



D2.1 Technical, environmental and scalability potential of case studies

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FERTITEC Project Synopsis

The EU Horizon CSA project FERTITEC, funded under the *HORIZON-CL6-2024-ZEROPOLLUTION-01-02* call, promotes the circular economy by advancing **alternative fertilising products** derived from secondary raw materials. By reducing dependence on conventional mineral fertilisers, the project addresses challenges in **waste management and environmental pollution**, contributing to sustainable nutrient recovery. Conventional fertiliser production depletes natural resources and generates pollution, underscoring the need for more **resource-efficient solutions**.

FERTITEC builds on expertise from previous EU-funded initiatives – including Novafert, SUSFERT, FER-PLAY, SOILUTIONS, MainstreamBIO, SuMaNu, CINURGI, and NUTRIMAN – by integrating advanced **waste recycling technologies** into fertiliser production. The goal is to develop **competitive, bio-based alternatives** that enhance both agricultural productivity and environmental sustainability.

Aligned with the **EU's strategic priorities** in sustainable agriculture, waste reduction, and the bioeconomy, FERTITEC also works to harmonise **sustainability certification systems** and improve the marketability of bio-based fertilisers. Through its **Knowledge Exchange Platform (KEP)**, the project fosters collaboration with key agricultural stakeholders to drive innovation in the fertiliser industry.

By **bringing forward Best Available Fertilising Techniques (BATs) in several EU countries and extrapolating outcomes to the African Union**, FERTITEC supports the broader transition to sustainable fertilising solutions. With a commitment to both **environmental sustainability and economic viability**, the project integrates learnings from past initiatives, engages industry actors, and applies state-of-the-art fertiliser technologies, helping shape the future of sustainable agriculture in Europe and beyond.

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List of Terms and Definitions

Abbreviation	Definition
AD	Anaerobic Digestion
AF	Alternative Fertiliser products derived from side stream recovered nutrients
AU	African Union
BAT	Best Available Technologies/Techniques
BBF	Bio-Based Fertiliser
Biowaste	Organic waste, including food and plant residues
Corg	Organic Carbon
Ca	Calcium
Case Studies	Selected existing installations of nutrient recovery technologies in the EU and AU (in FERTITEC T1.1)
CMC	Component Material Categories
DM	Dry matter
EU	European Union
Fisheries & Aquaculture Residues	Side streams from fish processing systems
GHG	Greenhouse gas
HTC	Hydrothermal Carbonization
Industrial Side-Streams	By-products from industrial processes
K	Potassium
KEP	Knowledge Exchange Platform
LCA	Life Cycle Assessment
N	Nitrogen
NH ₃	Ammonia
NH ₄ ⁺	Ammonium
NH ₄ NO ₃	Ammonium nitrate
(NH ₄) ₂ SO ₄	Ammonium sulphate
NO _x	Nitrogen oxides
NR	Nutrient Recycling
NUTS	Nomenclature of territorial units for statistics
OM	Organic matter
P	Phosphorous
PFC	Product Function Categories
REACH	Registration, Evaluation, Authorisation and Restriction
RNF	Recycled Nutrient Fertiliser
RP	Reporting Period
S	Sulphur
Scalability Potential	The ability of a technology to expand to a larger scale
Secondary Raw Materials	Side stream and waste-derived inputs used for fertiliser production
Soil Improver	Improves soil quality and functioning rather than supplying nutrients directly to crops
Technology Records (T1.1)	Dataset of 190 mapped nutrient recovery technologies
TRL	Technology Readiness Level
WP	Work Package
WWTP	Waste Water Treatment Plant

Executive Summary

This deliverable (D2.1) advances FERTITEC Objective 2.1 by providing a comprehensive assessment of the technical, environmental, and scalability aspects of nutrient recovery solutions across selected case studies in the EU and the African Union. It builds on prior mapping work (T1.1 and T1.3) and examines 30 representative case studies derived from a broader dataset of 190 technology records, covering five key secondary raw material streams.

The analysis evaluates the technical feasibility of technologies by examining their Technology Readiness Levels (TRLs), performance characteristics, and operational requirements. It further investigates resource efficiency, offering insight into how effectively these systems recover and reuse valuable nutrients. Environmental feasibility is assessed through analysis of impacts on climate, soil, and water, including factors such as nutrient leaching and greenhouse gas emissions, alongside consideration of pollution prevention measures.

In addition, the deliverable explores the availability and reliability of feedstock supply and assesses the potential for scaling up technologies by analysing their current application, commercial maturity, and adaptability across different operational scales and contexts.

D2.1 also contributes to a holistic evaluation framework aligned with FERTITEC Objective 3, integrating technical and environmental findings with broader value chain perspectives. The results are structured into detailed case study datasheets, forming a robust knowledge base to support cross-case comparisons (T3.1) and subsequent work package outputs, including socioeconomic and adoption analyses (T2.2).

Overall, the deliverable identifies promising, scalable, and sustainable nutrient recovery solutions and provides evidence-based insights to support their wider uptake. By doing so, it contributes to advancing circular economy practices and facilitating the broader adoption of alternative fertilising products across diverse regional contexts.

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1. Introduction

The move from mineral and fossil-dependent systems toward a circular economy calls for redesigned approaches. Developing alternative fertiliser products is a critical part of this shift, as it enables more sustainable farming practices and helps bring nitrogen and phosphorus cycles back within ecological limits. Yet, much of the existing knowledge on nutrient recovery technologies is scattered across different projects and platforms, which has slowed progress toward circular solutions.

The EU-funded FERTITEC project responds to this gap by compiling current nutrient recovery technologies, identifying operational cases, and examining their performance and ability to scale.

Deliverable D2.1 presents a comprehensive assessment framework and initial results for evaluating technologies and case studies related to the recovery and recycling of nutrients into alternative fertilising products. The mapping and analysis activities conducted under WP1 provided a foundation for this deliverable, which draws upon a data mining process that was systematically developed.

The work underpinning D2.1 integrates insights from 190 mapped technology records in T1.1 and 30 selected case studies identified in T1.3 (selection described in D2.3) across the EU and African Union, covering five key secondary raw material streams (Figure 1). These case studies represent proven practices and emerging solutions for nutrient recovery, whose current performance, maturity, and scaling potential are further examined in this deliverable.

Aligned with Objective 3 (O3), D2.1 (together with D2.2 and D2.3) establishes and applies a holistic assessment approach to evaluate the selected case studies across multiple dimensions. This includes an in-depth review of their technical and environmental aspects, and practical perspectives from across the value chain. The findings presented in this deliverable contribute to a set of structured case study datasheets and lay the groundwork for other analyses and outputs under WP2. Ultimately, D2.1 supports the identification of scalable, sustainable solutions and provides actionable knowledge to facilitate the broader adoption of alternative fertilising products.

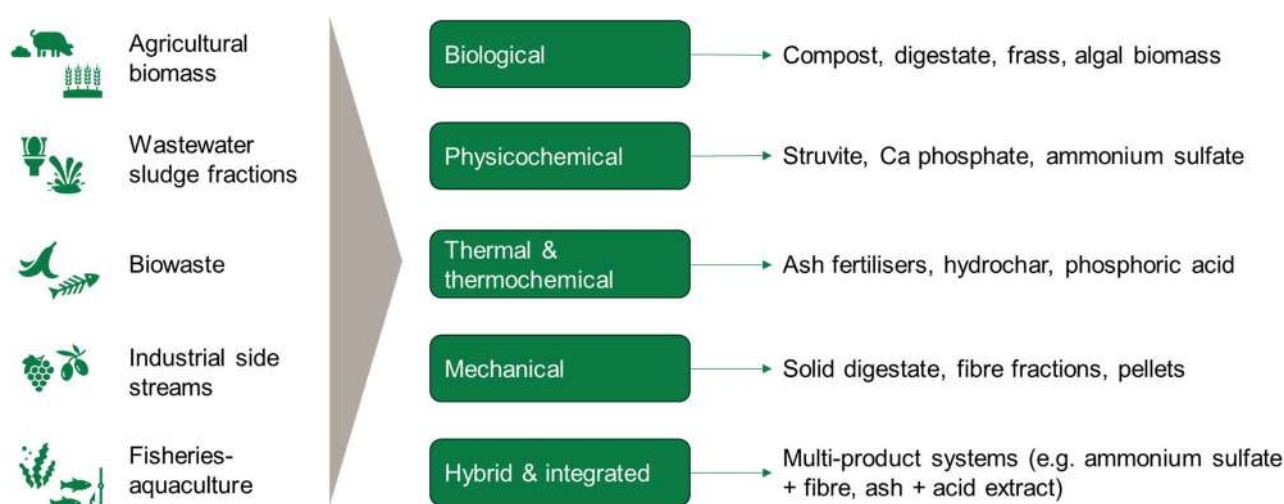


Figure 1. Overview of the selected case studies derived from the long-list of 190 mapped technology records.

2. Approach and methodology

The 30 case studies analysed in this work were selected in accordance with the criteria defined in T1.3 and Deliverable D2.3 (Ververis et al., 2026). The selection aimed to ensure a balanced and representative sample by considering several key factors. These included the geographical distribution of case regions to capture regional diversity, the scale of operations to reflect both smaller and larger systems, and the inclusion of both full-scale and pilot-scale installations. Furthermore, particular attention was given to the availability and quality of environmental and technical data, as well as the existence of reliable information on mass and energy balances and environmental impacts. In addition, coordination with our "sister project", FertiCovery, was undertaken to minimise overlap in the selected case studies as far as possible.

The assessment of technical and environmental performance was primarily based on publicly available data. This approach ensured transparency and reproducibility while allowing for a consistent comparison across cases. Data were gathered from a range of sources, including project reports, peer-reviewed scientific literature, and relevant online resources. The specific data sources used for each technology are documented in detail in Appendix 1.

For each case study, a comprehensive dataset was compiled covering key aspects of system performance, resource efficiency and sustainability. Information on raw materials and other process inputs was collected to assess resource availability and potential constraints. The nutrient recycling potential of each technology was evaluated by examining nutrient concentrations in outputs and nutrient the concentration potential of the technologies. These aspects were used to analyse implications for transportability and practical use of end-products. Details on the technologies, such as detailed description of the process phases, applied temperature and pH, if available, were collected to provide insights to the analysis. In addition, the consumption of external inputs, for example energy and chemicals, was included and further evaluated as part of the resource efficiency and environmental performance analysis.

The innovativeness assessment was based on the Web of Science dataset, using publication activity as a bibliometric proxy for research intensity and technological development. The assessment was executed using four time periods: 2006–2010, 2011–2015, 2016–2020, 2021–2025.

Environmental performance was analysed through reviewing previous studies on life-cycle assessments (LCAs) and other environmental studies. The data was collected with regard to the entire value chain of the circular fertilising products. The objective of this study was to collect data on various impact categories, encompassing both prevalent ones (e.g. climate impacts, eutrophication, ecotoxicity, acidification) and less common ones (e.g. biodiversity, soil health) to capture broader ecosystem effects and recognise their importance for long-term sustainability, but also acknowledging data limitations across some cases.

The collected data formed the basis for evaluating the technological readiness levels (TRLs), innovativeness, scalability potential, resource efficiency, and overall environmental performance of the assessed technologies. All information was systematically compiled in structured Excel spreadsheets, allowing for consistent analysis and facilitating cross-case comparison.

These compiled datasets enabled the development of concise syntheses for each case study, which were subsequently used to produce the datasheets under T2.3 and to contribute to the Knowledge

Exchange Platform (KEP). A more detailed analysis of the KEP's functionality can be found in FERTITEC deliverable D1.2 (Kalitsou et al., 2026). The full data from the datasheets is available to download from the project's Zenodo website. While the KEP datasheets provide more detailed, case-specific information, the present deliverable focuses on synthesising the key findings and highlighting overarching insights derived from the assessment.

3. Overview of 30 selected case studies across EU and AU

Table 1 presents the 30 selected case studies identified under T1.3, focusing on existing installations that recover alternative fertilising products from diverse secondary raw materials. The cases were selected based on predefined criteria, including TRL level, geographical representation, operational scale, and data availability, and cover regions across the EU and AU. A more detailed description of the case selection method can be found in FERTITEC deliverable D2.3 (Ververis et al., 2026). These case studies form the basis for the detailed analyses carried out in this T2.1.

Table 1. Overview of the 30 selected cases.

Technology	Tech no. in T1.1	Class	TRL and scale	Secondary raw material	Alternative fertilising product	Region
Hydrated ash of incinerated poultry manure	11	Thermal and thermochemical	TRL 9, full scale	Agricultural biomasses	PK fertiliser	Central EU
Nutrient recovery via membrane stripping and calcium precipitation	120	Hybrid and integrated	TRL 6, pilot	Municipal wastewater fractions	Ammonium sulphate, amorphous calcium phosphate	North EU
Insect mealworm frass fertiliser via bioconversion of organic waste	17, 41, 108	Biological	TRL 8, full scale	Agricultural biomasses	NPK fertiliser	South EU
Insect black soldier fly frass compost via bioconversion of food waste	42, 184	Biological	TRL 7, full scale	Biowaste	Compost	Africa
Bokashi fermentation, drying, and pelletising of fish by products	44	Hybrid and integrated	TRL 5, pilot	Fisheries-aquaculture	Soil improver	North EU
Thermomechanochemical fractionation of fish by products	19	Hybrid and integrated	TRL 5, pilot	Fisheries-aquaculture	NP fertiliser	Central EU
Anaerobic digestion of RAS fish sludge	159, 160	Biological	TRL 7, full scale	Fisheries-aquaculture	N fertiliser	North EU
Low temperature drying of poultry manure and pelletising	154	Thermal and thermochemical	TRL 9, full scale	Agricultural biomasses	NPK fertiliser	North EU
Anaerobic digestion and solid liquid separation of pig slurry	118	Hybrid and integrated	TRL 9, full scale	Agricultural biomasses	Soil improver	North EU

Incineration of dewatered sewage sludge and P recovery as calcium phosphate	178	Hybrid and integrated	TRL 8, full scale	Municipal wastewater fractions	P fertiliser	North EU
Precipitation and magnetic recovery of P as vivianite from anaerobic digestion	188	Physicochemical	TRL 5, pilot	Municipal wastewater fractions	P fertiliser	Central EU
Ammonia stripping to ammonium sulphate and anaerobic digestion	123	Hybrid and integrated	TRL 7, full scale	Municipal wastewater fractions	Ammonium sulphate, digestate	South EU
Anaerobic digestion, N stripping with gypsum for ammonium sulphate and liming material recovery, fibre separation	125	Hybrid and integrated	TRL 7, full scale	Agricultural biomasses	Ammonium sulphate, digestate liquid fraction, liming substrate	Central EU
Urine nitrification, activated carbon filtration and concentration	127	Hybrid and integrated	TRL 7, pilot	Municipal wastewater fractions	NPK fertiliser	Central EU
Urine stabilisation, drying and granulation or pelletising	126	Hybrid and integrated	TRL 6, pilot	Municipal wastewater fractions	NP fertiliser	North EU
Hydrothermal carbonisation, solid liquid separation, drying	85, 168	Hybrid and integrated	TRL 8, full scale	Agricultural biomasses	Soil improver	North EU
Concentration of potato cell water by evaporation	151, 156	Thermal and thermochemical	TRL 9, full scale	Industrial side-streams	K fertiliser	North EU
Mixing of compost and mineral nutrients, and pelletising	185	Hybrid and integrated	TRL 9, full scale	Agricultural biomasses	NPK fertiliser	Africa
Pyrolysis with additives for N binding, and recovery of mono ammonium phosphate	58, 59	Hybrid and integrated	TRL 7 for pyrolysis, 4 to 5 for ammonia recovery, pilot	Agricultural biomasses	Biochar and monoammonium phosphate	Central EU
Pig slurry separation and liquid fraction N recovery through stripping and scrubbing	60	Hybrid and integrated	TRL 7, pilot	Agricultural biomasses	Ammonium nitrate, ammonium sulphate	Central EU
Sludge drying, incineration, and P recovery as phosphoric acid	186	Hybrid and integrated	TRL 8 to 9, full scale	Municipal wastewater fractions	Phosphoric acid	North EU
N recovery of sludge liquid fraction as ammonium sulfate	177	Physicochemical	TRL 7, pilot	Municipal wastewater fractions	Ammonium sulphate	North EU
Pelletising of food industry side streams	180	Mechanical	TRL 9, full scale	Industrial side-streams	NPK pellets	North EU
P recovery as struvite precipitation from digestate liquid of WWTP	49	Physicochemical	TRL 9, full scale	Municipal wastewater fractions	P fertiliser	South EU

Composting of agricultural and wine production sidestreams	52, 54	Biological	TRL 9, full scale	Biowaste	Soil improver	South EU
Urine separation for fertiliser use from dry toilets	187	Mechanical	TRL 6, pilot	Municipal wastewater fractions	NPK fertiliser, soil improver	Africa
Pelletising of plant based digestate solid fraction	28	Mechanical	TRL 9, full scale	Agricultural biomasses	Fertiliser, soil improver	Central EU
Solid fraction of digestate	96	Mechanical	TRL 9, pilot	Agricultural biomasses	Soil improver	South EU
Composting of biowaste and plant biomass	189	Biological	TRL 9, full scale	Biowaste	Soil improver	Central EU
Algae cultivation and hydrolysis to biostimulant production	190	Biological	TRL 9, full scale	Industrial side-streams	NK fertiliser	South EU

The case overview provides an insight into the main nutrient recovery processes that are currently being used and developed across the EU and Africa. The selected cases include biological routes such as composting, anaerobic digestion, insect bioconversion, and algae cultivation, physicochemical routes such as struvite precipitation, calcium phosphate recovery, ammonia stripping, membrane-based concentration, and vivianite recovery, thermal and thermochemical routes such as drying, incineration, pyrolysis, hydrothermal carbonisation, and evaporation, as well as mechanical operations such as separation and pelletising. Taken together, these cases represent the main processing technologies, or chain of technologies, by which nutrients are currently stabilised, concentrated, extracted, or transformed into fertilising products.

The TRL distribution is broad enough to reflect the current development landscape of the sector. Mature technologies at TRL 8 to 9 include composting, pelletising, low temperature drying, struvite recovery, sludge incineration with phosphorus recovery, and evaporation-based concentration. At the same time, the cases include TRL 6 to 7 technologies such as urine treatment, membrane stripping, and integrated digestion and stripping systems, as well as lower TRL pilot concepts such as vivianite recovery, thermomechanochemical fish side stream fractionation, and pyrolysis coupled with ammonia capture. This spread is useful because it allows comparison of both established market options and emerging technologies with future scale up potential.

The feedstock coverage is also well aligned with the project focus, since the cases cover the main secondary raw material groups: agricultural biomasses, municipal wastewater fractions, biowaste, industrial side streams, and fisheries and aquaculture residues. These are converted into a wide range of alternative fertilising products, including soil improvers, NPK and PK fertilisers, struvite, calcium phosphate, biochar, digestate-based products and biostimulants, as well as raw materials for further fertiliser production, such as ammonium sulphate and phosphoric acid. Geographically (Figure 2), the portfolio also provides a useful spread across North EU, Central EU, South EU, and Africa, which helps capture differences in feedstock availability, infrastructure, and practical scale up conditions. As a result, the portfolio reflects not only the project case studies, but also the main biomass, products and regional contexts that are currently relevant to fertiliser recovery and recycling in circular bioeconomy strategies.

However, the coverage of cases in the AU region is limited, as obtaining relevant information proved to be highly challenging. Consequently, the analyses presented in this report are primarily focused on the European context. Nevertheless, similar biomass resources are also generated in the AU region, and comparable technological approaches could be applied there. However, adaptation to local conditions is essential (see Chapter 4.4). In many cases, simpler and lower-cost technologies, such as composting and anaerobic digestion, are more suitable than capital-intensive chemical processes due to limited infrastructure, energy supply, and technical capacity.

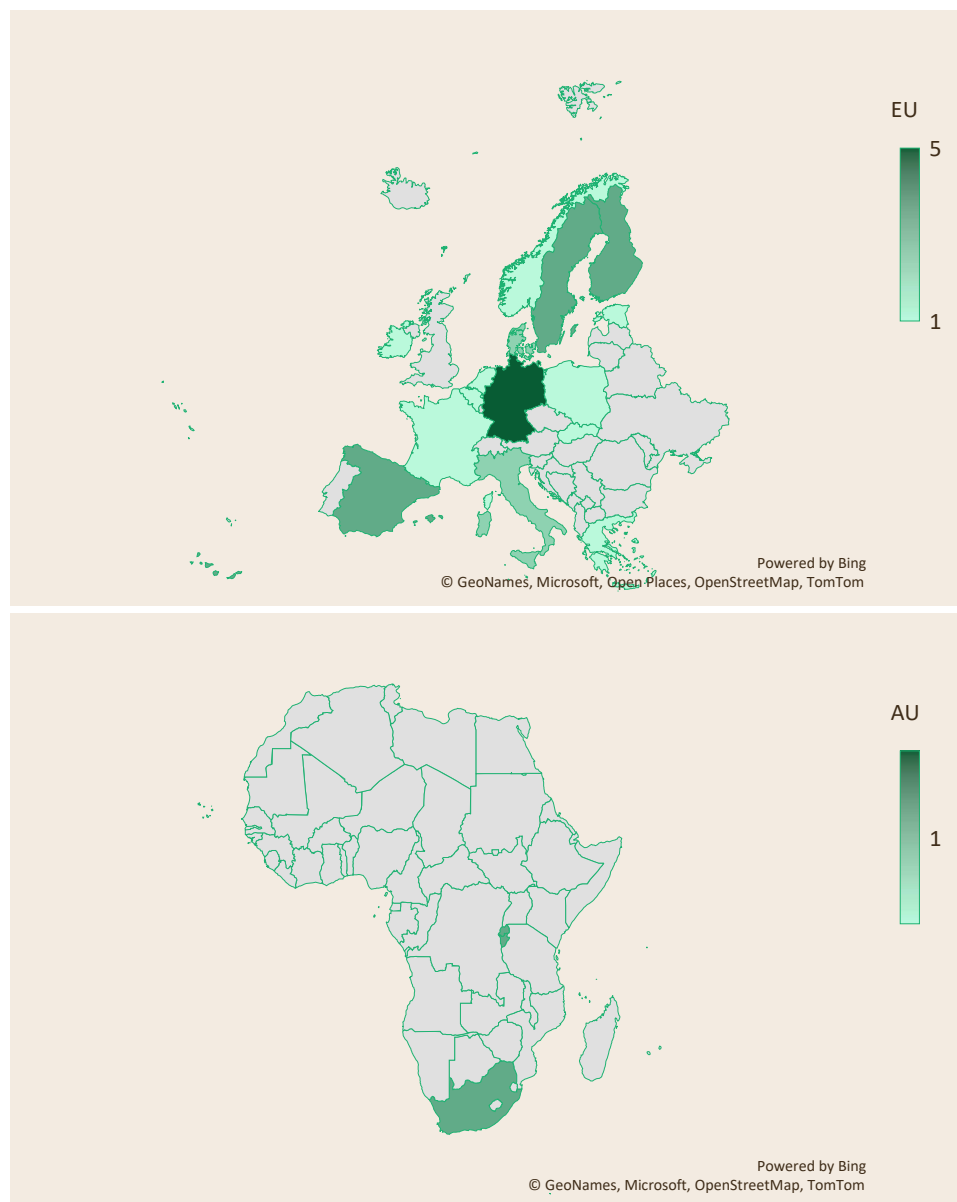


Figure 2. The geographical coverage in Europe and Africa of the selected 30 case studies. Scale represents the number of cases in each country.

3.1 Classification of selected technologies

The technologies applied in the selected cases are summarised in Figure 3. Agricultural biomasses represent the largest feedstock group and are processed using a wide range of technologies, including both thermochemical and biological approaches, such as anaerobic digestion and

composting. Biowaste is primarily treated through composting or insect-based processes and often serves as a co-feedstock alongside agricultural residues. Also, a significant share of the cases involves the treatment of municipal wastewater fractions, where chemical processes, such as stripping, precipitation, and nutrient recovery from incineration ashes, are most commonly used. In addition, source-separated urine is treated using a distinct set of methods. Industrial side streams are usually concentrated and processed further, for example into pelletised products. Biomass from fisheries and aquaculture is treated using conventional methods, such as anaerobic digestion, as well as more advanced processes, including thermochemical fractionation, fermentation, and hydrolysis.

It should be noted that the 30 case studies do not cover all available technologies for alternative fertiliser production. Several additional technologies exist and have been assessed in more detail within the FertiCovey project and overlap between the case selections between the two projects was intentionally avoided. The cases of the FertiCovey are presented in the corresponding deliverable D2.1 (Klempetsani et al., 2025).

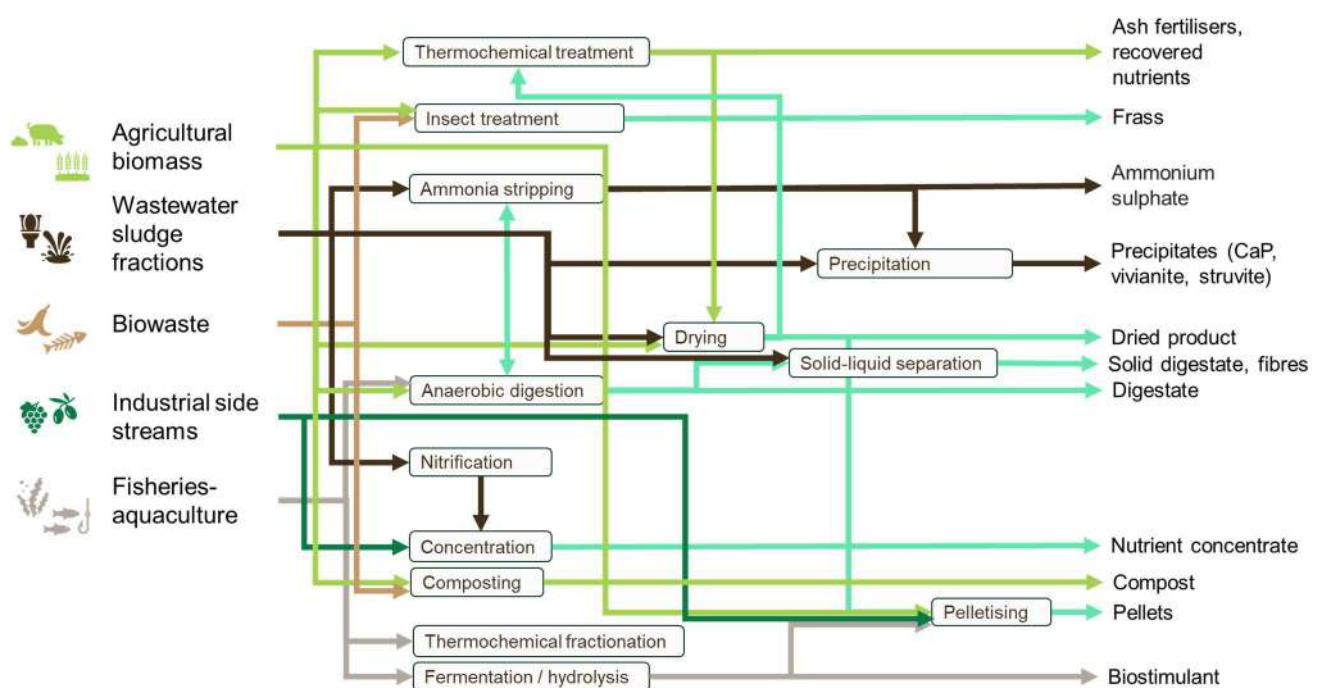


Figure 3. Combined process flows of the selected cases.

Table 2 shows the classification of nutrient recovery technologies based on principles, mechanisms, products, and role in treatment chains. The classification can be based primarily on the core treatment principle, followed by the recovery mechanism. This approach is more robust than classifying technologies by feedstock alone, as similar process types are applied across diverse side streams. An additional classification layer is defined by the mechanism through which nutrients are captured, concentrated, transformed, or extracted into fertilising products. For Task 2.1, this results in a practical two-level framework. The first level categorises technologies into biological, physicochemical, thermal or thermochemical, mechanical, and hybrid or integrated systems. The second level describes the nutrient recovery pathways, such as biomass accumulation, mineral precipitation, ammonia phase transfer, membrane concentration, sorption, wet chemical extraction from ash, or simple fractionation into nutrient-rich solid and liquid fractions. This structure is well suited for classification, as it accommodates both single unit operations and multi-step treatment trains, while preserving insights

into product quality, technological readiness, and scalability (Rey-Martínez et al., 2024, Vaneeckhaute et al., 2018).

Table 2. Classification of nutrient recovery technologies.

Main classification level	Defining principle	Main recovery mechanisms	Fertilising products	Role in treatment chain
Biological	Nutrients are accumulated, transformed, or stabilised by living organisms or biologically driven conversion	Composting, anaerobic digestion enabled release, algae uptake, insect bioconversion, biological phosphorus removal, linked accumulation	Compost, digestate, frass, algal biomass, biologically stabilised organic fertilisers	Can be a final route or an upstream release step
Physicochemical	Nutrients are separated or immobilised through phase change, reaction, selective transfer, or surface binding	Struvite and calcium phosphate precipitation, stripping and scrubbing, gas permeable membranes, ion exchange, sorption, membrane concentration, electrodialysis	Struvite, calcium phosphate, ammonium sulfate, ammonium solutions, sorbent based fertilisers	Often the main recovery step for marketable mineral products
Thermal and thermochemical	Heat driven conversion concentrates nutrients, destroys organics, and creates ash, char, or hydrochar for direct use or further extraction	Drying, pyrolysis, combustion, gasification, hydrothermal carbonisation, ash leaching	Ash based fertilisers, hydrochar products, phosphoric acid, calcium phosphate, thermochemically upgraded solids	Best for contaminated or solid rich streams and for strong volume reduction
Mechanical	Physical fractionation partitions solids and liquids without changing nutrient chemistry much	Solid liquid separation, sedimentation, centrifugation, filtration, pelletising as finishing	Solid digestate fractions, fibre fractions, densified pellets	Usually, an enabling concentration and logistics step rather than final recovery
Hybrid and integrated	Two or more classes are essential to the final product pathway	AD plus stripping, separation plus precipitation, nitrification plus filtration plus concentration, pyrolysis plus extraction	Multi product systems such as ammonium sulfate plus fibre, ash plus acid extract, concentrated liquids plus solids	Increasingly the most realistic category for high recovery and case specific optimisation

On this basis, the main top-level classes are biological, physicochemical, thermal and thermochemical, mechanical, and hybrid or integrated systems. Each class represents a distinct pathway through which nutrients are stabilised, concentrated, extracted, or transformed into fertilising products.

Biological processes rely on nutrient accumulation, stabilisation, or biologically mediated conversion, as exemplified by composting, anaerobic digestion, algal cultivation, and insect bioconversion. Physicochemical processes recover nutrients through selective transfer, reaction, or separation mechanisms, including precipitation, stripping, sorption, ion exchange, and membrane-based concentration. Thermal and thermochemical processes employ heat-driven transformations (such as

drying, combustion, pyrolysis, gasification, and hydrothermal treatment) to reduce volume, eliminate organic contaminants, and produce ash, char, or hydrochar-based products. Mechanical processes primarily enable fractionation, separation, or densification through operations such as solid–liquid separation, centrifugation, filtration, and pelletising. Hybrid or integrated systems combine two or more of these principles within a treatment choices and are increasingly representative of real-world nutrient recovery outlines.

An important interpretative consideration is the role of certain unit operations (such as mechanical separation, drying, and pelletising) within the classification. While these processes are often critical for transport, storage, handling, and marketability, they do not necessarily constitute the primary nutrient recovery mechanism. In many cases, they are better understood as enabling or finishing steps, unless they directly result in the formation of the fertilising product (Hjorth et al., 2011, Fuchs and Drogs, 2013). By contrast, processes such as precipitation, stripping, ash extraction, and biologically driven nutrient accumulation are typically regarded as the key recovery mechanisms, as they determine the nutrient form, concentration, and agronomic functionality of the final product (e.g. Mehta et al., 2015). Keeping this distinction clear helps avoid confusion between the main recovery processes and supporting steps.

3.2 Market and regulatory implications for alternative fertiliser production

Across the 30 selected cases, the main commercial divide is not simply between biological, physicochemical, thermal, or hybrid technologies. It is between products that can enter familiar fertiliser markets with clear specifications, and products that require new supply chains, new user confidence, or new regulatory interpretation before demand can grow. This reading is consistent with D1.3. Market dynamics and regulatory analysis of alternative fertilisers (Pisani and Soriano, 2025), which frames wider uptake as a joint market and regulatory challenge and reports input from more than one hundred market and policy actors. The case overview shows that market success depends on product concentration, transportability, traceability, and legal fit as much as on nutrient recovery efficiency (e.g. Wang et al., 2024).

A first implication is that concentrated mineral-like products have the clearest route to broader trade. In the selected cases, struvite, ammonium sulphate, calcium phosphate, phosphoric acid, dried urine fertilisers, and dense pellets all reduce transport cost per unit nutrient and fit better with existing storage and spreading systems. These properties matter commercially because they lower the friction of adoption for distributors and farmers. By contrast, composts, digestate solids, frass, and other soil improvers may have clear agronomic value, but their market is more sensitive to transport distance, local soil needs, odour, moisture, and variability in nutrient release.

A second implication is that many of the strongest business cases are built on combined value streams rather than fertiliser sales alone. Several hybrid cases in the table do not only make a fertilising product. They also reduce waste handling cost, improve dewatering, cut storage volume, or are linked to energy production and use available heat and energy. This is especially visible in sludge recovery, digestate stripping, manure drying, and integrated separation process chains. In market terms, this means that profitability often rests on plant integration and avoided disposal cost as much as on the headline fertiliser price (Vaneeckhaute et al., 2018).

The regulatory side follows the same pattern. The EU Fertilising Products Regulation, Regulation 2019/1009 (European Parliament and Council of the European Union, 2019), opened the harmonised market to CE marked fertilising products beyond conventional mineral fertilisers and set common safety, quality, contaminant, and labelling rules for product groups such as organic fertilisers, organo-mineral fertilisers, soil improvers, inhibitors, plant biostimulants, and growing media. The regulation works through Product Function Categories and Component Material Categories, which are directly relevant to the FERTITEC case structure because many of the selected cases can be understood through exactly these two classification profiles.

This creates a clear regulatory advantage for technologies that produce well defined products from recognised material categories. Cases such as struvite precipitation, ammonium sulphate recovery, calcium phosphate recovery, composting, digestate fraction upgrading, and standard pelletising are closer to an established compliance logic than highly novel blends or multifunctional products with less settled market identity. For the latter, the burden of proof is heavier. Producers must show not only nutrient value, but also contaminant control, process hygiene, labelling accuracy, and a clear product claim.

For several case groups, the fertiliser law is only the final step. Waste status remains critical because the Waste Framework Directive distinguishes between by products and waste and sets the conditions under which waste can cease to be waste and become a product or secondary raw material (Waste Framework Directive, 2008/98/EC, 2025/1892/EU, European Commission). This matters most for sewage sludge routes, mixed biowaste routes, and some integrated recovery systems where market scaling can be slowed by legal uncertainty around feedstock status, not just by process performance.

Animal by product legislation is another major filter. This is highly relevant for cases based on fish by products, manure, processed frass, composted animal derived inputs, and residues from biogas plants. The EU has recently clarified part of this pathway through Delegated Regulation 2023/1605 (European Commission, 2023), which sets end points in the manufacturing chain for certain organic fertilisers and soil improvers derived from animal by products, including ash, biogas residues, compost, processed manure, and frass used as component materials in EU fertilising products. For the relevant FERTITEC cases, this improves legal clarity, but it does not remove the need for strict process control and traceability.

Taken together, the 30 cases suggest that the market for alternative fertiliser production will grow fastest where three conditions align. The product must be physically tradable, its agronomic claim must be easy to understand, and its regulatory route must be predictable. Technologies that yield concentrated and standardised products are therefore favoured for broad market expansion, while bulk organic products remain highly relevant locally. The strategic implication is that alternative fertiliser production is not only a matter of recovering nutrients from secondary raw materials. It is also a matter of converting heterogeneous residual side streams into products that markets can recognise and regulations can clearly govern (e.g. Foged et al. 2025).

4. Technical and environmental potential of the case studies

4.1 Technical aspects

This chapter evaluates the technical aspects of the case studies. The analysis examines the maturity of the selected technologies by assessing their Technology Readiness Levels (TRLs), and their innovativeness by reviewing the volume of scientific publications. In addition, the chapter assesses the resource efficiency of the case studies, with particular attention to nutrient recovery and the effective utilisation of biomass side streams. Recognising feedstock supply as a key enabler of bio-based fertiliser production, the chapter analyses the availability of relevant biomass feedstocks at the European scale. The agronomic efficiency of the resulting fertiliser products is also briefly reviewed. Finally, the chapter integrates these technical aspects to assess the upscaling potential of the technologies examined.

4.1.1 Technology readiness level (TRL) of the case study technologies

The case studies span a range of maturity levels, including market-ready technologies, pilot- to demonstration-scale systems, and a smaller number of emerging integrated solutions. This enables both a clear picture of technologies already deployable and an assessment of approaches with potential to shape future scale-up.

The portfolio also achieves broad geographical coverage, encompassing cases from the North EU, Central EU, South EU, and Africa. This regional diversity is important, as technology performance and scalability depend not only on process design but also on factors such as climate, infrastructure, market conditions, source-separation practices, and energy integration opportunities.

The most mature technologies across cases are generally those that either solve an established waste handling problem or fit well into existing infrastructure (Table 3). Composting, separation, pelletising, digestion, drying, sludge incineration, and evaporation are mature because their operating logic is already well established at farm, plant, or industrial scale. Struvite precipitation and ash-based phosphorus recovery are also relatively advanced because they target relatively concentrated side streams and produce more standardised fertiliser products (e.g. Egle et al., 2016).

By contrast, pilot stage systems tend to be those that depend on tighter control of chemistry, multi-step integration, or less mature collection systems. Urine derived fertilisers are a clear example. Internal nutrient recovery can be very high, with about 98.5% N recovery in urine concentration and about 90 to 100% N recovery in urine drying, but the overall readiness of these systems still depends heavily on source separation logistics (e.g. Harder et al., 2019). The same pattern appears in integrated stripping and recovery chains, where the practical readiness of the full system follows the least mature essential step (Vaneeckhaute et al., 2018).

Table 3. Technology readiness level (TRL) profile of the selected cases.

TRL range	Main case types	Interpretation
TRL 8 to 9	Composting, pelletising, low temperature drying, struvite precipitation, sludge incineration with phosphorus recovery, ash hydration, hydrothermal carbonisation, evaporation of potato cell water, algae-based production	Mature or near market standard routes with proven operating logic
TRL 6 to 7	Membrane stripping plus precipitation, ammonia stripping trains, urine concentration and drying, fish sludge digestion, pig slurry stripping, reject water ammonium sulphate recovery	Proven at pilot or early commercial scale, but still sensitive to integration, site conditions, or infrastructure fit
TRL 5 and below	Thermomechanochemical fish side stream fractionation, bokashi fish granules, vivianite recovery, pyrolysis plus ammonia recovery	Promising but still less settled in scale up pathway, operating stability, or market proof

4.1.2 Innovativeness

The approach to assess innovativeness followed publication-trend methods that use temporal patterns to distinguish mature fields from emerging technologies (Cauthen et al., 2022; Keathley-Herring et al., 2016). For each subgroup, the dataset provides total records and their distribution across four five-year periods (2006–2010, 2011–2015, 2016–2020, 2021–2025). High and sustained publication volumes across all periods indicate mature technologies, while low early activity followed by strong recent growth indicates emerging ones, and continuous but moderate growth is classified as growing (Campani and Vaglio, 2014). As search strings are defined at the subgroup level, results reflect the maturity of technology routes rather than individual implementations.

Overall, the Web of Science dataset shows a spectrum from mature technology families to emerging process chains. The most established subgroups are composting biowaste, struvite precipitation from wastewater fractions, and thermal drying/evaporation. These have the largest publication volumes and were already well represented in 2006–2010 (Figure 4). Composting and struvite continued strong growth to 2021–2025, while thermal drying/evaporation remained high-volume but slightly declined in the latest period, indicating a mature field with slower expansion.

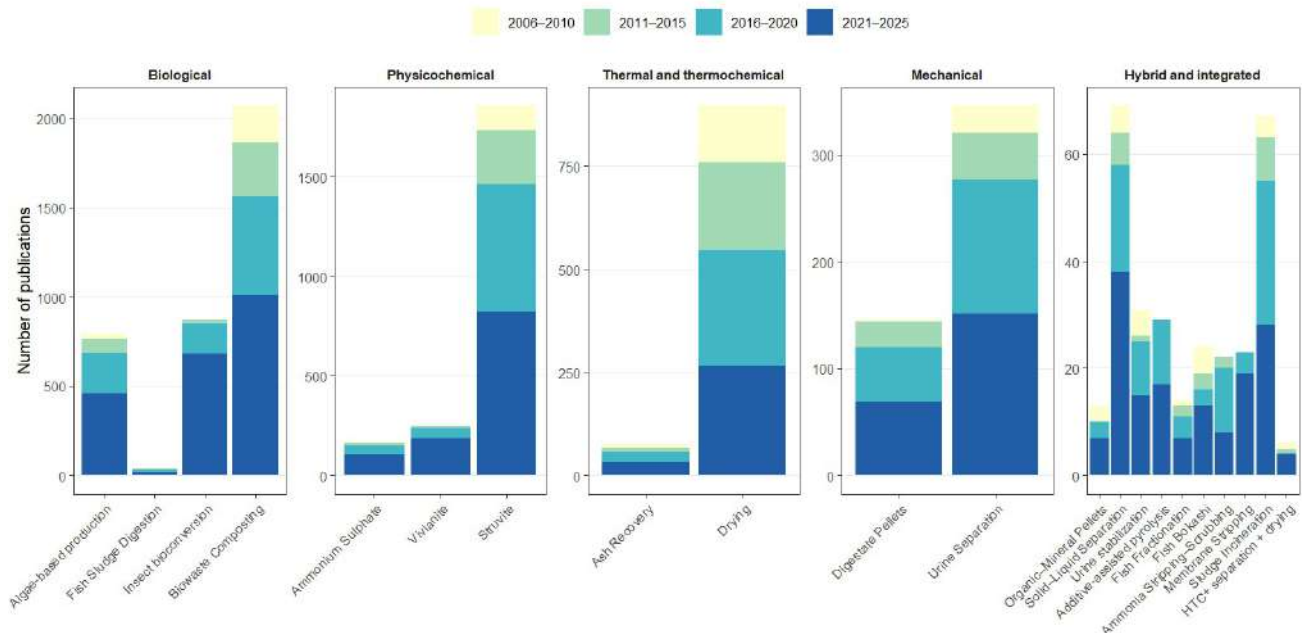


Figure 4. Publication trends in nutrient recovery and fertiliser technologies. Bars show total publication counts per subgroup within each main classification level, stacked by four time periods (2006–2010, 2011–2015, 2016–2020, 2021–2025). Note the different scales on the subgroup figures.

The strongest emerging signals are in topics with minimal early activity and sharp recent growth. Insect bioconversion to frass is the clearest case, rising from 1 record in 2006–2010 to 680 in 2021–2025. Vivianite recovery from sludge shows steady emergence from no early records to 244 total publications. Ammonium sulphate recovery also shows strong growth, reaching 169 total records. These growth patterns indicate recent research acceleration from very limited early bases. Also, algae-based production, urine separation, digestate pelletising, and fish sludge digestion appear as growing fields.

Hybrid and integrated chains are smaller but increasingly visible. Membrane stripping with calcium precipitation grows from zero early records to 19 in 2021–2025. Additive-assisted pyrolysis for nutrient recovery shows a similar pattern (0 to 17). Source-separated urine stabilisation and solid fertiliser recovery totals 31 records, mainly after 2016. Bokashi processing and thermomechanicochemical fractionation of fish by-products remain niche (24 and 14 total records), but both increase in the latest period. Hydrothermal carbonisation with separation and drying is the smallest subgroup (6 total records), indicating a highly specialised niche.

Overall, the innovative step often lies not in the core unit operation itself, but in transferring an established pathway to a new feedstock, improving the fertiliser form, or combining several steps into a marketable recovery train (Table 4). A key limitation is that publication trends indicate scientific attention rather than implementation of success, and subgroup-level searches cannot fully isolate the innovativeness of an individual case from that of its broader technology family.

Table 4. Innovation patterns in nutrient recovery technologies based on Web of Science data (2006–2025).

Main classification level	Technology subgroups	Innovativeness class	Likely source of innovativeness
Biological	Composting of biowaste and plant biomass	Mature	Innovativeness lies in feedstock mix, product positioning, and local chain design rather than the core process.
Biological	Insect bioconversion to frass	Growing	Innovation lies in using insect routes to turn biowaste into fertilising products with added value.
Biological	Anaerobic digestion of fish sludge; algae cultivation and hydrolysis	Growing to emerging	Innovation lies in applying biological conversion routes to specialised side streams and in moving toward higher-value products.
Physicochemical	Struvite precipitation from wastewater fractions	Mature to growing	Struvite is a well-established recovery route, but further innovativeness can come from feedstock targeting and product recovery within existing plants.
Physicochemical	Vivianite recovery with magnetic separation	Emerging	The recovery target is specific and the magnetic separation element points to a newer recovery niche.
Physicochemical	Ammonium sulphate recovery from sludge liquid fraction	Growing	Innovation lies in converting side streams into marketable mineral products rather than removing nitrogen only.
Thermal and thermochemical	Thermal drying and evaporative concentration for manure and industrial by-products	Mature	The main process principles are established, so innovation is more likely in industrial side-stream valorisation, energy efficiency, and final product forms.
Thermal and thermochemical	Manure and biomass ash recovery	Growing	The innovative element lies in nutrient valorisation after combustion rather than combustion itself.
Mechanical	Urine separation	Growing	Source separation is an active circular sanitation route, with innovativeness linked to nutrient capture.
Mechanical	Digestate solid fraction and pelletising	Mature	Separation and densification are established enabling steps, with innovation mainly in logistics and product quality.
Hybrid and integrated	Membrane stripping and calcium precipitation	Growing	The innovative feature is the integrated recovery of both nitrogen and phosphorus products in one train.
Hybrid and integrated	Bokashi processing and thermomechanochemical fractionation of fish by-products	Emerging and niche	Innovativeness lies in feedstock-specific hybrid processing and in combining stabilisation, fractionation, drying, or pelletising for aquaculture side streams.
Hybrid and integrated	Solid–liquid separation in anaerobic digestion; Pelletised organic–mineral fertilisers from compost and organic waste	Mature	Steps are established. Innovativeness lies mainly in integration, nutrient formulation, pelletising, and practical farm-level implementation rather than new recovery mechanisms.
Hybrid and integrated	Integrated ammonia stripping–scrubbing nutrient recovery from manure and organic waste	Growing	Innovativeness lies in integrating ammonia stripping–scrubbing into different stages of manure and digestion systems, enabling multi-product recovery rather than treating them separately.

Hybrid and integrated	Source-separated urine stabilisation, nitrification, filtration, and solid fertiliser recovery	Growing	Innovativeness lies in integrating chemical N stabilisation/purification (nitrification, activated carbon filtration) with physical conversion to solid fertiliser, creating a continuous urine-to-fertiliser chain rather than separate steps.
Hybrid and integrated	Thermal sludge processing routes (incineration, hydrothermal carbonisation, pyrolysis) combined with nutrient recovery	Growing to emerging	Thermochemical routes are matured for sludge treatment, but innovativeness lies in integrating process chains with targeted N & P recovery from ash, hydrochar, or char, moving beyond simple volume reduction toward resource recovery.

4.1.3 Feedstock supply

The primary feedstocks identified across the 30 case studies comprise agricultural biomasses and municipal wastewater fractions, municipal biowaste, industrial side-streams, and biomass from fisheries and aquaculture, in descending order of frequency (Figure 5). All of these biomass streams are widely available across Europe. In the AU region, comparable data on biomass availability are also limited. In addition, unlike in Europe, centralised treatment of municipal biomasses is less common in Africa, and the technologies applied for processing these streams are more diverse and context-specific (see e.g. Lamore et al. 2026).

Overall, the characteristics and relevance of each biomass for circular fertiliser production differ. Agricultural biomass represents the largest resource in terms of overall mass, whereas municipal wastewater sludge, industrial side-streams, and separately collected biowaste constitute more concentrated and controlled nutrient streams, thereby offering particular advantages for nutrient recovery and fertiliser production. However, the assessment on feedstock supply should not focus on comparing generated biomass volumes but to distinguish between theoretical availability, captured availability, and recoverable nutrient potential. This is consistent with recent EU biomass and bio-waste assessments (Favoio & Giavini 2024, Luostarinen et al. 2021), which emphasise both regional biomass balances and the gap between total generation and actual capture into valorisation chains.

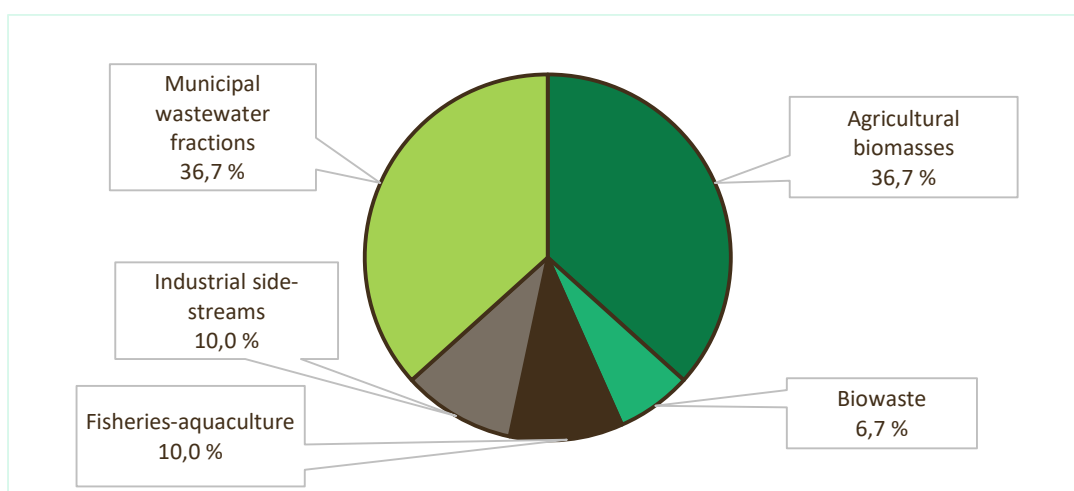


Figure 5. The main raw materials of the assessed 30 case studies. Percentages refer to number of cases focusing on each raw material.

Among the raw materials of the 30 case studies, agricultural biomasses are the largest pool together with wastewater-based fractions. The Joint Research Centre (JRC) has estimated total agricultural

biomass production in the EU at about 956 Mt dry matter per year, of which around 442 Mt are residues (e.g., straw, stalks and leaves) (Camia et al. 2018). As a fresh matter-basis, Köninger et al. (2021) estimate that there is around 1.4 Gt of livestock manure generated each year in the EU. This makes agriculture the main source for scaling bio-based fertiliser production in volumetric terms, especially where manure and crop residues can be mobilised beyond direct on-farm use. However, practical availability is much lower than theoretical availability because residues, especially plant-based residues, already have competing uses (for example, as feed or bedding material) and because residue removal can be constrained by soil-carbon and nutrient-management requirements.

As a total generated quantity in the EU, municipal wastewater is smaller in mass compared to agricultural biomasses, but highly strategic because nutrients are continuously collected and mainly processed in centralised facilities. EU sewage sludge generation is reported at just over 8 Mt dry matter per year, and sludge is explicitly recognised by the European Commission as a source of organic matter, nitrogen and phosphorus (Egle et al. 2023). This stream is attractive for scale-up because supply is steady and linked to urban population, but the effective fertiliser potential depends strongly on contaminant management, treatment route, and regulation, especially for heavy metals, PFAS, pharmaceuticals and microplastics. The EU-wide and regional limits to utilise sewage sludge as such have paved the way for new technologies (Lucia et al. 2025). Thus, the case studies focusing on this biomass, mainly focus on the nutrient recovery from wastewater or incineration ash.

Municipal biowaste is considered one of the most promising feedstocks for expansion, as collection systems are still developing. According to Eurostat, municipal biowaste generation reached 67 Mt in 2023, accounting for approximately 30% of total municipal waste. Over time, the shares of landfilling and incineration have decreased, leading to increased material recycling and composting (Eurostat, 2026). However, the proportion of separately collected biowaste may differ from the total reported biowaste generation. This is because Eurostat's biowaste category likely includes a broader range of biodegradable waste streams beyond food and green waste. Favoino and Giavini (2024) estimate that the potential for source-separated food waste in the EU is around 15 Mt, representing less than 26% of the total theoretical potential. This theoretical potential also includes food waste currently present in mixed municipal waste streams, which are not yet separately collected. These findings indicate that there is still substantial untapped potential to increase biowaste collection and treatment through improved source separation systems.

Industrial side-streams are more difficult to quantify at the EU level due to the lack of harmonised statistics. However, they are typically more homogeneous and less contaminated than municipal mixed waste, making them particularly suitable for nutrient recovery and the production of consistent fertiliser products. Eurostat provides only limited data on industrial waste streams. For example, statistics are available for "animal and vegetal wastes" under the category "generation of waste by waste category," but these data are only reported up to 2008 (Eurostat 2025). The absence of more detailed and up-to-date classifications restricts direct assessment of industrial side-stream potential. To address this gap, Luostarinen et al. (2021) developed an indirect estimation method. Their approach combines Eurostat production data with coefficients from the literature to estimate the generation of specific side-streams, including animal-based residues as well as grape and olive pomace. Using this method, they estimated that annual generation amounts to approximately 15.4 Mt of slaughter waste, 3 Mt of grape pomace, and 3 Mt of olive pomace.

Fisheries and aquaculture biomasses are smaller in total volume than agricultural resources, but they are nutrient-dense and geographically concentrated near landing sites, processing facilities, and

aquaculture hubs. In the EU, approximately 4 million tonnes (Mt) of aquatic organisms are produced annually through fisheries landings and aquaculture (EUMOFA 2026), while Norway contributes an additional ~4 Mt per year (FAO). A significant share of this biomass becomes processing by-products. Typically, fish by-products account for 30–70% of the wet weight of the fish (Ahuja et al. 2020), implying that their total volume in Europe could reach up to 5.6 Mt annually. These streams contain considerable amounts of recoverable nitrogen and phosphorus. Although fisheries- and aquaculture-derived biomasses are unlikely to dominate overall feedstock volumes at the European scale, they represent a valuable resource for nutrient recovery, particularly in coastal regions. In countries such as Norway, they can play an important role in the development of regional biofertiliser systems.

Overall, agricultural biomasses dominate total mass, municipal biowaste and wastewater offer the most scalable urban nutrient recovery, industrial side-streams provide cleaner and more standardised inputs, and fisheries/aquaculture streams are niche but high-value regional resources (Table 5). However, regional availability must be carefully considered when assessing feedstock supply. In practice, specific biomass streams may already be utilised locally or processed by existing value chains, thereby reducing their availability for new applications. These regional dynamics could not be accounted for in this study due to the lack of detailed, case-specific data.

Table 5. Overall assessment of the feedstock supply at the EU level.

Feedstock supply in EU per year		Supply for alternative fertiliser production
Agricultural plant biomass	442 Mt DM	Overall, a very large supply available, regional availability needs to be evaluated case by case
Livestock manure	1.4 Gt	
Municipal wastewater fractions	8 Mt DM (sewage sludge)	Overall, a large supply is available, regional availability needs to be evaluated case by case Availability of e.g. source-separated urine is dependent on separation
Municipal biowaste	15 Mt (source-separated food waste) 67 Mt (all biowaste)	Overall, a large supply is available
Industrial side streams	Over 20 Mt	Overall, a large supply is available, regional availability needs to be evaluated case by case
Fisheries/aquaculture	5.2 Mt	Supply region-specific

4.1.4 Resource efficiency

Resource efficiency was assessed through two complementary dimensions: nutrient recovery efficiency and efficiency in the use of energy and external inputs. Nutrient recovery efficiency is primarily evaluated based on mass balance data, capturing the proportion of nutrients successfully separated and recovered from secondary raw materials. In parallel, efficiency in energy and external resource use is assessed using reported operational data, including energy consumption, energy generation, and the use of chemicals and other inputs. This dual approach enables a balanced understanding of both the effectiveness of nutrient recovery processes and their broader resource implications, supporting a more comprehensive evaluation of the sustainability and scalability of the technologies.

Nutrient recovery efficiency

Table 6 summarises the overall resource efficiency patterns related to nutrient recovery and concentration observed across the assessed cases, linking key technologies to their main implications for nutrient recovery, product quality, and scalability. It highlights how different processing approaches influence nutrient concentration, retention, and transportability. The table also illustrates key trade-offs between nutrient recovery efficiency, energy demand, and the suitability of resulting products for agricultural use.

Table 6. Overall nutrient recovery and concentration efficiency assessment of the cases.

Nutrient resource efficiency pattern	Main technologies	Main implication
High nutrient concentration and high recovery	Urine concentration and drying, reject water ammonium sulphate, struvite, calcium phosphate, ash based phosphorus recovery	Strong fit for transportable fertiliser products and nutrient targeted use
Strong phosphorus retention but weaker nitrogen retention	Separation based manure routes, composting, digestate solids, biochar routes	Good for phosphorus redistribution and organic matter management, weaker for readily available nitrogen
Strong volume reduction	Drying, evaporation, pyrolysis, hydrothermal carbonisation, combustion and ash routes	Improves logistics and scalability, but may raise energy demand or nitrogen loss
Good multi-nutrient and organic matter retention	Frass, compost, digestate based products, fish by product fertilisers	Supports soil organic matter and broad nutrient recycling, but product uniformity may vary

The case data show a clear difference between technologies that mainly concentrate nutrients and technologies that mainly stabilise or redistribute them. Physicochemical recovery routes from liquid side streams perform strongly on concentration. Membrane stripping and calcium precipitation achieve about 90% P recovery and about 50% N recovery. Reject water ammonium sulphate recovery reaches about 90-95% N recovery with an 80 to 140 fold concentration increase. Urine based systems also perform strongly, with 10 to 15 fold concentration in the distillation route and very high N, P, and K retention in drying based routes. These cases are resource efficient when the objective is to create concentrated fertilisers for targeted transport and use.

Biological and mechanically enabled organic routes show a different efficiency profile. Composting, frass production, digestate solids, and fish based organic fertilisers retain value across several nutrients and often preserve organic matter, but they usually produce bulkier products and frequently lose nitrogen during stabilisation or drying. In the black soldier fly compost route, more than half of the total nitrogen is lost across the full process. Composting of biowaste also shows the expected pattern of 40 to 60% N loss while largely conserving phosphorus. These technologies remain important because they support organic matter return in soils and local nutrient recycling, but they are less efficient when judged only by concentrated nutrient retention (Michaud et al., 2025).

Thermal and thermochemical routes are strongest where the main need is volume reduction, sanitisation, contaminant control, or phosphorus concentration. Hydrated ash from poultry manure and sewage sludge ash recovery are good examples. In the ash hydration case, P and K recovery is about 100%, but N and organic matter are intentionally lost. In the calcium phosphate and phosphoric

acid routes from sludge ash, phosphorus recovery exceeds 80 to 85% and heavy metal removal is strong. These cases illustrate that resource efficiency can be high even when the route is selective rather than multi-nutrient, provided the resulting product is concentrated, clean, and usable (Egle et al., 2016).

Hybrid systems often provide the strongest overall balance because they combine fractionation, concentration, and product upgrading. Pig slurry separation and stripping, digestate stripping chains, and membrane plus precipitation systems are the clearest examples. These systems are particularly relevant for advanced nutrient recycling, as they enable integrated management of material flows, carbon and nutrients, and energy (e.g. Rodríguez-Alegre et al., 2023, Lorick et al., 2020).

Energy and resource use efficiency

Energy use efficiency is a central parameter in assessing circular fertiliser production systems, as it directly affects both their environmental footprint and their operational feasibility. The efficiency of these systems is largely determined by the balance between energy consumption and energy generation, as well as by the type of energy required. Across the technologies considered here, heat demand emerges as the dominant factor shaping overall energy performance, while electricity demand typically plays a secondary role unless it is used for heat generation.

Anaerobic digestion produces biogas, which can be converted into heat and electricity and subsequently utilised within the same system (Table 7). This internal energy supply can significantly offset the energy demands of downstream processes, particularly those requiring heat. As a result, technologies that would otherwise appear energy-intensive may achieve favourable net energy balances when combined with anaerobic digestion. This highlights that energy efficiency should not be assessed solely at the level of individual processes, but rather at the system level, where synergies between technologies can significantly improve performance.

In contrast, composting represents a low-energy biological pathway. Its energy efficiency stems from the fact that the process is primarily driven by microbial activity, requiring only limited external inputs. However, the actual energy demand depends strongly on the operational configuration. Simpler systems, such as open windrow composting require minimal energy, mainly for turning and handling of material. More controlled systems, such as closed reactors, involve higher energy consumption due to forced aeration and process management. Despite these differences, composting remains one of the most energy-efficient approaches, particularly when implemented in low-technology configurations.

Thermochemical processes exhibit a different energy profile. Pyrolysis and incineration are characterised by their ability to produce energy, typically in the form of heat. This energy generation can compensate for the substantial heat input needed to initiate and maintain the process, resulting in a potentially favourable net energy balance. In contrast, hydrothermal carbonisation does not generate energy. Nevertheless, it can still perform well in terms of energy efficiency because it avoids one of the most energy-intensive steps in biomass processing, namely drying. By operating with wet feedstocks, hydrothermal carbonisation significantly reduces overall heat demand, which compensates for the absence of direct energy production.

Other processes, particularly those focused on nitrogen recovery or removal, tend to be more energy demanding. Ammonia stripping is a prominent example, as it requires elevated temperatures to transfer ammonia from the liquid phase to the gas phase. This reliance on heat makes it highly energy-

intensive, especially in situations where suitable waste heat is not available. Similarly, nitrification and denitrification processes require continuous aeration, which leads to substantial electricity consumption. In this case, energy demand is driven by the need to supply oxygen rather than heat, but it remains significant due to the continuous nature of the process. These technologies therefore present challenges in terms of energy efficiency unless their energy demands can be offset through system integration or alternative energy sources.

Table 7. Overall energy and resource use efficiency of the cases.

Technology	Energy use efficiency characteristics	Chemical use characteristics	Overall implications
Anaerobic digestion (in combination)	Produces energy (biogas), improving overall system energy balance and offsetting the heat and electricity needs of downstream processes	Limited direct chemical demand	Strongly improves both energy efficiency and system sustainability when integrated with other processes
Composting (open / closed)	Generally low energy demand; open systems very low, closed reactors require more electricity for aeration and control	Minimal chemical inputs; process relies mainly on biological activity	Highly efficient in both energy and chemical terms, especially in simple configurations
Pyrolysis and incineration	Produce energy (mainly heat), which can offset process demand and improve net energy balance	Very limited chemical inputs are required for the core process	Favourable energy profile due to recovery, with low dependency on chemicals
Hydrothermal carbonisation (HTC)	Does not produce energy, but avoids drying, resulting in relatively low total heat demand	Limited chemical inputs; process largely based on feedstock properties	Good overall efficiency due to low heat demand despite no energy generation
Organo-mineral pellet production	Moderate energy use (mainly electricity for processing such as pelletising)	Dependent on external nutrient inputs to adjust product composition	Chemical dependency reduces circularity, even if energy demand is moderate
Ammonia stripping	High heat demand, making it energy-intensive unless waste heat is available	Requires alkali addition to increase pH and enable ammonia recovery	Both energy- and chemical-intensive; efficiency depends on access to heat and optimisation of inputs
Precipitation processes (e.g., struvite, vivianite)	Moderate energy demand, mainly for mixing and handling rather than heating	Require specific chemicals such as magnesium for struvite or iron for vivianite formation	Chemically dependent processes with relatively manageable energy requirements
Membrane treatment	Moderate electricity demand for pressure and flow control; limited heat requirement	Requires chemicals for cleaning (e.g. acids) to maintain performance	Chemical use is indirect but continuous; efficiency depends on the maintenance strategy
Evaporation/distillation	High heat demand due to phase change requirements	Acids sometimes used to prevent nitrogen volatilisation during processing	Both heat- and chemical-dependent, with efficiency strongly influenced by the heat source

The predominance of heat demand across many of these technologies underlines a critical aspect of energy efficiency. Processes that involve temperature increases, such as drying, evaporation, distillation, or ammonia stripping, are inherently energy intensive. While electricity consumption is typically associated with mechanical operations such as pumping, mixing, or pelletising, its contribution can increase markedly if electricity is used as a source of heat. This conversion of electricity into heat is generally less efficient and can significantly raise total energy consumption. Consequently, access to direct heat sources is a key determinant of process efficiency.

Several overarching factors influence the energy performance of these technologies. The use of renewable energy and waste heat can substantially reduce the environmental impact associated with energy consumption. This is particularly relevant for heat-intensive processes, where the availability of low-cost or residual heat can improve overall efficiency. The most favourable outcomes are achieved when technologies are integrated, particularly with anaerobic digestion, and when energy flows are optimised through the use of renewable sources and waste heat. Climatic conditions also play an important role. In warmer climates, lower heating requirements lead to improved energy balances, while in colder environments the need for additional heat input can reduce efficiency. These contextual factors highlight the importance of adapting technology choices and system configurations to local conditions.

Chemical use in circular fertiliser production is closely linked to specific process requirements and product quality targets. Some pathways, such as organo-mineral pellet production, depend directly on external nutrient inputs to achieve balanced and standardised fertiliser compositions. While this allows precise control of nutrient ratios, it reduces the level of circularity by introducing materials from outside the recovered nutrient stream.

Nutrient recovery technologies typically require additional chemicals to enable or enhance recovery efficiency. In precipitation processes, specific reagents are needed to form stable compounds, such as magnesium for struvite formation or iron for vivianite production in upstream stages. Ammonia stripping similarly depends on chemical inputs, particularly alkali addition to increase pH and improve ammonia transfer. In addition to transformation processes, chemicals are also used to maintain system stability and efficiency. Membrane technologies require periodic chemical cleaning, often with acids, to prevent fouling and sustain performance. Acids are also applied in evaporation processes to prevent nitrogen losses through volatilisation. These uses are indirect but necessary for ensuring consistent operation and nutrient retention.

Chemical consumption is generally well optimised due to its direct economic impact. Process design typically aims to minimise input quantities while maintaining performance, resulting in relatively efficient use patterns. Nevertheless, chemical use remains an important consideration in overall system sustainability, as it influences both costs and resource dependency. Efficient circular fertiliser production therefore requires balancing the benefits of chemical inputs with efforts to minimise their use and integrate them effectively into the overall process system.

4.1.5 Agronomic efficiency of alternative fertiliser products

Agronomic efficiency of the fertiliser products of the cases depends mainly on nutrient concentration, nutrient form and release characteristics, and the presence of organic matter. Products rich in dissolved ammonium or soluble phosphate behave most like conventional mineral fertilisers. Products rich in organic matter contribute more to soil improvement and longer-term nutrient cycling but usually give a weaker immediate crop response unless combined with more available nutrients (Müller et al.,

2024, Schmidt et al., 2024). In FERTITEC “D1.4 Gaps and challenges of available recovering and recycling techniques”, Wach et al. (2025) conducted an extensive review and discussion of the challenges and risks associated with the use of NPK nutrients from alternative fertilisers and their agronomic application..

The case products show three dominant nutrient patterns: nutrient-selective fertilisers, balanced fertilisers, and soil improvers. Nutrient-selective products dominate the dataset and include recovered mineral N products such as ammonium sulphate and ammonium nitrate from stripping-scrubbing and related recovery processes. Agronomically, these behave similarly to conventional mineral fertilisers, with high mineral N and little or no P or carbon. High N:P ratios are most evident in urine-based products, fish-sludge digestate, and hydrochar, which are particularly useful in regions with P surplus or P application constraints. As a nitrogen source, alternative fertilisers may be less predictable than mineral fertilisers because N is often in organic form and must first be mineralised by soil microbes before plants can use it, so its effect may appear only after some time (Müller et al., 2024). Struvite is strongly phosphorus-based, while calcium phosphate and phosphoric acid function essentially as phosphorus carriers, with phosphoric acid serving mainly as a raw material for further fertiliser production. Struvite often performs similarly to soluble P fertilisers in terms of crop response (Müller et al., 2024). However, some ash- and Ca-rich products require further treatment or amendment to achieve higher P plant availability (Jastrzębska et al., 2016). Poultry ash is primarily a phosphorus and potassium source with no nitrogen, while potato cell water is strongly potassium-rich.

Secondly, some products show a more balanced NPK profile. Mealworm frass, poultry manure pellets, and mixed compost-mineral pellets fit this group. These materials represent suitable candidates for direct organic or organo-mineral fertilisation, as they combine a multi-nutrient supply with the return of organic matter to soils.

Organic matter and carbon are not side issues in this portfolio. They define the main agronomic value of a large share of the products. Composts, digestate solids, bokashi pellets, frass products, hydrochar, biochar, and some fish-based products return carbon to soil, enhancing soil aggregation, water retention, and biological activity, and can improve nutrient retention over time (e.g. Soinne et al., 2023,). Accordingly, these products should not be evaluated only against mineral fertilisers on first year crop response, as their agronomic benefits often manifest over longer timescales and through improvements in soil functioning.

Therefore, a useful practical distinction can be made between products where carbon (organic matter) is an additional benefit and those in which carbon represents the primary driver of application. In struvite, calcium phosphate, phosphoric acid, recovered ammonium salts, and urine concentrates, carbon is absent or negligible, so agronomic value rests almost entirely on direct nutrient supply or on value as a fertiliser raw material. In contrast, in compost, digestate solids, hydrochar, and biochar, carbon is a central part of the value proposition and should be counted alongside nutrient supply. In frass, fish products, poultry pellets, and organo-mineral pellets, both functions matter.

4.1.6 Potential to upscale

The upscaling potential of a technology can be dependent on different factors. Table 8 summarises the key factors influencing scalability across nutrient recovery technologies, linking each driver to the technologies that benefit from it and the challenges that arise when it is lacking.

The case data indicate that scalability is highest where nutrient recovery is paired with a logistics benefit. This is why drying, pelletising, evaporation, ash recovery, and mineral precipitation scale well. They do not only recover nutrients. They also reduce water burden, improve storability, and generate products that are easier to transport or sell. Potato cell water evaporation, low temperature poultry manure drying, ash-based phosphorus recovery, and struvite precipitation are strong examples of this logic.

Table 8. Scalability drivers and challenges in selected technologies.

Scalability driver	Technologies advantaged by scaling up	Main challenge when absent
Concentrated and homogeneous feedstock	Reject water recovery, struvite, urine derived products, potato cell water evaporation	Dilute and variable streams raise cost and lower product consistency
Strong volume reduction	Drying, evaporation, hydrothermal carbonisation, ash routes	Wet bulk products become costly to store and transport
Existing infrastructure and operational familiarity	Composting, digestion, slurry separation, pelletising, sludge incineration	Novel chains face slower adoption and a higher integration burden
Standardised product with known market use	Struvite, ammonium sulphate, calcium phosphate, phosphoric acid, pellets	Unclear product identity or local acceptance slows uptake
Energy integration with the host plant	Digestion plus stripping, low temperature manure drying, pyrolysis, incineration routes	Standalone energy demand can weaken economics

A second pattern is that scalability is often limited by the wider system rather than by the core recovery chemistry. Urine based products may perform extremely well in nutrient recovery terms but scale up still depends on source separation systems and collection practice (Larsen et al. 2021). Integrated manure and digestate treatment chains may be technically strong, but their deployment depends on the design of biogas plants, local heat access, fertiliser markets, and transport distances. In this sense, scalability is partly an infrastructure question rather than solely a plant- or reactor-specific issue (Choi et al., 2026).

The regional spread in the case overview also highlights that scalability conditions differ by context. North EU and Central EU cases are prominent in urine recovery, manure drying, digestate processing, reject water treatment, and sludge based nutrient recovery, reflecting stronger infrastructure for concentrated side stream treatment. South EU cases include struvite, sludge digestion and stripping, agricultural residue composting, and industrial vinasse valorisation, showing strong relevance where agro-industrial and wastewater side streams intersect. The African cases in the portfolio are important because they show that scale up is not only about technical maturity. In these cases, infrastructure reliability, input supply chains, and local market fit become central determinants of practical scalability.

Table 9 summarises the selected cases in terms of their technological maturity, resource efficiency characteristics, and scalability patterns. In conclusion, the comparison by technology class confirms that the assessment of alternative fertiliser production cannot rely on a single performance criterion. Each class shows a distinct strength profile. Biological routes are important for organic matter return in soils and local nutrient recycling, physicochemical routes are most effective for producing concentrated mineral like fertilisers, and thermal or thermochemical routes are particularly relevant

where strong volume reduction, sanitisation, or phosphorus concentration is required. Mechanical operations play a key enabling role, while hybrid systems often provide the most balanced overall performance. At the same time, their higher complexity means that practical success depends on the integration of the full treatment chain, the availability of supporting infrastructure, and the existence of suitable end markets.

Table 9. Comparison of maturity, resource efficiency, and scalability

Class	TRL pattern	Resource efficiency pattern	Scalability pattern
Biological	Mostly mature for composting and digestion, less mature for selective uptake systems	Good bulk nutrient recycling and organic matter retention, but frequent N loss and lower nutrient density	Strong for local and regional use, weaker for long distance transport unless further processed
Physicochemical	Medium to high, especially for struvite and ammonia recovery	High selectivity and high nutrient concentration from liquids	Strong where feedstocks are concentrated and product standards are clear
Thermal and thermochemical	High for drying and combustion, mixed for newer upgrading routes	Strong volume reduction and P recovery from solids, but often weaker N retention	Strong when heat integration exists and solids handling is already part of the system
Mechanical	High	Useful first step for fractionation and logistics, but limited as a standalone recovery route	High as an enabling step, but the value depends on the downstream use of fractions
Hybrid and integrated	Variable because readiness follows the weakest step	Often best overall balance of recovery, concentration, and product quality	High where plant integration, heat, and markets align, but sensitive to complexity

4.2 Environmental impacts of the case studies throughout their life cycle

The environmental performance of the case studies was analysed based on available literature. The data was collected considering the entire value chain of the circular fertilising products from production of inputs to field use. On the basis of this, material processing and field use were identified as the most significant life cycle stages for emission sources, and these were chosen as the focus area of this study. Overall, the most recurrent pressure points across the life cycle of fertiliser products are methane (CH₄) release, ammonia (NH₃) volatilisation and nitrous oxide (N₂O) formation from both processing and field use stages, the latter one including also nitrate leaching. These emissions are primary contributors to multiple environmental impact categories, primarily driving global climate change and severe air and water pollution.

The environmental performance of the case study technologies is shaped by how effectively they prevent nutrient and carbon losses by limiting these direct emissions to air and aquatic systems/water bodies from different life cycle stages. Several of these technologies provide clear environmental benefits by replacing conventional mineral fertiliser production, as well as reducing pollutant loads in

wastewater systems, improving nutrient targeting, or concentrating nutrients into cleaner and more transportable products. Cases with good environmental performance in terms of climate and nutrient loss are generally those that recover nutrients selectively from liquid side streams before they enter conventional treatment systems or are emitted during storage (Table 10). Ammonia stripping, membrane contactors, and other selective nitrogen recovery systems are widely discussed as alternatives to biological nitrogen removal because they can reduce direct nitrous oxide formation and convert reactive nitrogen into products such as ammonium sulphate rather than releasing it as inert nitrogen gas (Choi et al., 2026; Wang et al., 2024; Ye et al., 2018). More broadly, recovery of nutrients in concentrated forms is often environmentally attractive because it improves transportability, lowers pathogen risks, and gives better conditions for targeted agricultural use (Mehta et al., 2015).

However, the environmental performance cannot be inferred from nutrient recovery efficiency alone. Technologies with high recovery rates may still have notable burdens if they depend on drying, evaporation, chemical inputs, or thermal treatment, especially due to high energy demand and if they use fossil fuels as their energy source. On the other hand, technologies with relatively modest process energy demand may still perform weakly if nutrient (e.g. nitrogen) losses during composting, storage, or field application are not well controlled (Amann et al., 2018; Choi et al., 2026; Wang et al., 2024). For example, biologically based stabilisation routes such as composting and frass maturation tend to show a broader environmental trade-off. They support circular use of organic matter and can displace mineral fertilisers, but they often lose a substantial share of nitrogen during processing. These losses matter twice: they reduce nutrient recovery efficiency, and they increase the risk of acidification, eutrophication, and climate impacts through ammonia volatilisation, nitrous oxide formation, and subsequent nitrate leaching after land application (Harder et al., 2019; Puyol et al., 2017).

When interpreting results presented in Tables 10, 11 and 12, it is good to note that even if a risk or a benefit has not been observed in the literature for a particular case, it does not necessarily indicate the absence of a risk or benefit. It is more likely that the risk or benefit has simply not been the subject of study yet. Also, the comparisons between different technology cases should be used with caution and consideration, and they cannot be directly compared to each other. This is because in the perceived literature, the system limitations and methodological choices used for the calculation vary. For example, some cases do not take into account all chain stages, such as the field use aspect. In addition, some cases only consider the climate impact category, while others consider several different impact categories, such as acidification, eutrophication and ozone depletion. In addition, the functional unit (FU) needs to be the same, and it is important to consider the most representative one as it directly dictates how environmental impacts are quantified. Efforts have been made to address these methodological challenges by harmonizing calculation guidelines (Vikki et al. 2025; Vikki et al. 2026), when comparing products. For example, for fertiliser products, the FU is often selected based on the functionality of the fertiliser product, i.e. the amount of nutrients, e.g. per kilogram of nitrogen (Vikki et al. 2025; Vikki et al. 2026).

Table 10. Main environmental benefits and risks of the selected case studies

Technology	Environmental benefits	Environmental risks	Main implication
Ammonia stripping, membrane stripping, selective N recovery from reject water, source-separated urine systems	Lower direct N ₂ O emissions from treatment than conventional biological N removal Overall, lower GHG emissions compared to mineral N production		Avoiding conventional biological N removal can improve climate performance
Drying, evaporation	Strong nutrient concentration benefits.	Emissions from technologies due to high process energy demand.	Consider modest process energy demand. Avoiding fossil fuels as an energy source in high-energy-demand technologies.
Composting, frass composting, digestate handling, drying-sensitive manure routes	Overall lower GHG emissions compared to untreated material	Higher risk of NH ₃ loss.	Nitrogen not stabilised during processing is likely to remain environmentally vulnerable Processing stabilises carbon to some extent preventing its volatilisation.
Incineration, sludge drying, ash recovery, pyrolysis, evaporation	Strong nutrient concentration benefits	High process air emissions	Process emissions tradeoffs with product concentration, contaminant destruction, or energy recovery
Technologies involving additives, such as N-recovery technologies		Increased impacts due to the use of chemicals or other additives (emissions arising from the value chain of the additive)	Reduction in the use of chemicals and other additives, or finding replacements, lowers emissions
Final product	Environmental benefits	Environmental risks	Main implication
Struvite, calcium phosphate, phosphoric acid, ammonium sulphate, urine-derived concentrates	Lower risk of nutrient leaching through concentrated products		Product quality and dosing precision improve nutrient use and lower diffuse loss risk
Digestate, compost, separated urine	Strong dependence on management at the field stage		Application method, timing, storage, and soil conditions strongly influence final impacts

4.2.1 Impacts from the processing phase

Overview of the technologies categories by their main emission sources is presented in Table 11. Thermal processing routes show the clearest tradeoff between high process intensity and high product upgrading. Incineration of poultry manure and sewage sludge produces emissions such as NO_x, particulates, and biogenic carbon dioxide, while sludge drying can materially increase

greenhouse gas burdens. However, these routes also concentrate phosphorus, potassium, calcium, and micronutrients into ash products, destroy organic contaminants, and may deliver renewable energy. Reviews of phosphorus recovery show the same pattern at the system level: liquid phase recovery often has lower emissions and energy demand but lower total recovery, whereas sludge and ash routes reach higher recovery rates but usually at higher process burden (Amann et al., 2018; Egle et al., 2016).

Drying-based systems follow a similar pattern. Both drying, and evaporation-based concentration can generate valuable fertiliser products, but the drying stage often dominates the environmental profile. In urine and excreta treatment, this is especially important because urea hydrolysis raises pH and increases the risk of ammonia volatilisation, so stabilisation before concentration or drying becomes environmentally decisive (Harder et al., 2019; Simha et al. 2020). This burden can be reduced sharply where low-temperature operation, industrial waste heat, or other forms of energy integration are available.

Biological systems are less energy-intensive in some cases, but they are often more exposed to direct nitrogen losses. Biological recovery routes can perform well in dilute streams and can capture nutrients into biomass, yet they are also more dependent on process control and can suffer climate impacts from methane losses or unstable operation (Puyol et al., 2017). Digestate-based systems illustrate the same pressure. Anaerobic digestion can generate renewable energy, but the environmental result depends strongly on gas capture, digestate storage, and downstream nutrient management (Campos et al., 2019; Vaneeckhaute et al., 2016).

Table 11. Overview of the direct emissions during processing.

Technology group	Main direct emission sources	Overall reading
Composting and frass composting	NH ₃ , N ₂ O, CH ₄ from biological degradation and material handling	Emissions can be substantial unless aeration, moisture, and exhaust are well controlled
Digestion and digestate treatment	CH ₄ and NH ₃ from storage, some N ₂ O during storage and handling. Also, the possibility of CH ₄ leaks from the digester.	Strong climate benefits depend on effective gas capture and low emission digestate management
Stripping and selective N recovery	Lower direct N ₂ O than biological N removal, but still affected by energy and chemical demand	Often climate favourable when replacing conventional nitrogen removal
Drying	CO ₂ from heat and electricity use, possible NH ₃ release during drying	Strongly dependent on the heat source, drying temperature, and integration with waste heat
Incineration and ash recovery	NO _x , particulates, biogenic CO ₂ , pre-drying related emissions	Benefits derive mainly from energy recovery, sanitisation, and nutrient concentration
Hydrothermal and pyrolytic routes	Thermal conversion emissions, process energy use, some gain from internal energy recovery	Can perform well where wet feedstocks or carbon retention are priorities

4.2.2 Impacts from the field use-phase

Table 12 combines the analysis of the emissions from the field use. The cases based on selective nutrient recovery from liquids generally show the strongest potential to reduce nutrient leaching.

Struvite is especially important in this respect because it combines high phosphorus concentration with a comparatively controlled release profile, while other recovered mineral products also benefit from higher product consistency and more precise application potential (Egle et al., 2016; Mehta et al., 2015). In the same direction, Harder et al. (2019) distinguishes between quick-release nutrient solutions and slower-release sorbents or organic solids, showing that product form is central to field stage loss risk rather than a secondary issue.

Digestate, compost, frass, and other bulk organic products are more management sensitive. Their environmental performance depends strongly on storage time, covering, application timing, incorporation into soil, and crop uptake conditions. Reviews of digestate treatment show that direct land application in livestock-dense regions can lead to nutrient surpluses and associated environmental burdens unless separation, concentration, or redistribution is used to improve nutrient targeting (Campos et al., 2019; Vaneeckhaute et al., 2016). Several of the uploaded cases point in the same direction by showing that digestate injection and better fraction management can reduce ammonia loss and later nitrate leaching.

Some technologies also show that improving one environmental indicator can worsen another. Hydrothermal carbonisation has a favourable process climate profile because it avoids intensive drying, yet phosphorus losses to process water can create eutrophication risks if the liquid phase is not adequately treated. Potato cell water evaporation has relatively low nutrient-related field risks because nitrogen and phosphorus contents are low, but the evaporation step remains energy-intensive. More generally, (Wang et al., 2024) cautions that nutrient recovery technologies should not solve nutrient discharge problems by creating new burdens through excessive energy use, unsustainable material demand, fugitive ammonia, or contaminant transfer.

Table 12. Nutrient leaching and eutrophication risk during field use of the fertilising products.

Main technologies	Leaching risk profile	Interpretation
Struvite, calcium phosphate, phosphoric acid, ammonium sulphate, processed urine products	Lower leaching risk through targeted and more stable products	Concentrated products enable more precise nutrient management and lower diffuse loss potential
Digestate-based products, urine concentrates, organic pellets, separated solid and liquid fractions	Moderate risk if storage and application are well managed	Environmental performance depends on handling quality rather than product form alone
Compost, frass compost, raw or lightly treated digestate, bulky organic products	Higher risk where products remain bulky, wet, or variable in nutrient release	Nutrient release is harder to match with crop demand, increasing loss risk. However, risks are often lower compared to untreated feedstock.
Poultry manure pellets, some digestate systems, HTC process water streams	Specific residual risk despite processing gains	Some technologies reduce one emission pathway while leaving another partly unresolved

4.2.3 Conclusions from the environmental assessment

Taken together, the 30 cases indicate that the strongest environmental performers are usually the systems that keep reactive nitrogen under control throughout the full chain from processing to field use. Selective recovery routes from liquid streams perform well because they reduce direct nitrous

oxide emissions from treatment and produce fertiliser products that can be applied more precisely (Wang et al., 2024; Ye et al., 2018). Thermal and ash-based routes perform well where phosphorus concentration, contaminant control, and substitution of primary mineral fertilisers are the main priorities, even though their own process emissions may remain significant (Amann et al., 2018; Egle et al., 2016). Biological and bulk organic routes remain important for circularity, soil improvement, and local nutrient reuse, but their environmental performance is more management dependent because losses can occur at several stages (Campos et al., 2019; Puyol et al., 2017).

4.3 Data and comparability limitations in the assessment of nutrient recycling technologies

The analysis of 30 case studies on nutrient recycling technologies revealed significant challenges in data collection and comparability. A key limitation was the overall scarcity of available literature. For several technologies, only a small number of environmental assessments, including life cycle assessment (LCA) studies, have been conducted. This limited evidence base reduces the robustness of conclusions and increases uncertainty in the synthesis of results.

Even when studies were available, important aspects were often missing or only partially addressed. For instance, some assessments focused narrowly on selected environmental indicators, while omitting others such as resource depletion, emissions to water, or long-term impacts. This incomplete coverage complicates efforts to form a comprehensive understanding of the environmental performance of different technologies.

Another major challenge stemmed from methodological inconsistencies across studies. The reviewed literature applies a range of varying system boundaries, functional units, allocation methods, and impact assessment approaches. For example, results were reported per unit of treated waste, per kilogram of recovered nutrient, or per unit of energy produced, making direct comparison difficult. In addition, not all studies took the entire life cycle into consideration, for example, by not including emissions during field use. Furthermore, assumptions regarding input materials, operational conditions, and background systems differed widely.

As a result, comparing and synthesising findings across case studies required careful interpretation and, in some cases, simplifications. Overall, the lack of standardised methodologies and comprehensive datasets represents a substantial barrier to assessing and benchmarking nutrient recycling technologies on a consistent basis.

4.4 Results and their uptake potential in the AU context

Technologies developed and applied in Europe have clear potential for transfer to African contexts, but their suitability depends strongly on local conditions. Many of the core principles, such as nutrient recovery from organic residues, circular resource use, and waste valorisation, are equally relevant, as similar biomass streams (e.g. agricultural residues, biowaste, and animal manure) are widely available across African regions.

However, several factors need to be carefully considered. First, technological complexity and cost are critical constraints. Advanced processes commonly used in Europe, such as chemical stripping, precipitation, or thermochemical treatments, often require high capital investment, reliable energy supply, and technical expertise. In many African settings, simpler and more robust technologies, such as composting, anaerobic digestion, or low-tech drying and pelletisation, may be more appropriate, particularly in rural or resource-constrained areas.

Second, infrastructure and logistics play a key role. Efficient collection systems for municipal biowaste or wastewater, which underpin many European technologies, are often less developed. Therefore, decentralised solutions that operate close to biomass sources (e.g. farms or local markets) may offer better feasibility and scalability.

Third, regulatory frameworks and quality standards differ significantly. While the EU has well-defined fertilising product regulations, such frameworks may be less developed or differently enforced in African countries. This can both limit market uptake and, conversely, provide flexibility for innovation. Ensuring product safety, particularly regarding pathogens and contaminants, remains essential.

Finally, socio-economic factors must be considered, including farmer acceptance, affordability, and awareness of bio-fertilisers. Technologies should align with local agricultural practices and demonstrate clear agronomic and economic benefits to support adoption.

In summary, while European bio-fertiliser technologies provide valuable models, successful application in Africa requires adaptation to local technical capacity, infrastructure, regulatory conditions, and socio-economic context, with a strong emphasis on low-cost, decentralised, and resilient solutions.

5. Conclusions

D2.1 demonstrates that alternative fertiliser production cannot be judged by nutrient recovery, technology class, or TRL alone. A more useful aspect is the functionality: some technologies produce direct-use fertilisers, others generate intermediates for further fertiliser production, some produce balanced organic or organo-mineral fertilisers, while others primarily produce soil improvers. This is more informative than a simple ranking by total nutrient content because agronomic value, environmental performance, and market suitability depend strongly on nutrient form, product concentration, and handling properties.

No single technology class dominates across all criteria. Physicochemical routes such as struvite precipitation and ammonium sulphate recovery are strongest where the aim is to produce concentrated, standardised products from liquid side streams. Thermal and ash-based routes are strongest where phosphorus concentration, sanitisation, contaminant control, and volume reduction are the main goals, though they usually come with a higher process burden. Biological routes are important for local nutrient recycling organic matter return, and soil improvement, but they are more management-sensitive because nitrogen losses can occur during processing, storage, and field use. Hybrid systems often provide the best balance because they combine release, separation, concentration, and finishing steps, but their performance depends on the whole chain rather than one unit operation alone.

Product quality is as important as recovery efficiency. The strongest candidates for wider market uptake are products that are concentrated, transportable, and easily integrated into existing fertiliser markets. Struvite, ammonium sulphate, calcium phosphate, phosphoric acid, dried urine products, and dense pellets follow this logic. Composts, digestate solids, frass composts, bokashi, hydrochar, and biochar also have clear value, but mainly in local or regional markets linked to soil improvement and circular resource management rather than broad substitution of mineral fertiliser.

Agronomically, the main distinction is between products that give a clear short-term nutrient response and those that contribute more to longer-term nutrient cycling and soil improvement.

Environmental performance follows the full chain, not the recovery step alone. The strongest cases are usually those that keep reactive nitrogen under control from processing through storage and field use. Selective recovery from liquid streams often performs well because it can reduce treatment emissions and create products that can be applied more precisely. Biological and bulk organic routes remain important circular solutions, but they need tighter control of ammonia, nitrous oxide, methane, and leaching risks. Thermal routes are justified where phosphorus concentration, contaminant destruction, and volume reduction are decisive, but they should not be treated as low-burden by default.

Scalability is mainly a systems issue. Technologies scale best when they match concentrated feedstocks, existing infrastructure, available heat or energy integration, and product forms that can enter established markets. The limiting factors are often not the chemistry itself, but feedstock separation logistics, reagent needs, transport distance, energy cost, or regulatory conditions.

The technologies in D2.1 are selectively suitable for Africa rather than as a single package. The most promising options utilise local side streams, tolerate variable infrastructure, require low chemical and energy inputs, and produce outputs that can be used close to their source. Accordingly, composting, frass-based products, simple digestate valorisation, pelletising of local organics, and source-separated urine systems with basic stabilisation are broadly suitable, whereas more advanced recovery systems are better suited to larger municipal or agro-industrial settings. Overall, Africa is a promising environment for circular fertiliser technologies, where robustness, low infrastructure dependence, and local market fit are often more important than maximising recovery efficiency.

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7. Appendix 1

Table A1.1. Literature and other data sources used in assessing technological and environmental performance of the selected cases.

Case	Main project connection	References
Hydrated ash of incinerated poultry manure	NUTRIMAN	NUTRIMAN 2025. Technology for P recovery as PL fertilizer from the ash of poultry manure with "BMC Moerdijk" thermochemical process (ID 399). Technologies. NUTRIMAN-project. https://nutriman.net/farmer-platform/technology/id_399
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Nutrient recovery via membrane stripping and calcium precipitation	CiNURGi	NPHarvest 2026. https://www.npharvest.fi/en/index.html
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Insect mealworm frass fertiliser via bioconversion of organic waste	FERPLAY	FER-PLAY database. FER-PLAY project. Available via: https://fer-play.eu/resources/
		Zunzunwgui, I., Martín-García, J., Santamaría, O., Poveda, J. 2024. Analysis of yellow mealworm (<i>Tenebrio molitor</i>) frass as a resource for a sustainable agriculture in the current context of insect farming industry growth. <i>Journal of Cleaner Production</i> , 460, 142608. https://doi.org/10.1016/j.jclepro.2024.142608
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Insect (Black soldier fly) frass compost via bioconversion of food waste	RWACOF	Guo, H., Jiang, C., Zhang, Z., Lu, W., Wang, H. 2021. Material flow analysis and life cycle assessment of food waste bioconversion by black soldier fly larvae (<i>Hermetia illucens</i> L.). <i>Science of The Total Environment</i> , 750 141656. https://doi.org/10.1016/j.scitotenv.2020.141656
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Bokashi fermentation, drying, and pelletising of fish by-products	SEA2LAND	<p>Nutriloop OÜ. Launch of SEA2LAND project: Producing advanced bio-based fertilizers from fisheries wastes. https://nutriloop.org/wp-content/uploads/2021/05/SEA2LAND.pdf</p>
		<p>Nutriloop OÜ. . Results and discussion. https://nutriloop.org/wp-content/uploads/lisa-32plfa.pdf</p>
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		<p>Landert, J., de Baan, L., Wittmann, N., Fabre, J-F., Vialle, C., Sablayrolles, C., Teixeira, D.A., Monteiro, H.I., Moura, B.C., Bald, C., Iñarra Chastagnol, B. 2025. D7.2. Environmental impacts of the production and use of fishery-based bio fertilisers. SEA2LAND-project, deliverable. https://sea2landproject.eu/wp-content/uploads/2025/07/D7.2.pdf</p> <p>Zhang, J., Edesi, L., Talve, T., Akyol, Ç., Koll, B., Roman, I., Toom, M., Aranguren, M., Virgel Metnxaka, S., Kuu, A., De Neve, S., Meers, E. 2025. Recycling fishery waste into biobased fertilizers: Agronomic performance and soil health impacts. Soil & Tillage Research 253, 106686. https://doi.org/10.1016/j.still.2025.106686</p> <p>SEA2LAND 2024. Protocol to produce biobased fertilisers https://sea2landproject.eu/protocol-to-produce-biobased-fertilisers/#:~:text=In%20Baltic%20Sea%20pilot%2C%20bokashi,as%20soil%20improver/growing%20medium</p>
Thermomechanical fractionation (TMC) of fish by-products	SEA2LAND	<p>Asín, M. 2022. D9.4 Practice Abstracts M18. SEA2LAND-project, deliverable. https://sea2landproject.eu/wp-content/uploads/2022/08/SEA2LAND_9.4-Practice-Abstracts-M18.pdf</p>
		<p>SEA2LAND 2021. The Atlantic Area case. https://sea2landproject.eu/the-atlantic-area/</p>
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