on the presence of potential pathogens, also the presence of ARGs associated with these micro-organisms.

Organic xenobiotics also pose growing concern in terms of emerging pollutants and/or pollutants which are already ubiquitous but which are becoming a matter of emerging concern. In most regions and instances the environmental quality is ensured upstream in the process, from the input materials entering the plants, because the pollutants if any are closely related to what is

naturally present in the initial biomasses entering the plant. Nonetheless, further research should be conducted on emerging pollutants – also in other anthropogenic activities and industrial sectors – and the risks pertaining to them.

More particularly, treatment systems as well as monitoring systems will require improvement to provide adequate and transparent quality assurances. In the past, quality systems in place have been based on a well-defined list of inorganic pollutants and limitative list of organics. In recent years and in various regions, novel pollutants (or long existing pollutants with emerging policy interest) have received new attention such as PFAS/PFOS, amphetamines or other compounds. Management systems should be adapted to this varying field of novel pollutants throughout all sectors of society, including biogas. In the current setting, authorities and biogas operators faced with analytical anomalies (either from false positives or not-previously targeted organics) fall back on a strategy of obligatory digestate incineration in light of the precautionary principles.

Another topic of growing concern is the increased presence of antimicrobial resistance in our environment. Antimicrobial resistance (AMR) occurs when microbes no longer respond to an antimicrobial agent, increasing the risk of severe illness and even leading to death. According to the ECDC TECHNICAL REPORT 'Assessing the health burden of infections with antibiotic-resistant bacteria in the EU/EEA, 2016-2020' [116] AMR is responsible for more than 35,000 deaths every year in the EU/EEA. In 2019, the World Health Organization (WHO) declared AMR to be one of the top 10 global public health threats [117]. In July 2022, the EU Commission, together with the Member States, identified AMR as one of the top-priority health threats [118]. O'Neill (2016) [119] indicated that if AMR continued to grow it would result in an estimated 10 million deaths globally each year by 2050.

The overuse of antibiotics in the medical and veterinary sectors has created an environment where antibiotic-resistant bacteria (ARB) thrive and can transfer their antibiotic resistance genes (ARGs) to other members of the microbial community, thus exacerbating the spread of resistance. Singh et al. (2019) [120] stated that the sources of existing ARB and ARGs include domestic and hospital WWTPs (effluent and sludge), agricultural run-off, pharmaceutical industry effluent, urban surface water, aquaculture, wild and domestic animals and landfill sites. Hayhurst and Esteves (2021) [121] reviewed literature relevant to AMR in the environment, particularly wastewater treatment and agriculture including anaerobic digesters. The review concluded that AMR studies related to AD have been limited, with some inconsistencies in terms of results. In particular, there has been a lack of controlled laboratory evaluations as well as full-scale evaluations. Similar conclusions were referred to by Syafiuddin and Boopathy (2021) [122] who stated that more studies are needed to improve the performance of anaerobic sludge digestion in reducing ARGs that are difficult to handle and also differentiate between extracellular (eARGs) and intracellular ARGs (iARGs) to achieve more accurate quantification of the ARGs.

Storing and applying digestate can result in the emission of odorous compounds, contributing to unpleasant odors in surrounding areas. Emissions of these odors can lead to community discomfort and negatively impact the quality of life for nearby residents. Further R&I should be conducted on measuring odors and on the effectiveness of odor control measures such as biofilters, activated carbon filters, or chemical additives applied during digestate storage and application. In addition to odour leakage, also fugitive emissions of biogas from digestate storage

require attention both for their environmental impact as well as their impact on production losses [123].

Air pollution, specifically the release of ammonia (NH3) and volatile organic compounds (VOCs), may occur during both digestate land application and storage. Nonetheless, it is important to nuance that in livestock farming, the management of effluents (from animal housing to storage) is a source of emissions due to the high fermentability of the organic matter they contain. Therefore, the immediate transfer of manure to anaerobic digesters results in a significant reduction in emissions during subsequent storage and agricultural use, besides maximising biogas production. For this reason, a number of measures to reduce emissions have been developed at all stages of the farming process.

Reducing ammonia emissions during the process of spreading digestate involves a comprehensive approach that combines both low emission technologies and effective best practices. These strategies are pivotal in not only minimising the environmental impacts but also in optimising the management of nutrients. Mitigation measures towards application on land include: digestate injection into the soil, real-time nutrient monitoring, and precision agriculture methods. Acidifying digestate in storage, before or during application, can be employed to shift the chemical equilibrium away from dissolved NH3 towards non-volatile NH4+, thereby decreasing emissions [124]. In addition, microbial inhibitors can play a role in reducing methane slip from storage and application.



3.

Recommendations for Further Research

3 Recommendations for further research

3.1 Agronomic use of digestate

- The effective organic carbon (EOC) after amendment of digestate derived products and their forecasted build-up requires robust models and field-scale validation of such models over sufficiently long periods (years to decades). In this, also the net increase of EOC compared to a baseline of direct application of undigested manure needs to be assessed to determine effective gains in carbon sequestration. This line of research needs to feed and substantiate "carbon farming" principles and ambitions.
- Fertiliser replacement value (FRV) of digestate or liquid fraction of digestate needs to be better understood from soil nitrogen dynamics and crop availability perspective. This in order to better understand the substitution potential of synthetic chemical fertilisers – at the moment liquid fractions are found to have a chemical fertiliser substitution potential but this needs to be further corroborated. This line of research needs to assess nutrient use efficiency of digestates in raw form or with minimal treatment (mechanical separation) with expected crop uptake as opposed to potential losses to the environment.
- Combined use of precision farming techniques (sensors, telemetric visualisation using drones or satellite imagery, variable rate application etc.) with the inherent heterogeneous nature of digestate (in terms of composition) needs to be researched. The combination with precision agriculture, can help to address the current 'handicap' these digestates face compared to synthetic chemical fertilisers, as being themselves unformulated and unstandardised products in terms of composition.

3.2 Mineral nutrient extraction and valorisation

- At the level of nutrient extraction, much focus has been placed on N and P recovery techniques, yet by comparison less attention has been paid to recovery of other (micro-) nutrients. An expansion on the minerals being investigated and assessed for recovery and re-use is therefore merited in the upcoming periods – including K, S, Ca, Mg, Mn, Fe, Cu, Zn, B, Co, Mo.
- Even though N and P recovery has been studied in more detail than other minerals, still remaining research gaps and opportunities need to be addressed also for these two macro nutrients.
    - In terms of Nitrogen, technologies based on adsorption, membrane systems or bioelectrochemical systems are still in lower TRL.
    - Technologies focusing on Phosphorus can further expand on the various possible precipitates beyond struvite (e.g. vivianite, brushite…).
    - Also, more research is needed to extract P from solid fractions so one that the resulting OC rich soil enhancers after P-extraction could be used as soil enhancer and the recovered P be valorised separately as a mineral fertiliser. Rationale for this required decoupling of P and OC from solid fractions, is the current high P saturation status in agricultural soils in agro-intensive regions (so no to little extra

P required), while these soils do require additional SOC from such solid fractions to increase soil health.

- Also, mass balances and crop balances of the various minerals needs further scrutiny. For example, when applying digestate derived products based on macro-nutrient crop requirement, other elements might be added in insufficient amounts (requiring additional fertilisers) or in excess (leading to accumulation).
- This soil and crop-based information needs to be translated in more refined digestate treatment processes that result in Tailor Made Fertilisers (TMFs) which are more closely related to the complex crop and site-specific fertilisation requirements for each of wide range of the abovementioned mineral nutrients.
- Combination of thermochemic (pyrolysis, gasification, HTC) in conjunction with anaerobic digestion has received increasing attention and cascades of biological, thermochemical and/or electrobiochemical processes form a largely under-explored research domain.

3.3 Extraction of other valuable compounds

- Biostimulating effects of organic substances present in digestate in terms of stress alleviation or increased nutrient use efficiency are at the moment insufficiently understood from a mechanistic perspective. Most existing evidence of significant stimulating effects in existing scientific and commercial literature are empirical in nature without fully understanding yet the underlying principles of induced stimulations.
- Fermented or digested biomass produce a wide range of organics, such as volatile fatty acids, which have economic uses within and outside of conventional agriculture. Compounds such as acetic acid, (iso)butyric acid, propionic acid, valeric acid, all can be considered as platform chemicals for further valorisation pathways.

3.4 Microbial valorisation of digestate

The potential use of digestate for microbial cultivation in form of fungal or bacterial biorefineries, for production of enzymes or other added-value compounds.

Future studies are needed to investigate the potential of digestate in a biorefinery with the aim of obtaining:

- Microbial active biomass to be used in agriculture as microbial biostimulant (fertilisers) or biocontrol agents (plant protection).
- New drug discovery. Microbes fermenting digestate might produce bioactive molecules for medical and/or agriculture applications (agrochemicals).
- Organic acids in chemical, food, and pharmaceutical industries. Recently, crude extract containing citric acid was used for bioleaching of precious metal from RAEE [125].
- Enzymes (cellulase, amylase, xylanase, maltase, laccase, protease, alone or in cocktails [126]) for a wide range of industrial applications.
- Engineered composite construction biomaterials
- Mushroom production

- Another microbial pathway potentially stemming from digestate or digestate-derived nutrients is associated with micro-algae production [127], [128]. Although the authors validated the combinations of AD and algal technologies, there still remains uncertainty relating to food safety on the final applicability of algal biomass grown on digestate. Bauer et al. (2021) [129] provided an overview of the challenges and prospects of digestate as a sustainable nutrient source for microalgae. Further research is therefore needed to reconcile real and perceived risks associated with this end use. Other non-food endpoints are also being considered, such as use as fertiliser, biofuels and biostimulants [130].

3.5 Trans-sectoral use of digestate

In the previous chapter, a non-limitative number of alternative uses of digestate has been mentioned. In reality, the alternative non-agricultural uses has been largely un-explored at this stage. Considering the vast amounts of digestate being produced and the indicative values this bulk resource can hold for biobased materials or other non-agricultural endpoints therefore requires further research in a broad range of possible pathways.

3.6 Economic optimisation and social acceptance

Future technico-economic research on the volorisation of "fertilisers from digestate" should focus on:

- Cost reduction in fertilisation by completely replacing synthetic fertilisers with biogas-derived products. effects of the conflict in Ukraine/gas crisis, there has also been a staggering increase in the price of nitrogen fertilisers.
- Investing in technological innovation/machinery/efficient machine equipment for agronomic distribution for maximum operation capacity in precision agriculture. The synergy between innovations in precision agriculture and the opportunities (and challenges) of utilising and valorising biobased products, which in origin tend be heterogeneous in nature, offers multiple win-wins in environmental and techno-economic systemic improvements of the entire agro-food value chain.
- Marketing effect by promoting regenerative agriculture that utilises renewable resources, specifically the use of renewable fertilisers and the elimination of synthetic fertilisers.
- Introduction within biogas systems for the production, valorisation, and distribution of renewable fertilisers derived from AD, centralised and through consortia, to promote sustainable agricultural systems (precision farming and conservation agriculture) thus moving towards approaches that lead to reduced waste management and fertilisation costs for farmers.

Over the course of recent years, the drive to further economically optimise biogas operations with due attention to digestate management within this, has gained additional impetus due to the Russian aggression in Ukraine. The drive towards energy self-sufficiency and thereby replacement of Russian NG by home-grown biogas is one aspect, but the fact is that Europe has been overly dependent on Russia (and others) for NPK fertilisers too, while these market needs can be (partially) substituted by raw or further refined digestate.

In terms of social and societal acceptance, the high value is clear for those dealing with digestate yet is less known and less appreciated by those further away from this general topic. Acceptance amongst end-users and policy makers should be further researched and understood in relation to available scientific evidence and demonstration, but also quality assurances guaranteed through sound monitoring schemes in place. Such systems also require due attention for dealing with emerging pollutants and attention to overlooked performance indicators such as soil quality and biodiversity.

Policy and legislation in themselves are not research objectives. Nonetheless, lessons learned from EU projects need to find a productive way of engaging and supporting policy makers at European and national level. The legislative framework related to biobased products, including digestate at the moment is in ongoing flux of changes to stimulate a transition towards a more sustainable and more circular society. Some frameworks are under evaluation or revision; others (such as the FPR) have a continuous eye for adopting innovations and developments in the market, and yet other frameworks appear to be in need of changes in order to meet requirements arising due to emerging threats and opportunities.

As evidenced in section 1.2 above, there already exists a significant and bold body of legislation at EU level affecting digestate and its possible uses. As several streams of research explore alternative pathways of valorisation, a general policy could favour legislation that remains flexible and becomes an enabling factor, rather than just a controlling means. Without removing boundaries that are necessary to protect human and animal health, prevent pollution and maintain the equilibrium of ecosystems, for digestate research, development and experimentation, EU legislation could create regulatory 'sandboxes' as has happened in other fields where uncertainty due to technological complexity and speed of development suggested a more cautious approach. An experimental sandbox is a controlled environment where regulatory restrictions are temporarily eased to allow for innovation and testing of new products, services, or business models. This concept is often used in sectors such as finance, technology, and education to foster innovation while managing risks. In these sandboxes, companies can experiment with new ideas without the full burden of regulatory compliance. This allows them to test the viability and safety of their innovations in a real-world setting but within a contained and monitored space.

By creating sandboxes, on the one hand researchers could enjoy a reduced burden to clear ex ante the regulatory framework in which they are supposed to work, thus favouring all possible technical solutions. On the other hand, policy makers and legislators could monitor the evolution of the technologies with the double aim of refining existing legislation (as seen above, some of the EU regulations mentioned in 1.2 are undergoing revisions) and creating better conditions for the deployment of technologies that, other things being equal, are promising in terms of improved use of digestate.

3.7 Environmental impact

Further research should be conducted to map the benefits of various digestates towards soil quality, soil health, soil biodiversity and soil organic matter, depending on the soil type and other parameters. Positive and balanced contributions in terms of organic carbon and mineral nutrient household require further investigation.

Digestate treatment systems as well as monitoring systems will require improvement to provide adequate and transparent quality assurances. In the past, quality systems in place have been based on a well-defined list of inorganic pollutants and limitative list of organics. In recent years and in various regions, novel pollutants (or long existing pollutants with emerging policy interest) have received new attention such as PFAS/PFOS, amphetamines or other compounds.

Also evaluating potential causes and solutions for the rebound in selected antimicrobial resistant genes in digestates is critical. It is important to answer questions such as: if antibiotic residues are reduced in digesters, would it also reduce resistance persistence? What is the importance/risk of mobile genetic elements in the digesters and digestate? Ultimately, however, important answers are necessary in regard to the digestates i.e. how long can resistant bacteria survive in the digestate? What is the impact of storage of digestates and how do resistant organisms from the digestate interact with the soil microorganisms if digestate is used as a fertiliser or impact on fungi growing on digestates, or impact on microbial/algae fermentations if digestates are used as a nutrient growth media?

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