EBA
European Biogas
Association

Digestate in Europe

the state of play in 2026

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Executive Summary

Digestate, the nutrient rich coproduct of anaerobic digestion (AD), is a strategic but underrecognised resource for Europe's circular bioeconomy. Its use as fertiliser and soil improver directly supports EU objectives on soil health, climate and resource efficiency. By **recirculating nutrients** and organic matter from diverse feedstocks back to fields, digestate improves nutrient use efficiency along the agrifood chain, reduces dependence on imported and fossil based fertilisers and helps rebalance regional nutrient surpluses and deficits.

In 2024, anaerobic digestion plants in Europe produced an estimated **25 million tonnes (Mt) of digestate** dry matter (DM), mainly from agricultural feedstocks with manure as the key substrate **(60%)**. Around three quarters of European digestate is applied directly to agricultural land, with a further 20% applied after upgrading, confirming that land application remains the dominant outlet.

This digestate contains roughly **1.7 Mt of nitrogen (N), 0.3 Mt of phosphorus (P)** and **0.2 Mt of potassium (K)**. Today's digestate streams could technically replace more than **16% of mineral N** fertilisers used in European agriculture, and up to 30% and 10% of P and K respectively, with a combined environmental and nutrient value of over **€1 billion** per year. Europe's biogas sector could in total generate around 177 Mt DM of fertilisers from nutrient rich waste streams as secondary raw materials. The nutrient potential of digestate is projected to reach around **9.7 Mt N, 1.7 Mt P** and **0.8 Mt K** by **2050**.

Economically, digestate management is a core driver of biogas plant viability. The paper shows that logistics and storage typically account for a substantial share of digestate related operating costs, especially for plants with high volumes and long transport distances. Where digestate can be used locally on farms, its value is often realised through avoided mineral fertiliser purchases and more efficient nutrient management rather than through direct product sales. In contrast, larger centralised or industrial plants increasingly depend on organised business models and, where possible, upgraded digestate products with clearer market status.

The analysis confirms that digestate is not a residual waste stream but a high-value, multifunctional product in its own right linking renewable energy generation with circular nutrient management, soil health and farm economics. Realising this potential will require that EU and national frameworks on soils, fertilisers, nutrients and waste consistently recognise digestate based products as mainstream solution and facilitate their use.

Glossary/Definitions

AD	Anaerobic Digestion
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CO_2	Carbon Dioxide
DM	Dry Matter
FM	Fresh Matter
FPR	Fertilising Products Regulation
K	Potassium
LCA	Life Cycle Analysis
LF	Liquid Fraction
MAP	Magnesium Ammonium Phosphate
MS	Member States
Mt	Million Tonnes
N	Nitrogen
NF	Nanofiltration
NUE	Nitrogen Use Efficiency
NVZ	Nitrate Vulnerable Zone
OFMSW	Organic Fraction of Municipal Solid Waste
OPEX	Operational Expenditure
P	Phosphorus
RO	Reverse Osmosis
ROI	Return on Investment
SDG	Sustainable Development Goal
SF	Solid Fraction
S/L	Solid/Liquid
SOM	Soil Organic Matter
TN	Total Nitrogen
TOC	Total Organic Carbon
UF	Ultrafiltration
WWTP	Waste Water Treatment Plants

Digestate

Nutrient-rich fraction originated and co-produced from AD and valuable organo-mineral fertiliser composed of mineral (inorganic) macro- and micro-nutrients, used to fertilise soil at high efficiency with recirculated essential nutrients alongside organic matter. The liquid clarified level after solid-liquid separation represents the "equal" equivalent, analogous and assimilable to conventional chemical and mineral fertilisers for plant growth. It is thus associated with reducing dependence on non-renewable resources, promoting a circular bioeconomy and mitigating the environmental impact of nutrients, particularly nitrogen losses.

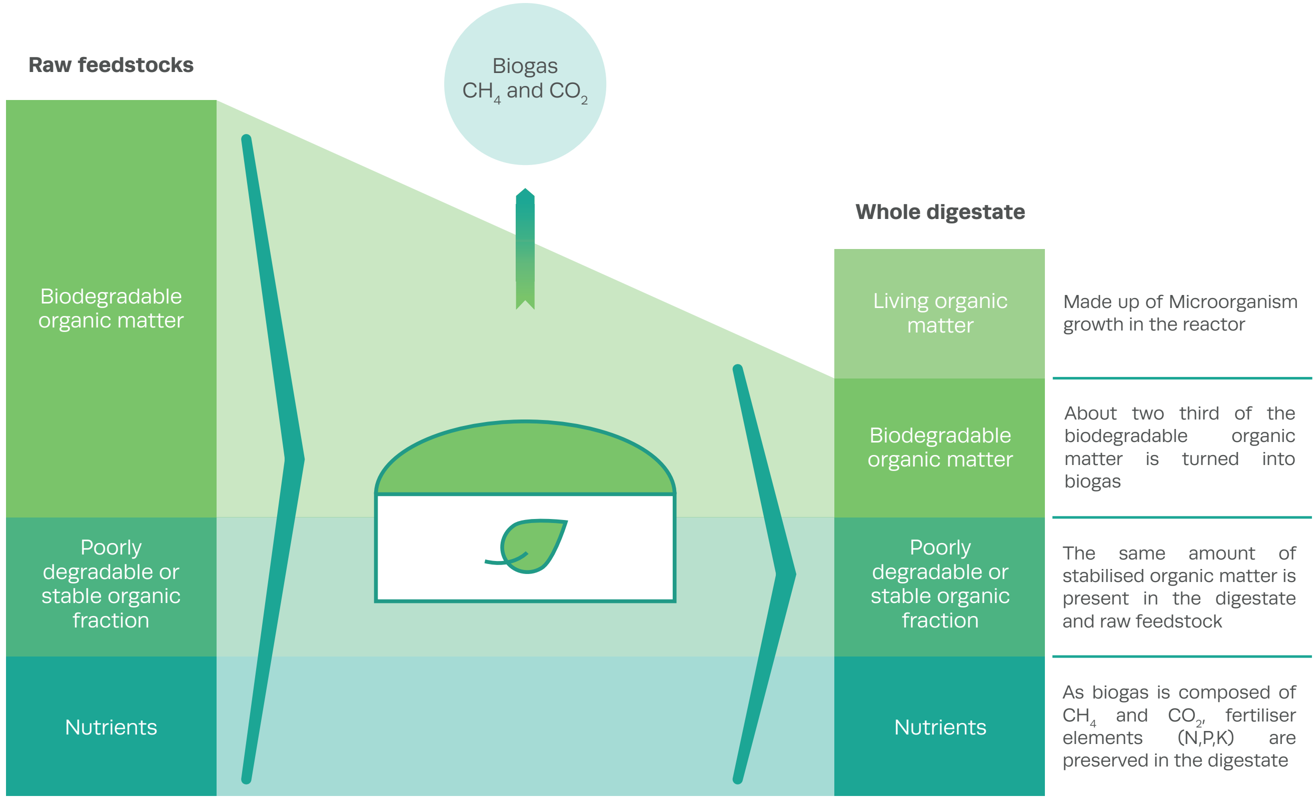
Petrochemical fertilisers

Conventional mineral (inorganic) fertilisers that are industrially manufactured/synthetised, formulated and produced from non-renewable sources through non-renewable energy and intensive chemical processes (such as Haber-Bosch) and/or extracted from mineral deposits. They are used to supply essential nutrients for plant growth but are associated with significant carbon emissions.

I. Introduction: the role of digestate in the circular bioeconomy

Producing digestate through AD addresses multiple interconnected societal challenges, contributing to circular bioeconomy mechanisms across environmental, economic, resource security and regulatory fields, while primarily supporting agricultural fertilisation. Digestate contributes to multiple United Nations (UN) **Sustainable Development Goals (SDGs)**: SDG 2 – food security and sustainable agriculture; SDG 6 – clean water and water resilience; SDG 8 – sustainable economic growth; SDG 9 – resilient infrastructure and sustainable industrialisation; SDG 11 – sustainable cities; SDG 13 – climate change mitigation; SDG 15 – ecosystems and biodiversity. [1]

Digestate improves the management of nitrogen and phosphorus along the agri food chain, helping to reduce pollution, **protect ecosystems** and **support food security**. The EU circular bioeconomy prioritises bio-based solutions with the highest added value and positive externalities, at a time when fertiliser raw material supply is uncertain and prices are volatile. In this context, biogas systems, with their **valuable co-products**, exemplify circularity by delivering benefits crucial for climate mitigation and industrial and agricultural competitiveness, **offering farmers and businesses new revenue streams.** By turning nutrient-rich streams into valuable residue-based fertilising products with **excellent agronomic properties**, the process maximises resource recovery and soil health. Nutrients in the feedstock are converted into **readily plant-available forms in the digestate,** resulting in higher nutrient use efficiency than raw feedstock. Europe's biogas sector could generate around 177 Mt dry matter of fertilisers from nutrient-rich waste streams as secondary raw material, technically able to displace more energy-intensive options.



What happens in digester (Source: reworked from 'L' utilisation des digestats en agriculture') [2]

Recirculating nutrients [3] [4] within the biomass and agricultural system enables a closed-loop cycle, boosts **on-farm circularity** and reduces dependence on petrochemical fertilisers, supporting a more resilient EU supply of long-term effective fertilisers.

By **decreasing the need for petrochemical-based fertilisers** (whose production via the Haber-Bosch process accounts for 1.4% of global CO_2 emissions) [5], digestate reduces environmental harm associated with their overuse (soil degradation and water pollution) and **lessens reliance on linear nutrient resources** by reintegrating N, P and organic matter back into agricultural systems.

Nitrogen pollution imposes a heavy financial and environmental burden across the EU, with annual costs estimated between €70 and €320 billion [6]. Yet smarter fertilisation practices show significant potential to reverse this trend [i] [7]

Beyond its fertilising value, digestate application has also been shown to improve a range of **soil-health** indicators, including build-up of soil organic carbon (SOC) and humus precursors, thus increasing the stable fraction of soil organic matter [ii]. These effects are primarily driven by cumulative digestate-C inputs and reduced endogenous SOC mineralisation (negative priming) [8] [9]. Other long-term trials indicate that digestate can increase soil aggregate stability by up to 36%, thus supporting better soil physical properties [10]. This, in turn, improves the capacity of soil to retain nutrients, with enhanced soil structure, soil aeration and ability to retain moisture. Further research is still needed to better understand climate dependent responses and to confirm these effects over periods exceeding ten years.

Better carbon content in soils also increases their **water storage capacity**, reducing the need for irrigation, offering a natural buffer against water shortages. Better water retention not only helps crops withstand periods of drought, but also minimises water runoff and soil erosion (common issues in conventional farming based on petrochemical-based fertilisers). This supports **agricultural productivity** and stable crop yields, even in challenging climatic conditions.

Together, these findings demonstrate that digestate can serve as **a dual-purpose tool for nutrient recycling and soil regeneration**, reinforcing its value as a cornerstone of sustainable farming systems.

Using local organic waste as feedstock enables **farmers and rural businesses** to diversify income, fosters energy independence and encourages community-driven circular energy solutions. This aligns with the sustainable agriculture goal in creating **resilient green industries and job opportunities**, generating skilled employment, including research and development roles and activities. Advances in treatment processes, improved management practices and new end-use applications, combined with synergies in circularity and sustainable agriculture, deliver **climate, environmental and landscape benefits.** Importantly, as digestate quality depends on input materials, **efficient separate collection of organic waste** in **urban** areas improves **waste management** while supplying high quality feedstock to **rural** biogas plants, reinforcing circular bioeconomy links between town and countryside.

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[i] Evidence from Denmark indicates that applying precision fertilisation could raise economic returns by €37.57/ha (6.2% improvement), while simultaneously generating a 2.8% gain in climate benefit

[ii] Several field studies have shown that repeated long-term digestate application increases SOC stocks in low-carbon soils by approximately 0.8 mg ha^{-1} yr^{-1} , likely an underestimate due to deeper soil layers not being accounted for

In summary, when biogas plants operate as hubs that aggregate nutrients by receiving biomass from multiple, geographically dispersed sources, they create opportunities for more **efficient nutrient redistribution**. Effective digestate managment [3, 4] can help reduce regional nutrient imbalances, mitigating surpluses in livestock-dense areas while alleviating nutrient deficits in crop-intensive regions. Effectively utilizing digestate in farming, particularly as a biofertiliser, not only supports the expansion of biogas and biomethane production but also helps advance progress toward EU and MS biomethane targets.

Despite these long documented benefits, the role of digestate is still not fully recognised in integrated policies on soils, nutrients and fertilising products, limiting its contribution to sustainable agriculture and the circular bioeconomy.

II. Overview of digestate production and application in Europe

2.1 Production

According to the EBA database[iii], an estimated 25 million tonnes (Mt) of dry matter (DM) digestate were produced in Europe in 2024, equivalent to 450 Mt of fresh matter (FM) (see Table A1 in the Appendix). Figure 2 presents the share of digestate types by feedstock source in each country.

The data reveal two main patterns in digestate composition, reflecting the dominant feedstock categories used in AD. **Agricultural feedstocks** form the backbone of biogas and digestate production across Europe, accounting for more than half of total digestate generated (FM basis). Within this category, manure is the key substrate, representing around 60% of agricultural feedstocks (about 135 Mt FM), with the remainder supplied by sequential crops and energy crops. Manure based digestate can be further broken down into approximately 13.9–42.3 Mt of pig manure digestate, 59.9–88.9 Mt of cattle manure digestate and 7–10 Mt of poultry manure digestate (Figure 3). Germany, France, Czechia, Italy and Denmark rely predominantly on these agricultural feedstocks, with energy crops now playing only a minor role (less than 3.5% in Denmark, for example, with the complete exclusion of maize).

Italy and Switzerland have well developed, **separate collection of organic municipal solid waste**, and a large share of this stream is treated via anaerobic digestion. As a result, in relative terms, up to around 70% of their digestate originates from organic municipal waste. In absolute terms, however, the United Kingdom stands out alongside Germany: nearly 5 Mt FM of digestate is produced from organic municipal waste in the UK, followed by Italy and Finland.

High volumes of digestate derived from **sewage sludge** are reported in Estonia and Lithuania. Sewage sludge is also an important feedstock in the UK, Spain, the Netherlands and Finland, in addition to Germany, and together these countries generate over 100 Mt FM of sludge based digestate. Processed **food industry residues** are mainly treated in Belgium, where they represent the primary input material, and they also serve as a major substrate in Denmark, Ireland, Sweden and Ukraine.

[iii] A standardised data collection procedure has been conducted annually among EBA members. This effort has resulted in a continuously updated database with industry statistics on production, consumption trends, technologies, grid connection, etc.

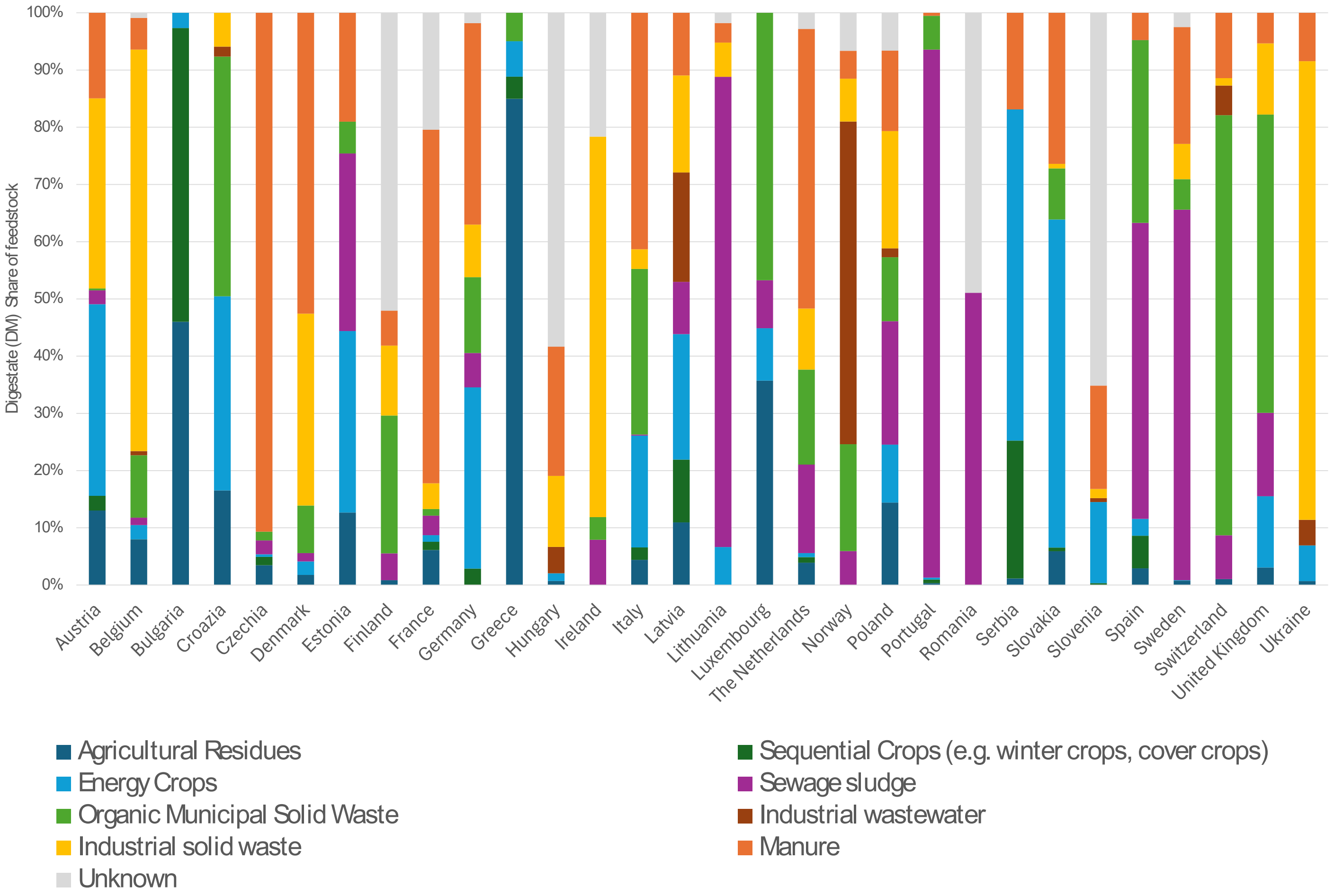

Figure 2 Share (%) of digestate types by feedstock source per country (DM basis) in 2024

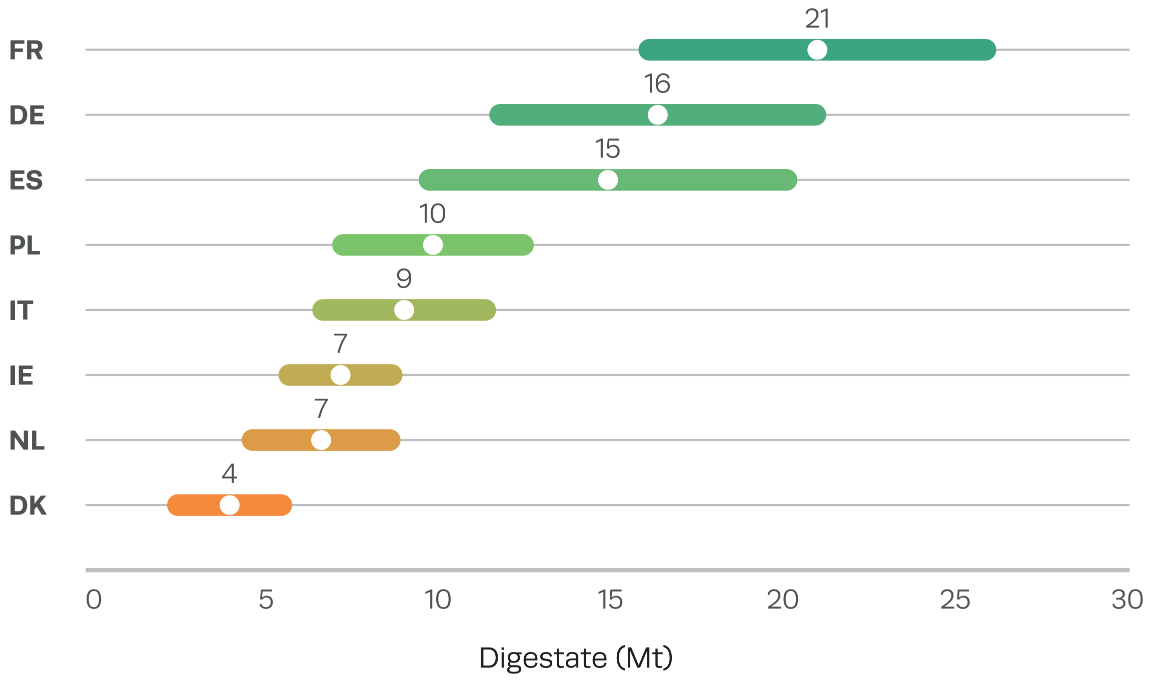

Figure 3 Estimated production of digestate (Mt) from cattle manure (FM basis) in 2024, selected countries [11]

2.2 Application

Aggregated data for Europe show that at present, approximately 75% of digestate is applied directly to soil in raw, unseparated form, serving simultaneously as both fertiliser and soil improver. About 20% is applied to the soil after upgrading, including solid–liquid separation, although details of the defined FPR or national product category are currently unknown. A share of 3%, in raw form or after upgrading, is exported and minor fractions are processed biologically (Figure 4). The share of digestate used as fertiliser depends on the country and contextual business models linked to **geospatial regulations for digestate application and location-specific environmental risks** (as discussed later).

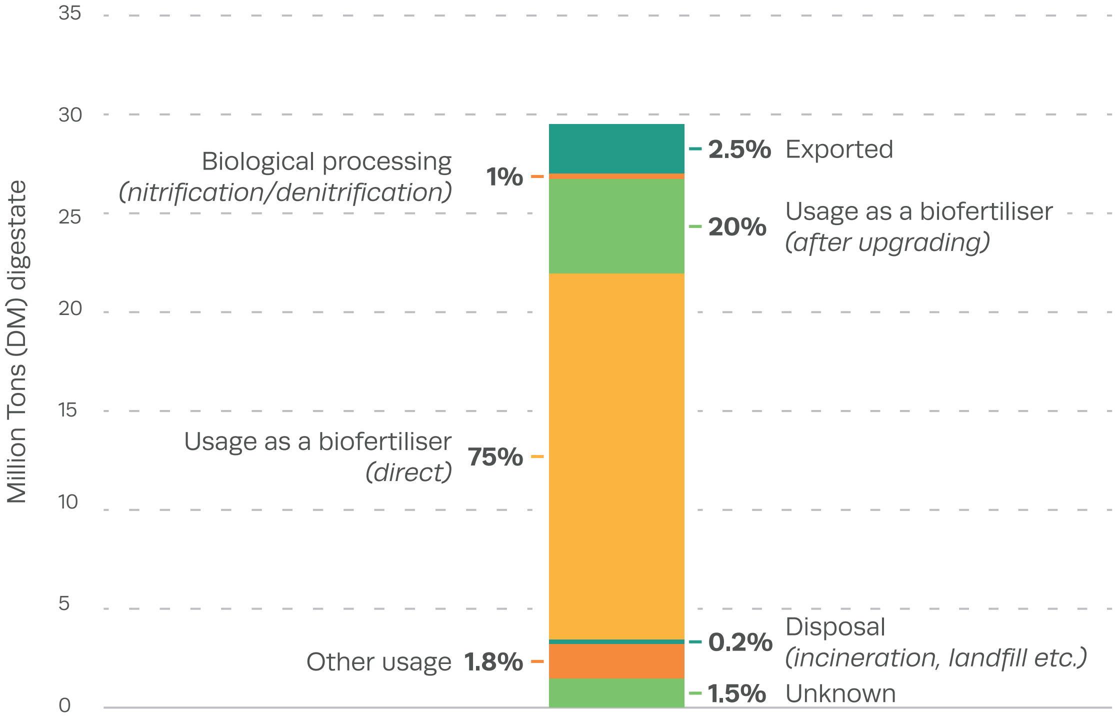

Figure 4 Digestate end uses in Europe

Additionally, digestate potential extends far beyond agriculture. Its nutrient-rich liquid fraction can act as a medium for **microalgae cultivation**, generating lipids, biomass for biofuels, proteins and bioplastics. Other emerging applications – such as **electrochemical processes** [12] **and volatile fatty acid (VFA) production** [13] – are not covered here, but represent fast-developing pathways for circular resource valorisation. Liquid digestate also shows promise as a **pretreatment agent** to boost biogas yields from lignocellulosic feedstocks, and even aids bioplastic digestion, creating added value for municipal organic waste management [14]. A particularly promising avenue lies in phosphorus recovery, where **vivianite** extracted from digestate or sludge can serve as a precursor for lithium iron phosphate (LFP) cathodes in cobalt-free batteries [15] [16]. Projects like Water4All [17] have already demonstrated this link between nutrient recovery and next generation clean energy materials.

III. Overview of digestate processing and nutrient recovery

Digestate can be used directly (raw digestate) or mechanically separated into solid and liquid fractions to enable targeted **nutrient management and reduce logistical costs** (as discussed later). Digestate contains both a readily degradable, labile organic fraction and a more stable organic matter fraction, which explains its dual agronomic function. The labile fraction, including ammonium nitrogen, provides nutrients that are readily available to crops, often in higher proportions than in untreated livestock effluents due to the mineralisation processes occurring during AD [18]. At the same time, the more stable organic matter fraction contributes to soil organic carbon pools, supporting soil structure [19] (Figure 5).

In contrast, mineral fertilisers supply nutrients in fully soluble forms and primarily address short-term plant nutritional needs, without contributing to soil organic matter. Overall, digestate can simultaneously provide readily available nutrients and contribute to soil quality, with agronomic practices adapted to its composition.

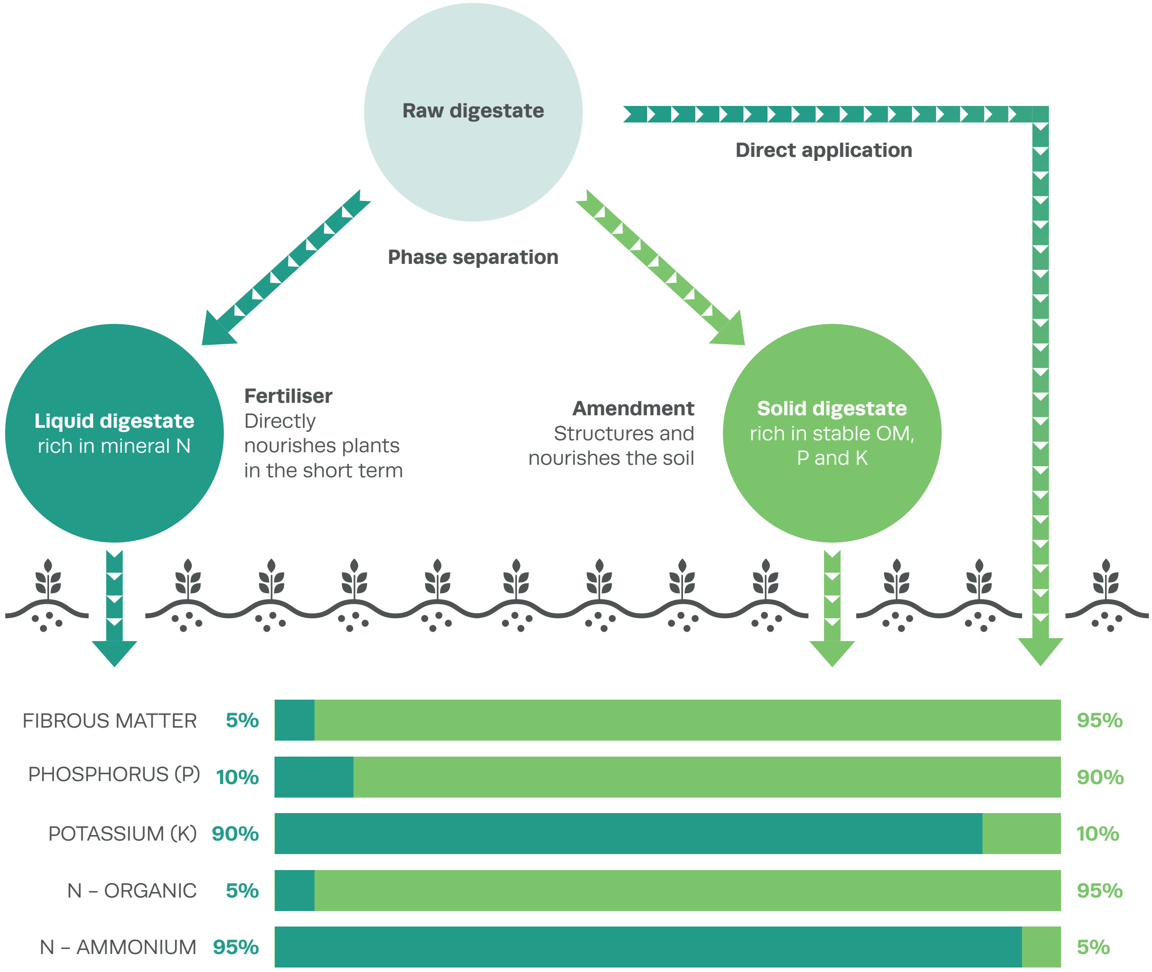

Figure 5 Digestate valorisation pathways with separation into a solid and liquid fraction. (Source: reworked from 'L' utilisation des digestats en agriculture') [2]

Typically, the liquid fraction represents between 70% and 97% of whole digestate, depending on the separation technology used. For the purposes of this analysis, an average share has been applied to total digestate quantities per feedstock category and then aggregated at Member State and European level, as shown in Table 1.

Table 1 Estimated raw digestate, solid and liquid fractions in Europe (Mt FM/year), based on combined biogas and biomethane production per feedstock category in 2024

Feedstock [iv]	Raw digestate (Mt)	Solid fraction (Mt)	Liquid fraction (Mt)
AGR tot	230–236	7–69	161–229
MAN	*135–142*	*11–41*	*94–131*
EN	*68–69*	*2–3*	*65–67*
SEQ	*10–12*	*2–3*	*7–10*
RES	*12–15*	*3–4*	*8–12*
OFMSW	17–18	2–5	12–16
IND	21–29	6–9	12–23
SEW	139–154	19–42	97–135
UNK	5.6–6	1–2	4–5
TOTAL	**408–464**	**13–122**	**300–400**

Various digestate treatment methods are used to extract valuable products and key nutrients for biobased fertilisers [20]. **Separation** is typically carried out most efficiently mechanically, using decanter centrifuges, rotary drum, screw presses, or belt filters, sometimes physically by evaporation or chemically supported by coagulants or flocculants, with substrate type strongly influencing separation efficiency.

For dewatering to above 30% DM and to produce water suitable for reuse, flocculants are often used to neutralise the anionic charge of digestate, form flocs and enhance centrifuge performance. Centrifuges usually separate more dry matter and total phosphorus than screw presses, although screw presses consume considerably less energy (around 4.5 times less) [21]. After mechanical separation [22], phosphorus (P) tends to concentrate in the **solid fraction** (SF), while nitrogen (N) remains in the **liquid fraction** (LF) and potassium (K) is found in both fractions. Separation efficiency depends on feedstock composition with high-fibre materials input improving dewaterability. See common commercialised technologies for nitrogen (N) and phosphorus (P) recovery in Table 2.

The solid fraction, rich in carbon (C) and phosphorus, is well suited to several downstream uses (e.g. soil conditioner) and can undergo treatments such as drying and composting. It may also be further processed into pellet form or briquettes to facilitate storage, transport and market uptake. Due to its high P content, the SF is exported out of vulnerable zones after being dried or composted and subjected to valorisation pathways (e.g. precipitation).

The liquid fraction, rich in N, may be directly applied as fertiliser or further upgraded through nutrient concentration technologies, using es-

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[iv] Definitions: AGR is short for agriculture, i.e. all substrates related to agricultural production. This includes manure and other residues, such as straw, husks and cobs stripped of kernels of corn; sequential crops that are grown before or after the main crop, such as cover crops or catch crops and other fresh crops, or primary crops. The following abbreviations are used: manure (MAN); monocrops (EN); sequential crops (SEQ); organic fraction of municipal solid waste (OFMSW); industrial food and waste and industrial organic waste (e.g. from the food and beverage industry (IND); sewage sludge (SEW); unknown (UNK)

tablished options extensively explored and documented by plant operators. It is a valuable resource for farmers but, depending on volume and transport distance, can create storage and logistics challenges that affect the overall viability of AD plants.

Additionally, pre- or post-treatment conditioning, including chemical (e.g. acidification or alkaline stabilisation) and biological processes for the solid fraction (e.g. composting), improves storage stability, hygiene and regulatory compliance.

Table 2 Common commercialised technologies for nitrogen (N) and phosphorus (P) recovery

Technology		Products
N recovery	· Gas stripping · Membrane	Ammonium sulphate $(NH_4)_2SO_4$, concentrated N solutions
P recovery	· Chemical precipitation · Chemical extraction	Struvite, PO_4 solutions, P salts, or concentrated (P or P_2O_5)
N & P recovery	· Membrane · Ion exchange	concentrated and/or precipitates

Digestate processing is a dynamic area of technological development in the biogas value chain, offering opportunities to improve nutrient recovery [23], optimise logistics and substitute carbon intensive mineral fertilisers. However, these innovations rely on adequate investment and a supportive regulatory framework for placing recycled materials on the fertiliser market.

In practice, digestate management (including storage) is a core element of plant operation, aiming to stabilise the material leaving the digester, separate the liquid fraction, improve handling and enhance market uptake. Although many pathogens are inactivated during anaerobic digestion, pasteurisation (hygienisation) [v] may still be required for some feedstock types to comply with sanitary standards [24]. Where fertiliser use is restricted or quality is insufficient for land application (e.g. sewage sludge from wastewater treatment plants or unsorted municipal solid waste), digestate may be used for energy purposes, for example by co combustion. The chosen management and application strategy ultimately depends on regulatory requirements, local nutrient balances and economic considerations.

Tables 3 and 4 summarise the main technological options currently used in Europe to process the liquid and solid fractions of digestate, including the treatment's purpose, operating principle, level of technological maturity and key performance characteristics.

RENURE: It is important to note that all three livestock manure-based products discussed in this section (ammonium salts, mineral concentrates and struvite) are covered by the RENURE amendment [25] to the Nitrates Directive, which was formally adopted by the European Commission on 9 February 2026. The amendment [26] provides an option for Member States to allow the use of RENURE fertilisers, beyond the Nitrates Directive limit of 170 kg N/ha/year (up to +80 kg N/ha), in exchange for additional quality and environmental safeguards. [27]

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[v] The pasteurisation conditions depend on the regions, typically involve heating at 70 °C for 1 hour or similar (24 hours at 60 °C)

Table 3 Treatment technologies – Liquid fraction of digestate

Treatment technology	Main principle	Maturity/deployment	Key products/ performance
Ammonia stripping and scrubbing	Chemical-physical process to recover **N** from the LF by increasing T (≈70 °C) and pH (≈10), **stripping NH_3** into a gas stream and scrubbing it (e.g. sulphuric acid, carbon dioxide)	Mature and widely deployed in Europe, with TRL 8–9, used in several demo and full-scale plants	Produces marketable ammonium sulphate solution; demonstrated N recovery as **ammonium sulphate** around 20% (depending on design). Helps comply with N limits (e.g. NVZs) [vi] [vii] reduces storage/transport costs and supports nitrogen autonomy [viii] [28] [29] [30] [31]
Struvite precipitation	Chemical-physical process to recover P by adding Mg and adjusting pH, with **crystallisation of struvite** (MAP, $NH_4MgPO_4 \cdot 6H_2O$)	Most popular P recovery route in Europe, and mainly applied as a practical solution post digestion in WWTP, with TRL 8–9	Produces **P-rich struvite** that can be directly used as fertiliser; operates at costs comparable to ammonia stripping while removing PO_4^{3-} as a recoverable product [ix]
Membrane filtration	Physical separation (UF, NF, RO) to reduce digestate volume and concentrate nutrients; separates a low salt permeate (**clean water**) from a **nutrient-rich retentate**	Broadly used in Europe (around one-third of biogas plants) in stand-alone or multistage configurations with TRL 7–9	Can recover 50–80% of digestate volume as water suitable for reuse, while concentrating **N** and **K** in the retentate; supports compliance with N/P application limits and addresses land/transport constraints [x] [32]

[vi] Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources

[vii] According to EU Council Directive 91/676/EEC, the amount of livestock manure applied to land each year shall not exceed 170 kgN per hectare

[viii] Integrated with AD as closed loop “biorefinery” systems that convert slurry and biowastes into renewable N fertiliser while mitigating N surpluses and enabling circular bioeconomy approaches

[ix] Often combined with pH adjustment, CO_2 stripping and metal salt dosing

[x] Configurations range from single stage UF to UF+NF+RO trains, often integrated with solid-liquid separation, struvite and stripping

Implementation examples

Among the frontrunners for digestate **ammonia stripping** in Europe are Italy (Acqua & Sole) [30] Flanders/Belgium (Byosis, Detricon, NITROMAN project [31]. and Germany (NutriSep [xi]). Demonstrated nitrogen recovery as ammonium sulphate is currently being implemented in several demo and full-scale plants [29] [28]. This is an effective strategy that contributes to nutrient recovery while minimising environmental emissions associated with digestate management.

A high concentration of full-scale commercial plant clusters for **struvite precipitation** is found in Belgium (e.g. ***Aquafin*** Leuven WWTP) and Denmark (e.g. ***Veolia Struvia*** at Helsingør).

Leading examples of digestate valorisation using **membrane technology** include the ***Twence Zenderen*** plant (NL), which treats pig manure, producing RO permeate (discharged after polishing) and NK concentrates classified as manure/RENURE ("mineral concentrate RENURE") or further processed via stripping/evaporation to K fertiliser and ammonium solutions; products are still often perceived as "waste" and may require payment for off take. In Greece, ***BioSfer*** valorises nutrient concentrate as a marketable biofertiliser/biostimulant rich in amino acids, validated through multi year field trials.

[xi] The technology is deployed to also produce peat replacement material https://upcyclingplus.de/content/projekt.php

Table 4 Treatment technologies – Solid fraction of digestate

Treatment technology	Main principle	Maturity/ deployment	Key products/performance
Pelletising	**Mechanical densification** of SF into small, stable pellets/briquettes [33] to facilitate storage and transport. Compression improves structural integrity	**Commercial** and widely available for solid biomass and digestate pellets	Produces stable **pellets** meeting high fuel quality standards (e.g. EN ISO 17225-1 [xii]) with reduced bacterial risks and good storage stability over several months [xiii]
Pyrolysis/gasification	**Thermochemical** conversion of dried SF (<15% moisture) at high T. **Pyrolysis**: 400–600 C [34] [35] 30–180 mins, no O_2. **Gasification**: 650–950 C, few mins, sub-stoichiometric oxidant	**Demonstrated** at pilot and full scale for various feedstocks; deployment growing but not yet mainstream	Produces renewable oil (pyrolysis) or syngas (gasification) plus biochar. **Biochar** is dry, **P/K rich** and carbonised, suitable as soil **amendment or adsorbent**. Improves handling and value of "burdened" digestates (e.g. sewage sludge) [xiv] [36]
Hydrothermal carbonisation (HTC)	**Wet thermochemical** process at 180–280˚C for 5–120 mins under pressure, no prior drying. Water acts as solvent, solubilising N and P and transforming solids into **hydrochar**	**Emerging** but advanced, with TRL around [xv] 8	Produces **hydrochar** suitable as **soil improver or adsorbent** [xvi], and nutrient-rich process water. Hydrochar can remove heavy metals, gas impurities and organic pollutants (e.g. dyes, pharmaceuticals, pesticides) [xvii]
Hydrothermal gasification (Supercritical Water Gasification)	Treatment of very high moisture materials (≈80%) at 400–700 ˚C and 200–300 bar [xviii]. Converts organics into gas under **supercritical water conditions**, with formation of both SF and LF	At **demonstration** stage, with TRL around 6–7; strong interest for future deployment [37]	Produces a combustible gas plus nutrient containing solids and liquids (**N, P, K, minerals, metals**). Can greatly reduce or even eliminate final waste streams and supports high degrees of resource circularity [38] [39] [40] [xix]

[xii] Biocombustibles solides — Classes et spécifications des combustibles https://www.iso.org/obp/ui/#iso:std:iso:17225:-1:ed-2:v1:fr

[xiii] Addresses major bottlenecks in digestate management (logistics, odour, hygiene) and facilitates market uptake as a standardised product

[xiv] Co-application of digestate (readily available N) with biochar (retention and carbon sink) offers a circular solution and higher end user acceptance. Example: FENIX project testing field applications. Trade-offs include high energy demand, N losses and reduced short term fertiliser value

[xv] Demonstrated at TRL 8 during the EU project Incover. https://incover-project.eu/bio-products/biochar

[xvi] Biochar can also be recycled after activation for treatment of wastewater and drinking water, thus being integrated within biogas production, cleaning and upgrading during the purification steps as adsorbent for hydrogen sulphide and carbon dioxide, thanks to its intrinsic physicochemical properties such aromaticity, porosity, alkalinity and hydrophobicity

[xvii] Avoids energy intensive drying, suitable for high moisture feedstocks. Offers combined waste treatment and production of sorbent materials, but downstream handling of nutrient rich liquors is still critical

[xviii] Supercritical fluid: a fluid heated above its critical temperature and compressed above its critical pressure without becoming a solid (for water > 374 ˚C and > 221 bar)

[xix] Considered as an alternative to incineration for sludge and digestate. Switzerland is a pioneer, with mandatory phosphorus recovery from sludge/digestate from 2026 driving this route. Integration with P recovery policies is a key driver

IV. Digestate as a petrochemical fertiliser alternative

4.1 Impact potential

Biomass used in AD contains nutrients originating from soil, therefore **energy production would lead to a net removal of nitrogen, phosphorus, potassium and organic matter from agricultural systems** if not returned to the soil in the form of digestate. Instead, the **recirculation of digestate within agricultural systems preserves the nutrient cycle**, allowing energy generation without depleting soil fertility. Due to the significant variability of the inputs used, it is difficult to precisely link agronomic characteristics to the digestates produced, especially since the accurate predictor of digestate depends on N fertiliser replacement nutrient characteristics (C/N, P/N), in combination with soil properties (pH levels).

Any attempt to standardise digestate must therefore be grounded in robust, product-specific laboratory analysis and established analytical and operational practices, rather than high-level assumptions. While broad product categories provide useful orientation, actual digestate characteristics can only be determined through systematic testing.

Typical ranges for key digestate typologies were identified in scientific literature with derived average compositions for each type. These typology based averages were then used to estimate the total amounts of nitrogen, phosphorus and potassium contained in digestate at European level. More precisely, average digestate compositions were multiplied by the total dry matter volumes of the corresponding digestate types, based on their feedstock origins. This approach was then used to summarise total digestate production per nutrient. See Table 5 and Table 6 for digestate characterisation by core source and for a more detailed breakdown of agricultural digestates by physical form and predominant feedstock origin.

Table 5 Characterisation of digestates by the various classified core sources [41]

Source [a]	DM	TOC	TN	N-NH$_4$	P	K	Ca	Mg	Reference
	g/kg FM				*g/kg DM*				
AGR	57–95	225–500	18–88	6–45	1.4–27	3.3–7	11–23	1.5–6.2	[18, 42, 43, 44]
OFMW	52–297	175–314	4–112	4–11	0.1–4.2	0.6–11	1–6	3–52	[45, 46, 47]
IND	3–20	321–398	1–40	29–75	6.9–18	2.6–9.3	6–8	3.5–12	[48, 49, 50, 51, 52, 53, 54]
SEW	0.4–5	227–300	25–46	15–36	1.4–12	2.4–4.9	10–69	3–4	[55, 56]

[a] AGR = agricultural feedstock; OFMW = organic fraction municipal solid waste; IND = industrial waste; SEW = sewage sludge

Table 6 Characterisation of digestates classified as AGR grouped by their physical form and by predominant feedstock origin (ruminant manure, non-ruminant slurry, or mainly plant-based substrates (adapted from source: AAMF)

		Main source and classes of digestate					
		Cow manure		**Pig manure**		**Crops/Plant/Residues**	
		Raw slurry	***Raw solid***	***Raw slurry***	***Raw solid***	***Raw slurry***	***Composted***
DM	*g/kg FM*	80–120	220–280	30–50	230–270	50–80	420–610
TOC	*g/kg DM*	242–513	311–550	180–600	304–435	225–560	179–471
TN		33–75 (0.47) [a]	18–32 (0.59) [a]	80–200 (0.47) [a]	33–48 (1) [a]	50–120 (0.49) [a]	13–40 (1.3) [a]
N-NH$_4$		8–25	3–9	60–133	11–22	25–60	0–7
Norg		17–50	14–27	20–67	15–26	25–60	13–36
P$_2$O$_5$		17–38	14–27	20–100	37–57	13–60	34–76
K$_2$O		42–50	16–27	40–167	7–26	38–100	13–31

[a] % of FM

Using the total digestate production number and the average digestate nutrient contents from Table 5, **digestate produced in Europe in 2024 is estimated to contain around 1.7 Mt of nitrogen (TKN), 0.3 Mt of phosphorus and 0.2 Mt of potassium** [xx]. According to Eurostat [57] [58] current agricultural use of nitrogen fertilisers in the EU is about 8.3 Mt/year, meaning today's digestate may technically reduce the need for over **16% of petrochemical-based N** [xxi] **fertilisers used in Europe**. The European Commission includes phosphorus in its list of 20 critical raw materials, and AD offers an important route to recycle it: with 0.9 Mt of P fertilisers used in 2023, digestate already provides the equivalent of around **25–30%** of mineral P use. For potassium, digestate could supply almost **10%** of current K use (this percentage is likely to increase due to a forecasted 1.4% reduction in demand by 2030). Looking ahead, the nutrient potential of digestate is projected to reach around 4.1 Mt nitrogen, 0.7 Mt phosphorus and 0.4 Mt potassium by 2030, and 9.7 Mt nitrogen, 1.7 Mt phosphorus and 0.8 Mt potassium by 2050. For a detailed breakdown of digestate production in European countries and the percentage of total digestate production based on combined biogas and biomethane production, see Table 7.

[xx] In order to estimate the replacement potential at national level, nutrient values from digestate were compared with national nitrogen and phosphorus fertiliser consumption, using the most recent Eurostat data (2023). For potassium, Eurostat does not provide directly comparable national consumption figures in its main agri environmental indicators, so an aggregate European value of 2.5 million tonnes was used as a reference. This simple nutrient based comparison offers only a first order indication of potential substitution and does not capture site specific soil conditions, agronomic practices or soil biological processes.

[xxi] Excluding ammonia volatilisation and parameters such as the nutrient fertiliser replacement value (NFRV), defined as the amount of N min. fertiliser saved by using organic N materials while achieving the same crop yield

Table 7 Country-level estimates of N and P in digestates and corresponding (%) N and P mineral fertilizer equivalent.

Country	Tonnes of mineral N in digestate [xxii]	(%) N mineral-based fertiliser equivalent	Tonnes of mineral P in digestate [xxiii]	(%) P mineral-based fertiliser equivalent
Austria	8,630	8.8	1,726	20
Belgium	14,401	13.5	2,869	72
Bulgaria	19,873	5.8	3,975	11
Croatia	375	0.43	91	1
Czechia	91,382	38.5	18,276	>100
Denmark	59,270	30.3	11,854	>100
Estonia	1,584	4.1	317	11
Finland	9,277	6.6	1,378	13
France	134,152	7.7	25,298	19
Germany	580,814	59.4	115,719	97
Greece	6,401	3.7	1,280	6
Hungary	4,586	1.7	654	3
Ireland	7,003	2.5	1,289	4
Italy	123,500	21.7	24,700	25
Latvia	2,121	2.6	424	4.2
Lithuania	5,560	4.4	1,093	6.6
Luxembourg	2,210	22.1	442	>100
Netherlands	69,007	36.5	13,724	N/A
Norway	28,857	33.2	5,718	83
Poland	45,979	4.4	8,285	7
Portugal	5,519	6.2	1,104	7
Romania	1,239	<0.5	238	<0.5
Serbia	1,716	0.7	343	N/A
Slovakia	4,512	4.2	902	11
Slovenia	487	2	97	3
Spain	62,282	8.1	12,661	12
Sweden	12,908	7	2,582	22
Switzerland	23,094	65.4	4,619	>100
United Kingdom	168,519	16.2	33,704	42
Ukraine	6,987	0.6	1,397	1
Europe	**1,516,646**		**297,206**	

[xxii] NTK tonnes (0.35% of FM digestate)

[xxiii] P tonnes (0.07% of FM digestate)

4.2 Nitrogen dynamics and soil budget

Digestate is suitable for N fertilisation, simultaneously providing P and K in line with demand, but **effective use requires management adapted to soil conditions and crop needs** [59]. Soil organic carbon constitutes about 58% of soil organic matter and directly influences the C/N ratio, affecting organic matter mineralisation and nutrient release from sources such as digestate. Efficient nitrogen mineralisation occurs when the soil C/N ratio is near 10; deviations slow organic matter degradation and reduce natural nitrogen release [xxiv].

Meta-analyses and field trials show that, when applied appropriately, digestate-based fertilisers can maintain crop yields while improving nitrogen retention and reducing losses via leaching and runoff compared with purely mineral fertilisation [60] [61]. Recent field-scale **LCA studies** using measured nitrous oxide emissions further indicate that the more stable organic nitrogen fraction in digestate can act as a slow-release pool, contributing to soil organic matter build-up rather than increasing reactive nitrogen losses [62].

Applying the digestate which results from the AD of livestock manure and organic waste generally presents a lower risk of nitrate leaching compared with untreated manure. Still, the risk of nitrate losses must always be assessed in relation to **local conditions** such as **soil type, climate and crop management**.

To ensure long-term sustainability of the agricultural sector when using digestates, **nutrient balances** [63] need to be regularly assessed to maintain soil quality and avoid losses, as negative balances reduce fertility, productivity and ultimately income for farmers. **Surpluses**, in turn, lower nutrient use efficiency, as crops do not absorb more nutrients than they need for their development, and increase the risk of environmental damage and hazards to public health when excess nutrients are dispersed into water bodies or the atmosphere.

Using FAOSTAT-based soil nutrient budgets, the relationship between current N inputs, crop uptake and digestate availability was analysed for each European country; the detailed methodology is presented in the ***«Appendix», page 39***. The resulting indicators are summarised in Table 8, which shows, for each country, average crop N uptake, current inputs from manure and mineral fertilisers, the soil N balance in a scenario without mineral N, and the digestate application rates that would be required to meet crop N demand under such a scenario. The last columns indicate the corresponding fresh matter digestate rates per hectare, the share of cropland that could theoretically be supplied with digestate, and the equivalent share of mineral N that digestate alone could provide.

This analysis shows that digestate can make a meaningful contribution to petrochemical fertiliser substitution, provided its use is aligned with regional nutrient balances, cropland availability and logistics. Its integration into broader nutrient management strategies should be taken into account, rather than treated as a simple one-to-one replacement for synthetic fertilisers.

Taking into consideration country-specific crop N uptake and reported nitrogen use efficiencies (NUE) [xxv] , and using the digestate volumes presented earlier, indicative calculations suggest that, to meet crop N requirements without mineral fertilisers, digestate application rates would typically range between 9 and 50 t FM/ha. Under these assumptions, current digestate production could potentially supply nitrogen to cover around **12% of European cropland**, independent of any additional nitrogen supplied via manure.

[xxiv] Soils rich in organic matter can provide up to 100 kg N/ha for crops, while nitrogen-fixing bacteria in certain crop roots can add up to 80 kg N/ha. In contrast, soils low in organic matter supply negligible amounts of naturally released nitrogen

[xxv] https://www.fao.org/faostat/en/#data/ESB cropland N use efficiency of 57%

The values presented here are European averages; in practice, nutrient surpluses and deficits vary significantly between regions, and fertiliser performance is strongly influenced by local soil and climate conditions. To better match crop nutrient demand across Europe, several studies and projects have combined nutrient budgets with spatial optimisation and LCA-based approaches, particularly in areas with concentrated livestock manure production, long transport distances and high recycling costs that hinder circular nutrient management. Detailed assessments at **NUTS2** level in HE projects such as Fertimanure [64] and Walnut [65] among others, as well as in the scientific literature, underline the importance of spatial variability in nutrient availability and demand [66], not only between regions but also between individual farms within the same region. Recent work from Finland [52] further shows that nutrient recovery can be integrated into regional circular bioeconomy planning to minimise transport costs for manure and digestate, limit over application of nutrients and clarify trade offs between alternative waste management strategies.

Nutrient budget indicators and substitution ratios therefore provide only a first order picture of digestate's contribution to fertilisation. They are useful to understand orders of magnitude and regional patterns, but they cannot fully capture the complexity of soil-plant-microbial interactions, carbon dynamics or the diversity of farming systems across Europe. The results presented above should therefore be seen as indicative and always considered alongside local agronomic knowledge and site specific conditions. Aligning digestate use with long term soil sustainability goals requires close collaboration with farmers and other practitioners to co-develop context appropriate management practices and to progressively build field based evidence on performance over time.

Table 8 Country-level evaluation of nitrogen balance in soil and digestate-based fertilisation per hectare as an alternative to mineral nitrogen fertiliser

Country	Crop uptake (kgN /ha)	Input N from manure (kgN /ha)	Input mineral N (kgN/ ha)	Balance (kgN/ ha-1) without N mineral fertilisation	Input N from digestate needed to meet avg. crop uptake without the use of conventional – N fertilisers (kg/ha)	Input FM digestate needed to meet the crop req. without the use of conventional – N fertilisers (t/ha)	% ha covered by digestate on total cropland surface	% N equivalent from digestate (tonne/ha) share of mineral N provided by digestate-only application per ha
Austria	88	63	72	–1.29	86	44	4	5.7
Belgium	97	168	123	86.43	69	48	10	1.3
Bulgaria	69	11	102	–46.52	57	34	5	5.3
Croatia	79	30	93	–28.82	94	40	0.4	0.5
Czechia	87	27	94	–42.14	118	43	24	26.3
Denmark	97	65	82	–19.15	113	48	15	17.9
Estonia	59	15	54	–26.59	62	30	2	3.4
Finland	37	13	63	–14.96	41	18	6	10.2
France	76	36	88	–23.51	89	38	7	8.2
Germany	94	45	82	–28.55	97	47	30	47.7
Greece	55	20	61	–21.94	65	28	2	3.2
Hungary	52	18	62	–19.78	67	26	1	1.4
Italy	43	41	60	14.64	48	22	17	19.1
Latvia	61	13	59	–34.13	68	30	1	2.2
Lithuania	68	14	55	–34.05	69	34	2	3.9
Luxembourg	59	45	158	–4.56	65	29	34	40.7
Netherlands	80	134	182	73.82	87	40	47	37
Norway	35	59	108	28.36	79	18	58	21.4
Poland	74	28	90	–24.86	76	37	4	6.3
Portugal	19	51	50	36.79	23	9	9	5.1
Romania	52	21	54	–17.17	58	26	0.2	0.2
Serbia	66	23	87	–24.34	84	33	1	0.7
Slovakia	69	17	80	–32.89	83	34	3	3.5
Slovenija	46	49	107	12.74	61	23	3	2.2
Spain	31	35	46	13.55	37	15	7	5.8
Sweden	57	28	73	–18.90	75	28	5	29.3
Switzerland	64	120	84	70.26	42	32	49	33.2
UK	99	66	172	–11.57	118	50	18	19.4
Ukraine	47	6	36	–25.62	44	24	0.25	0.6
Mean ± SD	**64±38 min. 19 max. 99**	**44±38**	**Avg. 85±36 Median 82**	**n/a**	**72±24**	**32±11**	**13**	**Min. 0.6 max. 48; Avg. 12.2 Median 6**

4.3 Best digestate practices

Ensuring that digestate can effectively replace part of petrochemical fertiliser use depends not only on its nutrient content, but also on its quality and the way it is managed and applied. Key factors include intrinsic properties (nutrient content, pH, dry and organic matter and homogeneity), health and safety parameters (pathogens, trace elements and impurities), as well as practical aspects such as ease of calculating application rates, availability of suitable machinery and farmers' confidence in the product. In several countries, guidance documents and, in some cases, mandatory analyses are used to verify compliance with threshold values and to promote appropriate agronomic use. Where non agricultural feedstocks are used, upstream control of input materials is particularly important, as changes in feedstock mix can affect dry matter, nutrient forms and therefore fertiliser performance.

Proper management after the digester is equally important to preserve fertilising potential and limit emissions. Covered, floating roof tanks, gas tight storage connected to the gas system and cooling of digestate helps minimise residual methane and ammonia losses, while sufficient hydraulic retention time with near-complete breakdown of the digestible organic matter is the most important mitigation measure contributing to its biological stability [67]. At field level, prompt incorporation or injection of the liquid fraction reduces ammonia volatilisation [68] and nitrate leaching and increases crop nitrogen use efficiency. Quality assurance and certification schemes for digestate, where they exist, can support these practices and provide farmers with clearer information on nutrient content and stability.

Advances in **digital agriculture** are making sensor based analysis and precision farming important tools for reducing nutrient losses and improving the fit between digestate supply and crop demand. Precision farming integrates **GPS guided machinery**, on the go scanners and satellite or drone imagery to monitor crops and soils in real time, and to better account for non agricultural contributions when designating vulnerable zones. These tools are gradually making digestate management more precise and viable by combining spatial and temporal data to guide day to day operations and farm planning. Platforms such as EU FAST [69] and the Cool Farm Tool [70] combine information on soils, crops, organic resources and weather under the 4R nutrient framework (right source, rate, time, place) to support calculations of soil carbon sequestration and nutrient performance.

Relevant information on best practices is covered in Exploring digestate's contribution to healthy soils [71] and more extensively in the recent BIP report [72]. Additionally, guidelines for the use of the liquid fraction of digestate were developed under the SYSTEMIC project [73] [74]. Further information on the quality criteria and standards is extensively discussed in literature [22] [75]. Most countries with a developed biogas sector have implemented frameworks which include lists of material **input feedstocks**, digestate **certification systems, quality standards and good practice guidelines** [76].

In this regard, a clear certification that communicates the rapid release fraction (mineral N) versus the slow release fraction (organic N) would help farmers calibrate application dosages and timing.

Quality assurance schemes and product certification for digestate, whether voluntary or mandatory, are in place in only a limited number of countries, such as Belgium (Flanders) [xxvi], Finland [xxvii], Germany [xxviii], Sweden [xxix] and the UK [xxx]. Regulatory frameworks aimed at guaranteeing the production of high quality digestate are also applied in Denmark [xxxi], Austria [xxxii], Switzerland, France [xxxiii], Spain [xxxiv], Italy [xxxv], Ireland [xxxvi] and the Netherlands [xxxvii]. These schemes and frameworks involve costs for analyses and audits, which can, however, be partly offset by the added value of digestate and by avoided waste permit related costs.

At the same time, the legal classification of digestate as a product, by product, waste or end of waste material differs between jurisdictions. This creates uncertainty for producers, regulators and market actors (especially smaller operators) and can complicate commercialisation, making it harder to fully unlock digestate's environmental and agronomic potential within circular economy strategies. These legal and market aspects go beyond the scope of this paper; readers are referred to previous analyses for a more detailed review of assurance programmes and schemes across Europe [77], [78]

Table 9 Guidelines for digestate liquid fraction use (source: RICICLA [79]) [74]

Parameter	Obligation/suggestion
Nitrogen	N-NH$_4^+$/TKP >70%
N/P/K	To be declared on FM and DM basis
Meso and oligoelements (e.g. Ca^{2+} Mg^{2+})	To be declared on FM and DM basis
Agronomic use	Distribution by spreading plus immediate incorporation or by direct injection
Biological stability	To ensure reduced odour emission, OM must be highly stable (i.e. low oxygen demand in 20h respirometric test (OD$_{20}$ < 100g O$_2$/kg DM/20h))
Microbiological quality	*Salmonella* spp. – absent *Escherichia coli* < 1,000 MPN

[xxvi] VLACO QAS

[xxvii] "Laatulannoite" certification, managed by Suomen Biokierto ja Biokaasu ry, in Finland

[xxviii] "Gärprodukt NawaRo" certification for digestate derived from manure and energy crops and "Gärprodukt" certification for digestate from biowaste by BGK in Germany RAL GZ 245-246

[xxix] SPC120 and REVAQ, SPCR 120 for biofertilisers operated by Avfall Sverige and REVAQ certification for digestate from sewage sludge operated by the Swedish Water & Wastewater Association. Both SPCR 120 and REVAQ are developed in close collaboration with agricultural and food organisations, e.g. the Federation of Swedish Farmers (LRF), the Swedish Food Federation, the Swedish Food Retailers Federation, the Swedish Environmental Protection Agency and the Swedish Board of Agriculture. Both SPCR 120 and REVAQ are Swedish quality assurance schemes. QAS, "Certifierad återvinning"

[xxx] PAS 110

[xxxi] Order No. 1060 of 26/07/2023 on the use of fertilisers by agriculture in the planning period 2023/2024 Gødskningsbekendtgørelsen 2023/2024 (retsinformation.dk)

[xxxii] ECN-QAS

[xxxiii] NF U44-051 (Norme Française) https://www.actu-environnement.com/ae/news/consultaiton-norme-afnor-amendements-organiques-44590.php4

[xxxiv] Royal Decree No. 506/2013 on fertiliser products (amended by 529/2023) https://www.boe.es/diario_boe/txt.php?id=BOE-A-2023-15736

[xxxv] Decree No. 75/2010, CIC QAS

[xxxvi] BCS (Biofertiliser Certification Scheme), Renewable Energy Assurance Ltd (REAL)

[xxxvii] "Keurcompost"

V. Policy context

The European Union is facing multiple interconnected challenges, and the uptake of digestate could contribute to addressing many of them.

First, the EU remains heavily dependent on fertiliser imports from commercial partners that have proven to be highly unpredictable and reliant on non-renewable resources. This dependence creates significant risks of price volatility and directly threatens farmers' competitiveness, livelihoods and food production in Europe. The recently implemented CBAM adds further pressure to this context, with early warnings of rising fertiliser prices. These challenges are compounded by a struggling European fossil-based fertiliser industry which faces urgent decarbonisation needs. While these factors should create momentum for policymakers to accelerate the transition towards a **European organic fertiliser industry**, the transition has yet to occur. The upcoming **Fertiliser Action Plan**, announced by the European Commission and expected in May 2026, offers hope that it can tackle these interconnected challenges.

Second, soil health remains a pressing concern. Despite recent steps taken through the Soil Monitoring Law, which entered into force on 16 December 2025, 70% of EU soils are unhealthy, further jeopardising farmers' competitiveness, livelihoods and food production.

Digestate can play a key role in building an ambitious bioeconomy by 2040, by promoting greater use of organic fertilisers, reducing import dependency, cutting greenhouse gas emissions and improving soil health. Beyond scaling up the recycling of sustainable feedstocks via AD, two complementary pathways must be pursued with regard to digestate:

- **Building local circular systems:** farmers should be equipped with the right tools and receive appropriate training. This approach concretely supports local circularity by promoting best practices, encouraging the adoption of suitable equipment, and advancing precision agriculture to minimise nitrogen and ammonia emissions. While some Member States are relatively advanced in this regard, much of Europe still has considerable progress to make.

- **Developing biorefineries:** materials that cannot be valorised locally should be transformed into strategic products. Specialised biorefinery hubs could process these materials to produce, depending on local, national or even European needs, the necessary products – particularly focused on nutrients and organic matter, depending on soil requirements. Beyond fertilisers, digestate could also support other applications, such as insect farming, pre-treatment to enhance biogas production from lignocellulosic biomass, or extraction of volatile fatty acids for bioplastics production.

Unlocking these pathways requires:

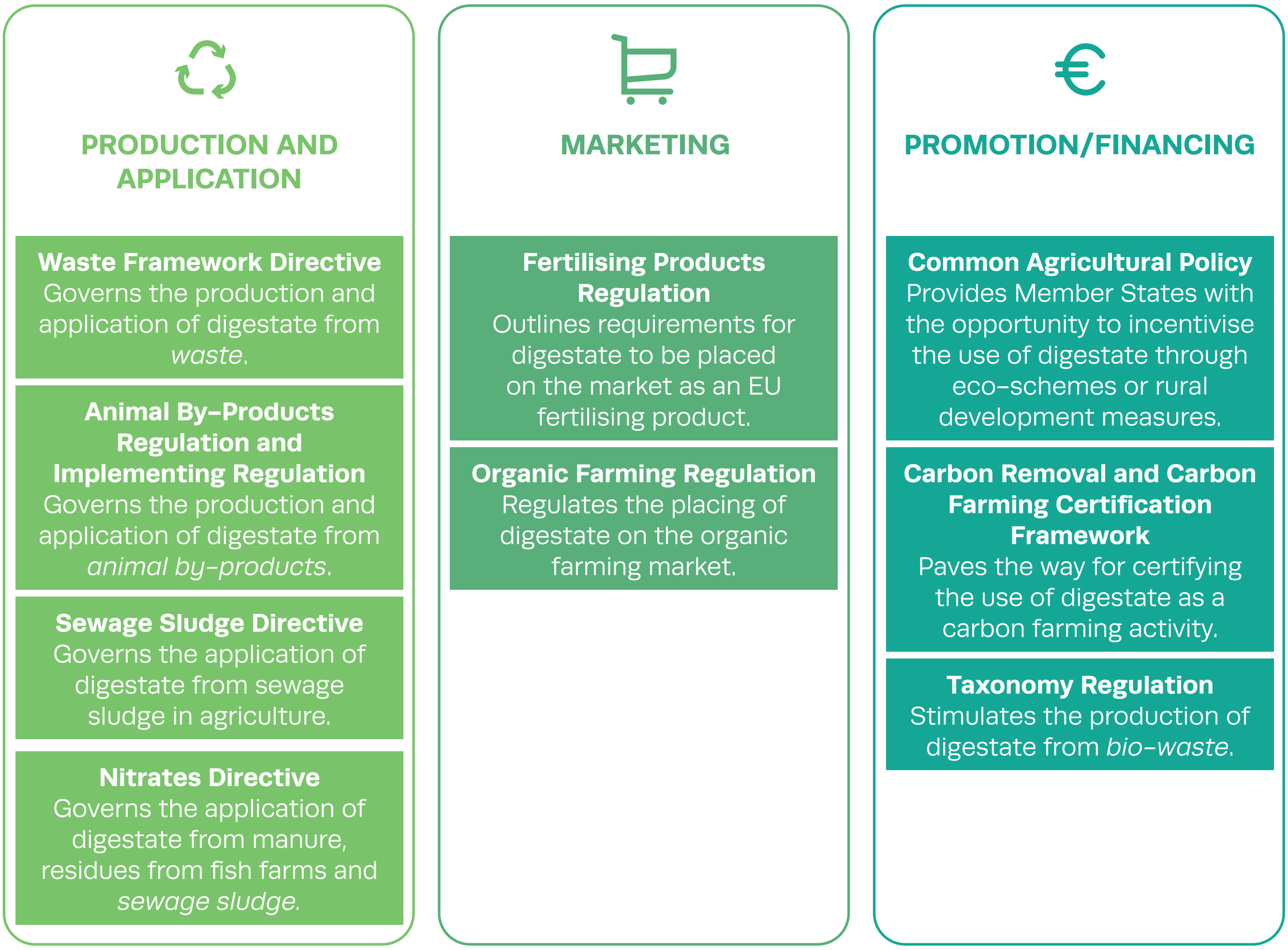
- **A clear strategy and planning:** a shared vision with clear objectives is essential. As import dependency decreases, Europe must evaluate the capacities that need to be developed and the actual needs of each region.

- **Investment:** resources are needed for tools, equipment and farmer training, but also for developing biorefineries.

- **Stakeholder engagement:** all stakeholders must be involved and see themselves reflected in this common strategy. Resistance to change is inevitable, but every actor – including the fossil-based fertiliser industry – must play their part.

The European regulatory framework can support all these dimensions. **The Bioeconomy Strategy**, published in November 2025, promised the development of "Industrial Symbiosis Valleys", potentially providing a basis for regional needs assessment and biorefinery development. Investment may be mobilised from a range of funding instruments, yet early indications of a reduced **Common Agricultural Policy** budget send a worrying signal. Regulation can also create supply-side incentives, for example by investigating the set-up of a **recycled content obligation for fertilisers sold across Europe**, thereby encouraging the fossil-based industry to integrate recycled nutrients into their product lines. Moreover, digestate producers and end-users need a clear regulatory framework for their products. While some Member States have introduced clearer legislation that provides legal certainty and operational requirements for digestate and digestate-derived products, including end-of-waste criteria, many national frameworks remain highly complex, misclassifying digestate or providing unclear or unfit criteria (see regulatory analysis [77] attached to the 2024 White Paper). The **Fertilising Products Regulation (FPR)** offers an opportunity for an EU-harmonised framework, although technical barriers – such as excessive nutrient content requirements for organic fertilisers – still exist. While originally designed for cross-border trade, the FPR does also have the potential to simplify local use if technical requirements and costs are rationalised. Fortunately, the legislation is currently under review, offering hope for improvement.

For a detailed analysis of the current regulatory framework for digestate, see the report [77] produced in the context of the European project FER-PLAY [80].



PRODUCTION AND APPLICATION

Waste Framework Directive
Governs the production and application of digestate from *waste*.

Animal By-Products Regulation and Implementing Regulation
Governs the production and application of digestate from *animal by-products*.

Sewage Sludge Directive
Governs the application of digestate from sewage sludge in agriculture.

Nitrates Directive
Governs the application of digestate from manure, residues from fish farms and *sewage sludge*.

MARKETING

Fertilising Products Regulation
Outlines requirements for digestate to be placed on the market as an EU fertilising product.

Organic Farming Regulation
Regulates the placing of digestate on the organic farming market.

PROMOTION/FINANCING

Common Agricultural Policy
Provides Member States with the opportunity to incentivise the use of digestate through eco-schemes or rural development measures.

Carbon Removal and Carbon Farming Certification Framework
Paves the way for certifying the use of digestate as a carbon farming activity.

Taxonomy Regulation
Stimulates the production of digestate from *bio-waste*.

Figure 6 Digestate policy framework in the EU

VI. Economic aspects associated with digestate management

6.1 Regulatory economic context

Across Europe, the economics of digestate use are highly context-dependent. Variables such as **plant scale, feedstock type** and the **availability of land** in the surrounding area shape the cost structure of different digestate management configurations, while distinct regulatory and market conditions in each country lead to very different economic trade-offs for biogas-digestate systems.

The value driving components for EU regions depend primarily on **regional nutrient status**, creating divergent priorities between building soil carbon stocks and increasing nutrient export capacity. In livestock intensive agrifood systems and surplus regions constrained by **Nitrate Vulnerable Zone (NVZ)** regulations, such as Belgium (Flanders), the Netherlands, Denmark and north western Germany, the local market for digestate is restricted. Nitrogen must be displaced over long distances, with these areas effectively acting as nutrient processing hubs. They mainly import raw materials (feed, food commodities) and export processed products (meat, dairy) alongside manure based digestate. In 2024, manure production from pig, cattle and poultry in these regions exceeded 60 t/ha. In such landscapes, nutrient imbalances constrain how digestate N and P can be applied and are likely to drive a shift towards more processed digestate products, as already observed or anticipated in countries such as Sweden [3]. In these contexts, a key strategy to manage surpluses and reduce the need to export digestate is to apply RENURE compliant, manure-based post-processed digestate locally in place of mineral fertilisers, although the regulatory framework itself can be a major barrier.

By contrast, in many other countries, the absence of a clear regulatory framework for digestate complicates application on farmland, and the lack of specific national fertiliser regulations for digestate products further impedes market development. To date, only one support scheme targeting digestate has been implemented, in Finland. This was aimed at developing a market for recycled fertilisers and promoting the use of recycled nutrients in biogas facilities. However, the impact of the scheme was limited, as it covered only five installations [81]. Liquid-solid separation can improve compliance with nutrient loading thresholds, while processing and upgrading (e.g. ammonia stripping or membrane technologies) can achieve over 80% nutrient recovery, enabling spatial redistribution to regions with N and P deficits and limited access to fertilisers [82]. However, treatment costs in the range of €2–12/ kg nutrient or per m³ of digestate [50] are often prohibitive for farmers, compared with conventional fertilisers. At the same time, examples from low fertility land show that digestate from a 1 MW plant can generate additional income of roughly €941–€2,095 per day through increased crop productivity [83], in addition to energy revenues.

Large biogas plants generate proportionally more digestate, and the cost of handling raw digestate is closely linked to plant size and the associated land area required for application. For a 1 MW agricultural biogas plant, the minimum land area needed can range from around 500 to 2,000 ha, depending on national conditions. In nitrogen and phosphate sensitive areas, digestate management becomes a bottleneck due to storage and transport logistics, with distance as a main cost driver. Storage and field application can account for roughly 16% and more than 20% of total logistics costs, respectively.

In summary, in nutrient deficit areas, the focus shifts towards building soil organic matter and carbon stocks, and these regions can benefit from importing digestate derived products and nutrient concentrates. In arid and semi arid climates, such as many Mediterranean systems characterised by water scarcity, intensive cropping and variable livestock densities, SOC depletion and seasonal nutrient demand make local digestate application to improve soil organic matter and structure more valuable than nutrient export, with careful timing of applications being critical. In all cases, regulations and policies that integrate nitrogen, phosphorus and carbon cycles are needed to scale up circular nutrient technologies and close regional resource loops.

6.2 Digestate application models

To clarify strategic options, cost implications and implementation pathways for nutrient recirculation on European soils, EBA, in collaboration with biogas experts, has identified the main digestate use options and application models across different AD contexts and operator types in Europe. The options are grouped by predominant feedstock:

(i) agricultural plants mainly supplied with livestock manure,

(ii) agricultural plants mainly using crop residues,

(iii) plants treating municipal waste,

(iv) plants based on sewage sludge.

The key cost drivers associated with these configurations are briefly discussed and schematically presented for the main cases in Figure 7. A summary of the main strategic drivers for digestate valorisation, and of management considerations across different biogas model dimensions, is provided in Figure 7 and Table A2.

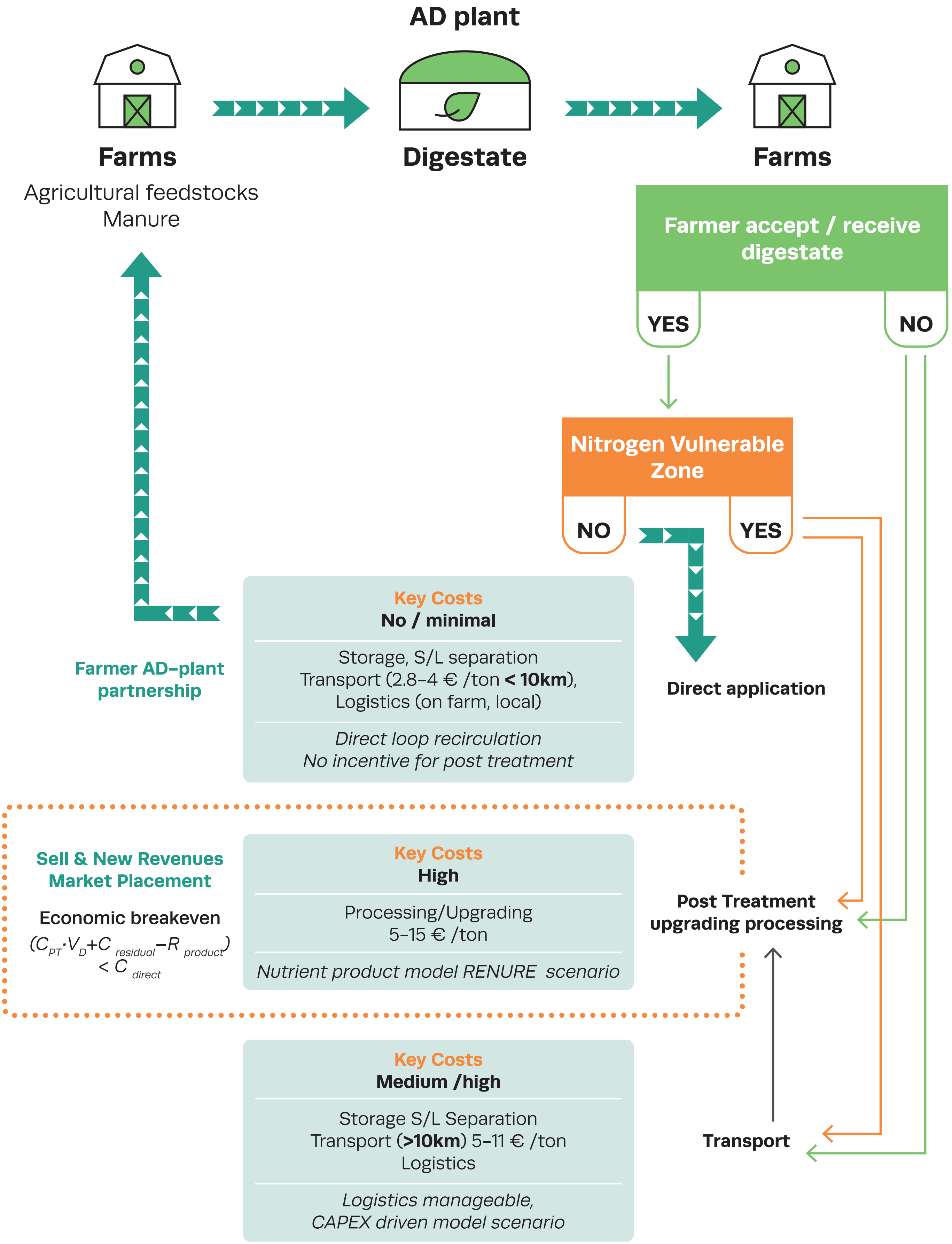


Figure 7 Flow chart of digestate use options and application models for livestock manure and agriculture-based options (see Table A2 for details of OMSW and sewage models) ;cost of process treatment (C_{PT}), volume of digestate (V_D) , cost of residual spreading ($C_{residual}$) , product revenue ($R_{product}$), cost of direct spreading (C_{direct})

- **Option (i) Agricultural AD with primarily livestock manure** (e.g. Denmark): for farm-scale plants, no extra logistical costs are applied for the AD operator, as digestate distribution is usually combined with the existing manure logistics. In many cases, most of the digestate can be delivered back to the farm suppliers or their neighbours (i.e. minimal distances and transport cost internalised by manure). On the other hand, in a context where the farmer livestock producers are often reluctant to receive digestate (e.g. in Spain), higher costs arise for transport and logistics, creating stronger incentives to explore costly post-treatment of the digestate.
- **Option (ii) Agricultural AD with primarily crop residues**: in this case, the main cost drivers are the higher truck loads due to the additional volume and dedicated transport to bring digestate to the field. However, the greater cost of AD will be reflected in the value of the digestate, which contains a high energy density and thus a high value of produced digestate.
- **Option (iii) Municipal biowaste-based AD (separated collected food waste)**: in this case, spatial distribution is critical, and economies of scale are needed to offset the higher costs associated with longer distribution distances. In Europe, the most established value chain for this feedstock is AD combined with composting, which adds cost and time. An additional cost is that many municipalities must implement specific quality assurance systems to prove to farmers that digestate can be used safely, without contamination risks.
- **Option (iv) Sewage sludge-based AD**: in this case, logistical costs are compounded by regulatory constraints and limited acceptance among farmers and downstream users, who are often reluctant to apply sewage-derived digestate on agricultural land.

In summary, the main business model drivers for digestate differ across contexts and countries. In some cases, they are primarily driven by OPEX reduction.

In other cases, where regulatory constraints and more advanced systems are in place, additional revenue streams from higher value fertiliser products can be envisioned.

For agricultural AD facilities treating primary livestock manure, the digestate business model is dominated by on-site fertiliser savings through direct application on owned land, as well as by centralised local cluster AD facilities.

These enable closed circular nutrient loops, ensuring a short transport distance and nutrient cycling within the agricultural system. In contrast, for industrial or municipal organic AD and sewage sludge, the business model is shaped by gate fees paid for accepting feedstock (e.g. from municipalities) and by the need to organise a logistics chain from the plant to end-users of the digestate.

Across all configurations, the objective is to avoid wasteful approaches without nutrient recirculation and to resort to disposal only when it is contaminated.

6.3 Considerations on the costs of logistics and storage of digestate

Due to the high water content of raw digestate (~95% water), moving digestate to farms is often the most expensive part of the whole system, with **transport typically the dominant cost component**. This is particularly true for livestock-based systems without sufficient own land and in NVZs, and for industrial plants, where transport alone can exceed €300/ha and be more expensive than the nutrients are worth. Under different scenarios with different feedstock-based digestates and assumed distances of 20–100 km, several studies have calculated the total cost for the different stages of digestate management. **Logistical** costs for raw digestate are highly sensitive to **backhauling** rates and **loading/unloading times** [84], therefore plant location plays a key role in viable nutrient recycling [4]. According to a recent Danish report [85], the cost of transport logistics typically ranges between **€2.80–3.75 per tonne**. Other analyses (e.g. by CIB for Italy) show that reducing average transport distance from 17 km to 8.5 km can lower costs by about 30%, with overall transport costs often falling between €4 and €11 per tonne of digestate, especially when distances exceed 70–90 km [86], [87], [88], [89]

In Sweden, a digestate price below €4.5–5.5/tonne suggests that facilitating shared storage could help decouple the short spreading period from peak transport needs. **Storage** costs vary with plant scale, storage type (tank infrastructure and maintenance) and whether storage is centralised or decentralised, but they generally represent a smaller share of total management costs, with transport and logistics remaining dominant. Processing can help reduce overall costs by decreasing storage volumes and lowering transport needs, in some cases saving up to about 60% of total costs; however, some transport will always be required, and processing itself introduces additional costs.

6.4 Considerations on the costs of processing digestate

Separating the two phases contributes to cost abatement and enables application at the most suitable times (i.e. close to sowing and/or when crops show the highest nitrogen efficiency uptake). Common strategies to optimise transport and distribution include [84] decentralised digestate storage near fields and underground pipelines and the use of large wheeled tankers (≥ 28 m³) to supply farm-based storage or directly support spreading. As previously discussed, distance to farms and usability of the liquid fraction are key factors in determining whether processing is justified. However, relatively low nutrient concentration of the liquid fraction remains a major barrier to effective nutrient redistribution. From both cost and environmental perspectives, simple options such as **solid-liquid separation** (e.g. screw press, membrane clarification) are often preferable to more complex processes such as ammonia stripping/scrubbing or struvite precipitation, which reduce but do not eliminate transport challenges. While advanced nutrient recovery technologies have proven technically feasible at pilot scale, they do not always reflect the financial and logistical constraints of full-scale deployment in European conditions; scaling up involves high operating costs, infrastructure needs and market uncertainties. In practice, additional nutrient recovery processing is most justified where transport distances are significant or where no local market exists for liquid digestate.

Processing costs range from low values for simple mechanical separation to much higher costs for complex multi-stage treatment chains that combine centrifugation, membrane filtration, evaporation and drying. For example, **centrifuge** typically costs €111,000 (€70,000–€202,000), whereas **screw press** is cheaper at approximately €30,000 (€17,000–€40,000). In general, thermal drying and advanced nutrient recovery options (e.g. belt dryers, vacuum evaporation, membrane systems, stripping) fall within the range of a few to several tens of euros per m^3 of input digestate, reflecting significant energy and capital requirements, whereas basic solid-liquid separation is at the lower end of the cost spectrum (see Figures 8, 9 and A1). For examples of the cost breakdown, see Figure 8.

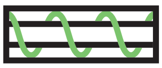
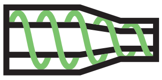
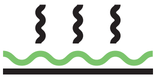
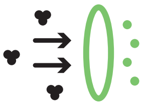
Technologies	Screw Press	Centrifuge Decanter	Belt filter	Dryer	Membrane	Stripping
Working principle	 particle size	 particle density	 particle size	 volatility	 permeability	 volatility
CAPEX€/tonne	**≃ 0.25**	**≃ 1**	**≃ 0.45**	**≃ 2.5**	**≃ 2.74**	**≃ 1.58**
OPEX €/tonne	**≃ 0.35**	**≃ 0.69**	**≃ 0.65**	**≃ 3.3**	**≃ 3.23**	**≃ 2.86**

Figure 8 CAPEX and OPEX for main digestate separation techniques (Source: ENGIE REX and literature survey [90] [91] [92])

The addition of chemical pre- or post-treatment **conditioners** (e.g. acidification or alkaline stabilisation) increases costs by about €12,000–€50,000, but improves stability, hygiene and regulatory compliance. Pasteurisation (or **hygienisation**) [24] of digestate may be required for certain animal by-products, according to a strict interpretation of the Animal By-Products Regulation in national law. In this case, the thermal energy requirements, which typically depend on the starting temperature (225 MWh/h year and 41 kW) and the heat recovery efficiency (heat exchanger recapture) are the main factors affecting OPEX [92] Table 10 summarises typical processing costs and main cost drivers for the principal technologies, including indicative comparisons with the equivalent cost of synthetic fertiliser.

In summary, solid-liquid separation increases total costs due to additional capital and electricity demand, but it also reduces transport costs. According to industrial internal studies, post treatment costs for membrane processes and nitrogen stripping are in the region of around €8 per tonne of digestate treated. Overall, the available data confirm that simple or moderately complex processing options can achieve costs in the range of €5–7/m^3, whereas energy and capital intensive technologies, such as advanced thermal treatments, lead to significantly higher treatment costs. This reinforces the importance of matching technology choice to local conditions, transport distances and nutrient recovery objectives.

Table 10 Cost breakdown per different selected processing technologies illustrating the different cost drivers and contribution of individual cost components

Technology	Key cost drivers	Capital costs	Energy costs	Costs (e.g. chemicals/ labour)	Processing cost	Equiv. mineral fertiliser cost [a]
		(€/m^3 input digestate)				
Mechanical separation (e.g. decanter)	Low complexity	–	–	–	~0.63	~1.5–3
Multi-stage (e.g. centrifuge + RO, evaporation, drying)	Medium-high complexity	–	–	–	Up to 37.8	~10–25
Centrifuges (vs. screw presses/rotary drums)	DM + P recovery (centrifuges superior)	–	Screw presses use 5x less energy	–	–	–
Thermal drying	CAPEX energy (heat)	2.51	1	–	~5.8	~8–15
Thermal drying + nutrient recovery (e.g. belt drying + fixed-bed drying + membrane + stripping)	CAPEX and energy (electricity and heat)	–	–	–	5–15	~10–20
Belt drying + solar drying	Incentive bonuses offset costs	Offset	Offset	–	~5–15	~8–15 (offsets)
Vacuum evaporation	CAPEX + energy (electricity and heat)	High	High	–	18–19	~15–25
Membrane filtration	CAPEX + electricity	High	High	Low chemicals	7	~12–18
Stripping	Low CAPEX/ significant chemicals	1.58	–	Chemicals 1.5; labour 0.3	5.4	~10–15
General operational (nutrient recovery)	Varies by config./ integration	–	–	–	2–7/kg nutrients; 8/m^3 liquid	N/A

[a] Estimated cost of replacing the recovered nutrient value of 1 m3 digestate with mineral fertiliser. It is derived from typical liquid digestate NPK content of ~5–10 kg/m^3 and indicative market cost for mineral NPK fertiliser (€300–800/tonne); representing competitiveness benchmark (not replacement value). The values vary with digestate composition, nutrient recovery efficiency and local market conditions and do not account for site-specific nutrient profiles, recovery rates and agronomic efficiency. (nutrients kg/m^3 digestate) × (€/kg fertiliser)

6.5 Overall economic relevance of digestate

The value of digestate-based biofertilisers (e.g. digestate N fertiliser replacement value) depends on several factors, such as the nutrient characteristics of not only NPK content, but also the proportion of C/N and P/N (always in combination with soil properties). The value can be linked to the market price of petrochemical fertilisers and the price competitiveness of digestate-based NPK relative to them. However, the associated **monetary value** is influenced by several other aspects, including seasonal-climate variation, soil status conditions and geopolitical situation, which can be addressed through models and dedicated research studies and are therefore beyond the scope of the present work. As discussed earlier, every digestate processing technology has CAPEX and OPEX that determine a *breakeven* price for the processed digestate product. Only when the market value of digestate – which depends on its quality and is driven by several of the aforementioned contextual factors – exceeds the breakeven threshold does it become economically attractive.

In addition, several indirect value benefits of digestate at system level are widely recognised. These include enabling expanded biogas production, reducing digestate management costs, improving the circular use of N, avoiding N losses during manure storage, and increasing NUE while lowering N runoff, as shown in detailed LCA studies [62] [93]. Since such marginal benefits determine the price that can be paid, a higher value for digestate-based fertiliser products may justify greater investment in processing and upgrading. Digestate holds significant value in agricultural systems in terms of fertiliser content and carbon, by effectively recirculating nutrients that would otherwise be lost. Current estimates suggest that digestate produced annually in Europe contains nutrients worth around **€750–800 million**; including the carbon value of digestate, the total is estimated at **€1.2 billion**.

Table 11 Estimated value (€/t) of digestate fertiliser based on NPK nutrients

Fertiliser	Estimated price €/t [ba]	Estimated value € million	N	P	K	N	P	K
				Mt			kg/t FM	
Liquid [b]	5–8 (8–15.57)					5.8	2.7	4.9
Solid [c]	15–20					6.8	5.7	7.9
Total	**3.8–10**	**560 130 63**	**1.4**	**0.22**	**0.175**	**3–7**	**0.5–2.5**	**2–5**

[a] A range of synthetic fertiliser prices is used. At the time of writing (end of February 2027), prices were: ammonium nitrate (at 27% and 33.5%) €392.5–501.2/t; DAP diammonium phosphate, 18% N, 46% P_2O_5 €774/t; potassium chloride (60% K_2O) €372/t; PK €517/t nitrogen solution €376/t; triple superphosphate (45% P_2O_5) €567 t; NPK (17–17–17) €593/t; and urea €576/t.

[b] Price range for N (NPK).

[c] Price range for NPK + organic matter, which is approximately 20% of total solids with a stability index of 60% and a carbon content of 50%.

As discussed, nutrient concentrations in digestate typically range between 1 and 5 kg per tonne, corresponding to approximately 1.4 Mt of plant-available N, 220,000 t of P, and 175,000 t of K. Using an average market price for these nutrients [94], the resulting value of liquid and solid digestate based on their NPK content and organic matter content (Table 11) is estimated at about €560 million for N, €130 million for P and €63 million for K, with total annual nutrient value of roughly €750–800 million.

Depending on composition and fertiliser price, each tonne of digestate can replace up to €5 of mineral fertiliser, which translates into avoided mineral fertiliser purchases worth up to €250/ha annually [xxxviii]. When the carbon dimension is included, the picture becomes even more compelling. Digestate organic matter typically contains around 20% stable carbon (i.e. humus value C content), or 60–70 kg of carbon per tonne [95]. On this basis, up to 1.5 Mt of stable carbon could be returned to soils annually. Using the factor 3.67 to express this as CO_2-equivalent sequestration, this corresponds to around 5.5 Mt CO_2, complemented by an estimated 10 Mt CO_2 in avoided emissions [xxxix]. At a current CO_2 market value of about €80/t, this corresponds to over €1.2 billion in combined environmental and nutrient value potential.

Digestate production by AD generates profound **positive socio-economic externalities** that act as an engine for sustainable growth (Figure 10). As such, it catalyses rural development by revitalising local economies, creating jobs and sustaining resources and workforce retention, thus also boosting local tax revenues. In addition, diverting biowaste from landfills and incineration is reported to save local authorities from disposal problems, while actively monetising circular bioeconomy principles. Estimates from previous monetary studies suggest that these externalities can deliver strong economic benefits, demonstrating a positive ROI with values potentially over €170/MWh.

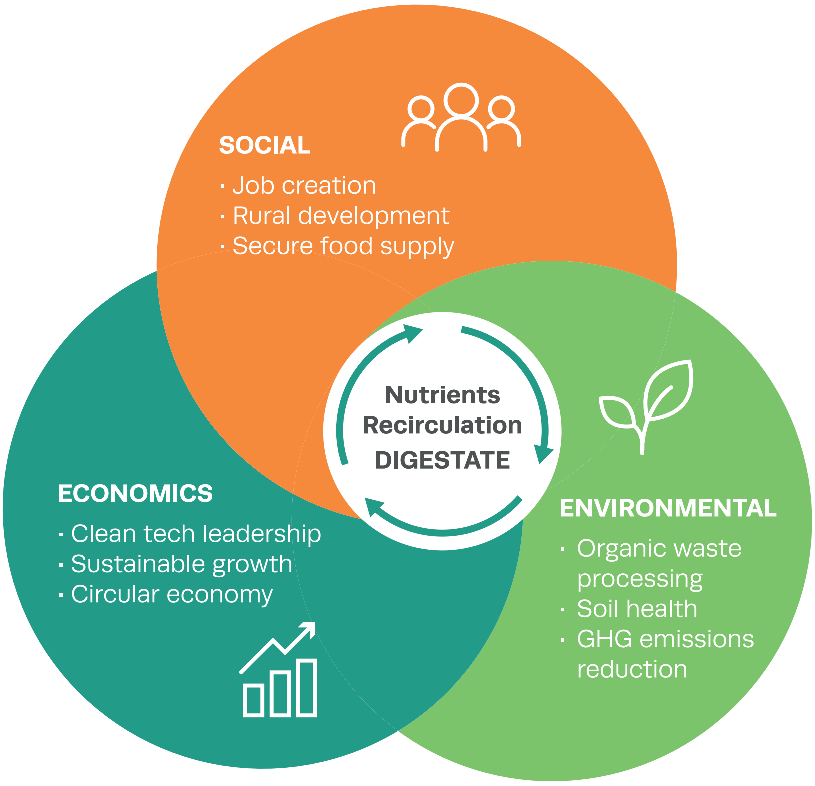


Figure 10 Socio-economic impact of digestate value chain

[xxxviii] Calculated based on average N content in digestate (3.5 kg/tonne digestate) and assuming the lower and upper limits of 75% and 95% for the Nutrient Fertiliser Replacement Value (NFRV) of raw manure-based and processed digestate respectively, each tonne of digestate provides 2.5 to 3 kg N as plant-available mineral synthetic fertiliser, which at the current price of €0.8–1.5/kg N is worth €3–5 per tonne of digestate. This translates as a total annual saving of over €250/ha, considering N application of 170 kg N/ha/year (ND).

[xxxix] 10 Mt of CO_2 avoided emissions and 5.5 of CO_2 sequestrated, i.e. a total of 15 million tonnes of CO_2.

VII. Market uptake and adoption barriers

The current EU digestate market remains underdeveloped. Although digestate is generally recognised as a valuable fertiliser, it is often perceived and treated as waste by farmers. Many are reluctant to pay for it, particularly when transport and application costs exceed those of conventional fertilisers, or when concerns exist regarding contamination and variable quality. Additionally, as previously reported, there is a lack of clear economic valuation in various European contexts., it may be hard to see the economic value associated with clearly defined nutrient specifications, while the non-monetary transactions and exchange practices between farmers and biogas operators is widespread.

In several countries, particularly where larger centralised plants operate, the digestate is returned/provided/redistributed to farmers to balance out the feedstock that was sent to the AD facility [xl]. This practice brings additional availability of nitrogen fertiliser for farmers, who have to compensate for the cost of transporting their raw slurry to the AD plant. In this arrangement, the biogas plant operator effectively compensates farmers for the manure they supply by providing digestate **free of charge**. If this digestate were not returned to the farm, the nutrients would be lost, and farmers would incur additional costs to purchase fertilisers. By receiving digestate, farmers achieve net savings on fertilisation costs (savings they would not otherwise afford), while valuing digestate primarily as a cost-saving alternative to conventional fertilisers. This dynamic sits at the intersection of **environmental ambitions and European market reality**. On the one hand, it supports EU policy objectives for climate change mitigation, nutrient recycling and soil health, by accelerating the adoption of fertilisers derived from secondary raw materials. By doing so, market pricing is not the objective, but rather a tool for policy success towards the acceleration of nutrient recycling adoption, speeding up nutrient recycling by delivering fertiliser products with high agronomic value at zero cost, while minimising dependency on petrochemical-based fertilisers.

On the other hand, if digestate continues to be perceived as free waste to be dumped and if the fertilisation benefits it provides remain poorly recognised and supported within both European and national regulatory frameworks, it will be systematically undervalued as a useful product. Under the current situation in Europe, digestate is typically applied directly without further processing, as any additional treatment incurs extra costs, with no guarantee that the market will be willing to pay a premium for recycled nutrients compared with conventional petrochemical NPK fertilisers. **This market distortion based on an artificially low price and undervaluation of digestate hinders quality improvements and discourages investment**. Lack of investment in precision agriculture could increase the risk of over-application, leading to nitrate leaching in NVZs, potentially resulting in violations of the Nitrates Directive or undermining compliance. Additionally, this approach is also in contrast to circular bioeconomy ROI goals, because the economic margins and profitability for biogas operators who are absorbing the economic burden of digestate management and cover payments are not competitive. This further weakens innovation by discouraging digestate processing and upgrading, due to the lack of competition created by a mutual dependency and the bilateral lock-in between farmers and a single preferred biogas plant. In the long term, this could create a lose-lose scenario, undermining the scalability of biogas-digestate systems.

[xl] In some cases, such as in the Netherlands, AD operators even pay a penalty for its supply and application to the land

In conclusion, when treatments are applied to digestate, they should aim to produce renewable fertilisers in order to capture market value and enable relocation from surplus areas. In this case, digestate could represent a win-win solution, particularly for regions with nutrient surpluses, since producing fertilisers and relocating them offers an opportunity to address the problem while generating economic value. Therefore, as such, biogases from organic resources contribute to a strong economic foundation for nutrient redistribution that would otherwise be economically challenging. Instead, rather than relying on linear nutrient resource-intensive pathways and harmful waste management practices, AD-based biorefinery systems enable efficient nutrient recirculation across regions.

Appendix

Basic soil science and agronomy

Nitrogen is essential for plants, microbes and life as it builds proteins, DNA and chlorophyll. However, most nitrogen in the air (N_2 gas, 78% of the atmosphere) is unusable. The nitrogen cycle involves the transformation of N compounds through natural processes in the soil, water and air, with the key players being bacteria, plants, light and fertilisers. Nitrogen **fixation (i)** (conversion of atmospheric N_2 into usable forms) unlocks atmospheric N, making it available for assimilation by plants and microbes. **Assimilation (ii)**, (uptake of N by organisms) incorporates usable nitrogen into tissues, forming organic matter.; **Ammonification or mineralisation (iii)**, Ammonification (decomposition of organic matter releasing ammonium) occurs when organic matter decomposes, returning N to the soil as ammonium ($NH4^+$).**Nitrification** (conversion of ammonium to nitrate) is carried out by bacteria in two steps: first, ammonium is oxidised to nitrite (NO_2–), then to nitrate (NO_3–), which is readily absorbed by plants due to its solubility. **Assimilative reduction and organification** allow nitrate to be reduced back to ammonium and incorporated into the C skeleton of amino acids. **Denitrification** (conversion of nitrate to nitrogen gas) takes place in oxygen-poor environments, releasing N gas (N_2) back into the atmosphere and completing the cycle. Recent findings indicate that practices such as N stabilisers and **nitrification inhibitors** added to digestates have been shown to reduce or suppress the activity of nitrifying bacteria, thereby improving nitrogen retention and lowering nitrous oxide (N_2O) emissions and ammonia (NH_3) volatilisation and loss by slowing the conversion of ammonium (NH_4+) into nitrate (NO_3), which is more prone to leaching.

Phosphorus is vital for plant growth, metabolism, energy transfer and cell division, but its bioavailability depends largely on soil **pH**. In acidic soils, P reacts with aluminium and iron; in alkaline soils, it binds with calcium, making it insoluble and limiting root uptake. As a result, part of the P supplied through fertilisation or already present in the soil becomes **retrograded** – incorporated into non-assimilable forms – often requiring additional doses to maintain nutrient levels. P in soil primarily occurs as phosphate, in the pentavalent state (+5). It is present in both inorganic and organic matter, and exists in different pools representing dynamic **reserves** that regulate P supply to plants over time: **(i) soluble P** in the soil solution, directly available to plants; **(ii) adsorbed** P, attached to soil particles and gradually released; **(iii) mineral P, contained in soil minerals and rocks** and liberated through rain and weathering; and **(iv) organic P**, bound to complex molecules and mineralised from organic matter by hydrolytic bacteria releasing inorganic phosphate. Insoluble phosphates remain unavailable to plants until microbial activity converts them into soluble forms. Certain microorganisms produce organic and inorganic acids that lower soil pH and dissolve immobilised phosphates, thereby enhancing P bioavailability. Part of the phosphorus in water settles into sediments eventually forming new rocks over very long timescales, completing the cycle.

Potassium is a key macronutrient that supports plant growth, yield and quality. Beyond its structural role, potassium regulates osmotic balance and cell turgor, maintaining tissue integrity and promoting cell-wall reinforcement and key physiological processes. It enhances photosynthesis, respiration and transpiration, and aids in the synthesis and transport of sugars and proteins. These effects contribute to better crop quality, greater drought tolerance and increased resistance to fungal diseases and climatic stresses, helping to mitigate the negative effects of surplus nitrogen, such as excessive vegetative growth, and reducing disease susceptibility. In the soil, potassium is present mainly as a cation with a positive charge (K+), which binds to **negatively charged colloids** such as clay particles and organic matter. Part of the potassium is **dissolved** in the soil solution; this soluble K is readily available to plant roots and is transported by water, but is also prone to leaching, especially in sandy or low cation exchange capacity soil. Another fraction is **exchangeable K**, held on colloid surfaces and available for plant uptake when the soil solution becomes depleted. A further portion, the **non-exchangeable or “reserve” K,** is loosely held within clay lattices and can be gradually released, acting as a slow-release reservoir. Finally, a large share of total potassium is **structural K,** embedded in the crystal lattice of primary minerals and only slowly weathered over long timescales.

The **carbon** cycle comprises two main phases: an aerobic phase and an anaerobic phase. In the aerobic phase, atmospheric CO_2 is fixed by photosynthetic drivers of C fixation (e.g. plants and microorganisms) and converted into organic matter, which follows two principal pathways. If this organic matter is oxidised, it is released back into the atmosphere as CO_2 through respiration and degradation processes. In the absence of oxygen, decomposition proceeds under anaerobic conditions via fermentation, generating CO_2, H^2, short-chain organic acids and methane (CH_4). Soils host substantial reserves of both organic and inorganic carbon. Besides the atmosphere and oceans, the largest **inorganic carbon** reservoir is **calcium carbonate** in soil, whereas major **organic carbon pools** include **humus**, petroleum, peat, fossil coal and natural gas. These reservoirs act as long-term carbon sinks, slowly exchanging carbon with the atmosphere and biota through mineralisation, weathering, combustion and microbial transformation.

A1 Digestate production per country (t FM/year) and tonnes digestate DM / GWh biogases produced for 2024

Country	DM/GWh	Digestate (t FM/year)
Austria	145	2,465,610
Belgium	175	4,114,479
Bulgaria	N/A	5,678,000
Croatia	N/A	130,530
Cyprus	N/A	15,499,146
Czechia	211	26,109,197
Denmark	131	20,227,745
Estonia	112	452,679
Finland	321	2,650,523
France	124	38,329,192
Germany	175	165,946,816
Greece	N/A	1,828,928
Hungary	N/A	1,310,400
Ireland	N/A	2,000,980
Italy	114	35,285,600
Latvia	159	605,986
Lithuania	172	1,588,495
Luxembourg	78	631,350
The Netherlands	126	19,716,322
Norway	364	8,244,890
Poland	291	13,136,901
Portugal	93	1,576,894
Romania	148	354,001
Serbia	57	490,409
Slovakia	267	1,289,006
Slovenia	151	139,216
Spain	93	18,086,923
Sweden	134	3,688,000
Switzerland	284	6,598,400
United Kingdom	139	48,148,170
Ukraine	285	1,996,264
Total		**448,321,052**

A2 Comparison of digestate management for selected common biogas model dimensions in Europe

AD operator	Basic model dimension	Digestate end use	Key costs	Revenue streams	Selected country	Bottleneck strategy
Farm-based ownership	**a.** LM + AD+ C & ha	Crops Field direct recirculation loop	· Storage · S/L separation (~€1–2/m^3) · <€2/m^3 direct application	· Sale of energy · Fertiliser cost saving · Crop sales	FR, DK DE, SE, NO	· Requires plan for direct land application · Define for input feedstock and digestate NPK, DM, OM, C/N, microbiology contaminants · Economic breakeven[c] *(CPT · VD+C residual–R product)<C direct*
	b. LM + AD + ha	Pasture/grassland Field direct recirculation loop		· Sale of energy · Fertiliser cost saving	Small farms (UK, IE)	
	c. LM + AD	· Own or 3rd party installation for processing/upgrading · Sale (export SF) after S/L separation	· Storage · S/L separation (~€1–2/m^3) · Transport costs by distance[a] · Advanced processing/upgrading installations[b]	· Sale of energy · Market uptake/placement · Sale of organo-mineral equivalent fertiliser products & soil improvers	NL, Flanders BE	
	d. C & ha + AD	Field application – circular loop	< €2/m^3 direct application	· Sale of energy · Fertiliser cost saving	DE, IT	
Industrial/ centralised (AGR Not farm ownership based)	**e.** AD LM	· Farmer partnership & exchange · Digestate delivered back to the supplier's farm or neighbours (paid or free of charge) · Own or 3rd party installation for processing/upgrading/formulator partnership	· Storage · S/L separation (~€1–2/m^3) · Costs by distance[a] · Advanced processing/upgrading installations[b]	· Sale of energy · Fees for receiving digestate · Market uptake/placement · Sale of organo-mineral equivalent fertiliser products | soil improvers |	DK, NL, FR co-ops all EU	· Requires plan for direct land application · Economy of scale offsets transport logistics · Define for input feedstock and digestate NPK, DM, OM, C/N, microbiology contaminants · Economic breakeven[c] *(CPT · VD+C residual–R product)<C direct*
	f. AD C		· Transport (> 15 km)			
Industrial/ centralised OFMSW Municipal organic waste	**g.** AD mono OFMSW	· Post-processing liquid/upgrading → sale of composting solid	· Storage · Source separation + pre-treatment + depackaging · Separation/processing/upgrading installations · Transport/logistics chain for the digestate to users	· Sale of energy · Paid fee · Fertiliser value · Agricultural digestate value · Sale of mineral equivalent fertiliser products · Market uptake	ES, IT, SE	· Strict bio-bin collection · Machines to remove inerts · Quality certification · Hygienisation
	h. AD mix OFMSW + LM	· Return to manure supplier's farm (paid or free of charge) · Post-processing liquid/upgrading → Sale of composting solid	· Storage · Source separation + pre-treatment depackaging · Separation/processing/upgrading installations · Hygienisation/pasteurisation [i] · Transport/logistics chain for the digestate to users		DK IT	· Strict bio-bin collection · Machines to remove inerts and contaminants · Production in a closed and monitored collection system, accepted by the MS (additional contaminant levels) · Quality certification mandatory · Hygienisation/pasteurisation
Industrial/ centralised Sewage WWTP	**i.** AD	· Processing to recover P · Mineral equivalent P	· Storage · Processing	Sale of mineral equivalent fertiliser products, market uptake	SE, UK	· Strict legislation · Quality control · Acceptance

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i Pasteurisation/hygienisation unit must not be mandatory for biogas plants transforming only "animal by-products which may be applied to land without processing [...] if the competent authority does not consider them to present a risk of spreading any serious transmissible disease to humans or animals".

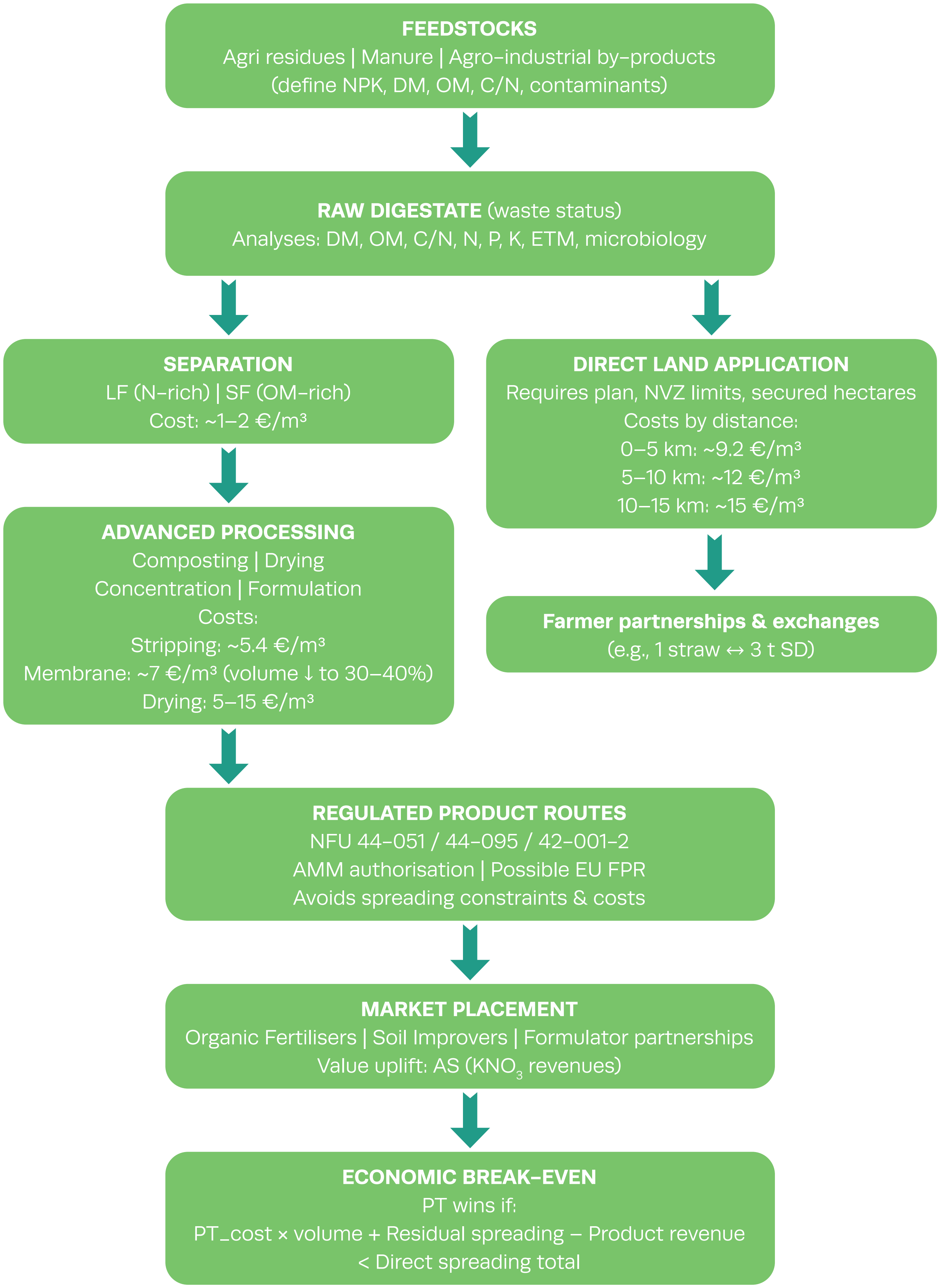
Scenario Basic Model Dimensions FARM BASED OWNERSHIP (a) farmer with livestock (i.e. manure) (LM), operates anaerobic digestion (AD) and growing crops (c) on own land (ha); (b) farmer with livestock (i.e. manure) (LM), operates anaerobic digestion (AD), own pasture land (ha); (c) farmer with livestock (i.e. manure) (LM), operates anaerobic digestion (AD), without land; (d) farmer growing crops (C&ha), operates anaerobic digestion (AD); CENTRALISED AGR BASED (e) centralised livestock (i.e. manure) (LM), anaerobic digestion (AD); (f) centralised crop-based (C) anaerobic digestion (AD); CENTRALISED OFMSW INDUSTRIAL (g) operates anaerobic digestion (AD) in mono-digestion; (h) operates anaerobic digestion (AD) in co-digestion with (LM); CENTRALISED WWTP (i) municipal waste water treatment facility operates anaerobic digestion (AD) of sewage sludge.

a Cost by distance: 0–5 km: ~€9.2/m3 5–10 km: ~€12/m3 10–15 km: ~€15/m3.

b Advanced processing (e.g. composting, concentration, drying, formulation): Stripping: ~€5.4/m3 Membrane: €7/m3 Drying €5–15/m3

c Economic breakeven: Processing/Treatment (PT) wins if: CPT $_2$VD+C residual–R product)<C direct where CPT costs of Processing/Treatment; VD volume of digestate; C residual cost of residual digestate distribution; R revenue from fertiliser product; C cost from direct spreading

Figure A 1 Decision tree for digestate use options and application



Nitrogen dynamics and soil budget calculation methodology

Following the approach adopted in the Fertimanure project [64], nitrogen and phosphorus balances from FAOSTAT [xli] were analysed for each European country, and compared with the amounts of nitrogen and phosphorus available from digestate. This allowed the estimation of **the percentage of mineral fertiliser substitution with digestate at which the annual nitrogen surplus currently applied to soils would be reduced, or conversely, the deficit that would result.**

First, according to the latest database [96] [xlii], the nutrient status of soils under current state was determined for both N and P by adding together all the available inputs (including N from mineral fertiliser, manure, biological fixation and atmospheric deposition) and subtracting uptake based on crop removal, with and without losses (leaching and volatilisation), bearing in mind that losses depend on soil type, rainfall, temperature and agricultural practices, not surplus alone.

Second, the balance under a scenario completely excluding the use of mineral fertilisers was evaluated. In this case, total uptake was again calculated with and without the reported losses (i.e. leaching and volatilisation). Data for Malta, Ireland and Cyprus were excluded from the dataset because the results obtained were deemed unrealistic.

1. Calculation of soil balance based on manure + mineral fertilisers

Current average annual N application on European soils is in the range of 48–121 kg N/ha, showing a strong variability between countries in the amount of N applied to soils.

- The countries that use the highest amount of N from manure on soils are Belgium, the Netherlands and Switzerland (168, 134 and 120 kg N/ha respectively), while the countries that use the highest amounts of mineral N on their soils are the Netherlands, the UK and Luxembourg (182, 172 and 158 kg N/ha respectively) [xliii].
- On the other hand, the countries that apply the lowest amounts of N from manure, besides Ukraine, are Bulgaria, Finland and Latvia, with 11–13 kg N/ha, whereas Spain and Portugal apply the lowest N mineral amount (46–50 kg N/ha). The national average N uptake from European soils is 64±38 kg N/ha, with Belgium, the UK and the Netherlands showing the highest N uptake value.

Under the first scenario in both situations (i.e. with and without considering losses from leaching and volatilisation), the countries that show the highest surplus or average annual excess are the Netherlands, Belgium and the UK, with values of 204±73kg N/ha, 169±59kg N/ha and 121±56 kg N /ha respectively. These also exhibit the highest losses from leaching and volatilisation, of about 100 kg N/ha. The results indicate that there are no actual deficit situations in any European country and that the lowest N surpluses are found in the Baltic countries and Ukraine.

[xli] According to EU Council Directive 91/676/EEC, the amount of livestock manure applied to land each year shall not exceed 170kgN/ha

[xlii] Calculation according to https://www.fao.org/faostat/en/#data/ESB; the balances consider the nutrient inputs and outputs from the dataset for cropland nitrogen where inputs are: mineral fertilisers, manure applied to soils, atmospheric deposition, biological fixation and seed; and outputs are: crop removal, leaching and volatilisation

[xliii] The comparison was carried out on the basis of nitrogen use efficiency

2. Calculation of soil balance based on manure + digestate, without mineral fertilisers

Next, the exclusion of inputs from mineral fertiliser sources from the nutrient balance for agricultural soil was used, as previously proposed, to understand to what extent the nutrient requirements of national agricultural production can be satisfied solely through the recovery of nutrients derived from manure and digestates. In this case, the balance also considered losses that may partially derive from the mineral fertilisers.

Ignoring the input from petrochemical-based N fertilisers, the soil N balance of most European countries shows a deficit, except for Belgium and the Netherlands. These countries display a strong surplus, as mentioned earlier, likely due to the high annual application of manure in combination with low reported cropland nitrogen use efficiency. Other countries that also maintain nitrogen surpluses include Switzerland, Italy, Portugal, Spain, Norway and Slovenia, likely for the same reasons. In these countries, total nitrogen inputs already exceed crop uptake, and priority should therefore be given to the use of existing organic nitrogen sources. This may require nutrient reallocation or improvements in nitrogen use efficiency, including the conversion of manure into digestate with higher plant-available nitrogen. Optimised timing and application practices following digestate processing are essential to ensure efficient plant uptake.

This was confirmed by a strong correlation (r=0.89) between input of N from manure and the balance. The balance ranges between -1.3 kg N/ha to -46.5 kg N/ha, indicating a general European nitrogen deficit under a complete abandonment of petrochemical-based fertilisers. Overall, a complete renouncement of mineral fertilisers across European soils would result in a total N deficit of -2.36 million tonnes, with significant disparities between countries with the highest N deficit per ha (Bulgaria, Poland, Germany and France). By moving away entirely from the use of petrochemical-based N fertilisers in agriculture, it was estimated that with current digestate production, it would be possible to meet over 10% of the current N needs of European agriculture.

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The European Biogas Association (EBA) is committed to the deployment of sustainable biogas and biomethane production and use across the continent. EBA counts today on a well-established network of over 380 national associations and other organisations covering the whole biogas and biomethane value chain throughout Europe and beyond.

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