FertiCovery

Deliverable 3.1

Assessment of the technical aspects of the technologies

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Technical References

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1 PU = Public
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Summary of Deliverable

Deliverable 3.1 provides a systematic analysis of technical aspects of the selected nutrient recovery and biobased fertilizers production technologies. The deliverable represents the initial task of Work Package (WP) 3 and uses a set of indicators, which are the technical assessment indicators. These indicators include the technology operation performance, the N and P recovery, the treatment capacity, the yield and productivity, the sensitivity to variations in the composition of the inlet, the technical requirement of the equipment, and the operating conditions. The indicators have been quantified to benchmark each selected nutrient recovery and biobased fertilizers production process from the technical point of view.

To prepare this deliverable, dedicated questionnaires were developed by the consortium partners and they were distributed to the relevant stakeholders and representatives of the top 25 technologies of biobased fertilizers production, as these were identified and described in Deliverable 2.3.

The top 25 technologies were selected from an initial list of 167 technologies, as these are described in Deliverable 2.1: "List of existing/operating installations converting secondary raw materials into fertilising products". These technologies were ranked by the project consortium and from this procedure the top 25 technologies were listed. The project partners came in contact with representatives of the first 25 technologies, by sending them the dedicated questionnaire and asking them to fill it in. The technology providers who declined participation were removed from the list of the top 25 technologies. The technologies for which no answer was received, neither positive nor negative, remained in the final top list. In these cases, the descriptions were completed using publicly available literature. The final list of the 25 technologies covers seven different categories ensuring broad representation of the nutrient recovery landscape: anaerobic digestion, composting, hydrolysis, physical, physicochemical, thermochemical, and the plasma category.

Task 3.1, together with Task 3.2, will open the path for Task 3.3 in which the technical performance and the environmental impact of the selected nutrient recovery and biobased fertilizers production technologies will be compared. The results of Task 3.2 will be described in Deliverable 3.3.

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Abbreviations Table

Abbreviation	Full term / meaning	Abbreviation	Full term / meaning
ABP	Animal By-product	MCDA	Multi-criteria decision analysis
AD	Anaerobic Digestion	NEO	Nitrogen Enriched Organic
AMU	Ammonia Mining Unit	Norg / N-organic	Organic nitrogen
BioAbfV	German Biowaste Ordinance	NR	Nutrient Recovery
BBF	Bio-Based Fertiliser	NRR	Nutrient Recovery & Reuse
CHP	Combined Heat and Power	PFD	Process Flow Diagram
CIP	Clean-In-Place	PLC	Programmable logic controller
DM	Dry Matter	RO	Reverse Osmosis
EAIs	Environmental Assessment Indicators	TAI / TAIs	Technical Assessment Indicator(s)
FM	Fresh Matter	TM	Total Matter
FTE	Full-time equivalent	TSS	Total Suspended Solids
FVG	Fruit, Vegetable and Garden waste	VS	Volatile Solids
GRSs	Grit Removal Systems	WWTP	Wastewater Treatment Plant
HORECA	Hotel, Restaurant and Catering		

1 Introduction

The main objective of the Ferticovery project is to identify and assess the best available technologies for the recovery and recycling of fertilising products from secondary raw materials. Within this framework, Work Package 3 (WP3) focuses on the systematic evaluation of nutrient recovery (NR) and bio-based fertiliser (BBF) production technologies, addressing their technical performance (Task 3.1), environmental impacts and resource efficiency (Task 3.2), and enabling their comparative assessment (Task 3.3).

Deliverable 3.1 presents the results of Task 3.1 and provides a structured technical analysis of the selected technologies based on a set of Technical Assessment Indicators (TAIs). The selection of these TAIs was guided by the specific objective of Task 3.1, namely the analysis of the key technical aspects of the selected technologies. For this reason, the indicators were chosen to reflect the most representative and comparable technical dimensions across a heterogeneous set of NR and BBF systems, including process performance, nutrient recovery efficiency, treatment capacity, robustness to feedstock variability, equipment complexity, and operating requirements. At the same time, the selected TAIs were limited to indicators for which data could be reasonably collected through questionnaires, technical documentation, scientific literature, or publicly available sources. In this respect, the final set of TAIs represents a balance between technical relevance, comparability across technologies, and practical data availability. Other aspects, such as environmental performance and broader resource efficiency considerations, are addressed separately in Task 3.2 and will be integrated at a later stage in the comparative assessment of Task 3.3.

These indicators therefore include key aspects such as operational performance, nitrogen and phosphorus recovery, treatment capacity, yield and productivity, sensitivity to variations in feedstock composition, complexity of the required equipment, and operating conditions. The indicators have been systematically defined and, where possible, quantified, to enable a consistent benchmarking of the selected technologies from a technical perspective. To support this assessment, a dedicated questionnaire was developed by the project consortium to capture relevant technical, operational, environmental, and product-related information. The questionnaire was distributed to technology providers representing the most relevant NR and BBF production systems identified in previous project tasks. These technologies were selected from an initial pool of 167 cases (Deliverable 2.1) and further refined through a ranking process (Task 2.2), resulting in a shortlist of the most representative systems.

Despite targeted engagement efforts, including multiple follow-ups, the response rate from technology providers remained limited. In cases where “raw data” (i.e. completed questionnaires from technology representatives) were available, these were used as the primary source of information for the assessment. For technologies where such data were not provided, the corresponding tables were completed using information derived from scientific literature, technical reports, and publicly available sources.

Where data gaps still remain after this process, generic or indicative values will be used in order to ensure consistency across the assessment and enable comparability between technologies. These generic data will be utilised in Task 3.3, where a comparative evaluation of technical performance, environmental impacts, and resource efficiency will be carried out.

The final set of technologies analysed in this deliverable is organised into seven categories: anaerobic digestion, composting, hydrolysis, physical, physicochemical, thermochemical, and plasma-based technologies. This categorisation enables a structured comparison across different technological pathways, reflecting the diversity of approaches currently applied for nutrient recovery and fertiliser production.

Overall, this deliverable establishes a consistent technical knowledge base for the selected technologies and provides the necessary input for subsequent project tasks. In particular, the TAIs defined and quantified in this work will be further used in Task 3.3, where the technical performance will be evaluated in combination with environmental indicators, supporting a comparative and multi-criteria assessment of nutrient recovery technologies.

2 Anaerobic digestion technologies

Anaerobic digestion technologies represent a well-established option for the treatment and valorisation of biodegradable waste streams and secondary raw materials. By converting organic matter under oxygen-free conditions, these systems allow the simultaneous recovery of renewable energy and nutrient-rich outputs, thereby contributing to both resource efficiency and circularity. The resulting digestate may be used directly or further processed into fertilising products, depending on the technological approach applied. Moreover, anaerobic digestion can be implemented through a variety of configurations, including wet and dry systems, and may be integrated with complementary treatment steps such as composting, digestate separation, nutrient concentration, and gas upgrading. For the purposes of this deliverable, the selected anaerobic digestion technologies (from Task 2.2) are assessed in terms of their key process, operational, and product-related characteristics.

2.1 Operation performance – Anaerobic digestion technologies

Table 1 shows three clear groups of AD-based systems.
The municipal biowaste systems with composting/post-composting, generally deliver a moderate final fertiliser/compost yield, roughly in the range of 0.30–0.45 t product /t input, because a substantial share of the incoming mass is converted biogas, the mineral fraction remains largely intact in the digestate, making it an appealing organic-mineral fertiliser. Second, manure- and digestate-refining systems produce several product streams rather than one single fertiliser, so their “yield” is better understood as a product split into solid fraction, retentate and concentrated nutrient products. Third, wet co-digestion systems tend to preserve much more mass in the form of wet digestate, with the main product often being a liquid or wet fertiliser stream rather than a dry compost-like product.

- Productivity depends on the scale of the systems. The systems presented here operate at scales ranging from 20,000 to 150,000 t/a of waste treated.
- Regarding water consumption, all systems are designed to recycle process water, so they generally do not use freshwater from the public water network except for limited secondary uses such as rinsing or steam production.
- Waste generation refers to impurities present in the feedstock. In some cases, these impurities are separated and sent for recycling, while in others they are directed to landfill.

Table 1: Operation performance of anaerobic digestion technologies

	Tech 1: Integrated AD and tunnel composting for household, HORECA, and green biowaste streams	Tech 2: Integrated dry AD for biowaste and composting of dewatered sludge	Tech 4: Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration)	Tech 3: Integrated wet AD of biowaste and composting of dewatered digestate)	Tech 5: Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks)	Tech 6: Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendment)	Tech 11: Turning local industrial wastes into nutrient-rich fertilizer via AD)
yield	0.45 t fertilizer/t input	0.45-0.50 t fertilizer/t input	solid fraction: 0.18 t/t manure, RO-retentate: 0.55 t/t manure, If RO is further processed: Ammonium bicarbonate:0.026 t/t manure, Kali-concentrate: 0.069 t/t manure	0.35 t fertilizer/t input (19,000t compost/ 55,000t of food and green waste)	0.77–0.92 t wet digestate/t input, 0.10–0.20 t solid digestate/t input	0.36 t fertilizer/t input	n/a
Does the yield change based on the feedstock composition	Yes - [1]	Yes, depending on the feedstock and regulation of the countries	unknown stable input	Yes	Yes	Yes	Yes, input with stable composition

[1] for green waste, especially grass cuttings in summer period versus more woody branches and shrubs in spring and autumn

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	Tech 1: Integrated AD and tunnel composting for household, HORECA, and green biowaste streams	Tech 2: Integrated dry AD for biowaste and composting of dewatered sludge	Tech 4: Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration)	Tech 3: Integrated wet AD of biowaste and composting of dewatered digestate)	Tech 5: Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks)	Tech 6: Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendment)	Tech 11: Turning local industrial wastes into nutrient-rich fertilizer via AD)
productivity	about 20,000 t/a of biowaste in the AD unit.	Den, about 20,000 t/a of compost.	Based on real yearly manure processed (200 kt). Solid fraction: 35.9 t fertilizer product/a, RO retentate: 110 t fertilizer product/a.	a 25,000 t-55,000t	46,000-55,000 wet digestate t/a and 6,000-7,200 t/a dry digestate for a unit that treats 60,000 t/a of waste.	9,000 t/a	
water consumption	No additional freshwater use; only rainfall water used	No external water use.	No external water use. Only process water used	water re-used within the process additional water for Pulp and cleaning.	Minimal water use steam addition mixer. water largeley recycled.	water largeley recycled within process.	water largeley recycled within process.

	Tech 1: Integrated AD and tunnel composting for household, HORECA, and green biowaste streams	Tech 2: Integrated dry AD for biowaste and composting of dewatered sludge	Tech 4: Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration)	Tech 3: Integrated wet AD of biowaste and composting of dewatered digestate)	Tech 5: Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks)	Tech 6: Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendment)	Tech 11: Turning local industrial wastes into nutrient-rich fertilizer via AD)
chemicals consumption	Fe-salts application only if necessary due to increased S-content in the biogas	n/a	Dosages: NaOH (For clean-in-place CIP and air scrubber): 0.4 kg/t input, HCl (for ion exchangers): 2.3 kg/t input, H_2SO_4 (For CIP and air scrubbing):1.3 kg/t input, Flocculant (for solid-liquid separation): 1.05 kg/t input, Anti-foam for stripper: 0.2 kg/t input, Iron sludge water (For H_2S removal in digestors): 36 kg/t input	Flocculants are used but their quantity is n/a. Perhaps conditioning chemicals before or after the dewatering process. [2]	No sufficiently detailed public evidence was identified to confirm the routine use of specific process chemicals in these plants. Some chemicals that can be used are: - Dewatering chemicals, if mechanical digestate separation is applied -Desulfurisation / biogas cleaning agents, if gas upgrading is used - Cleaning chemicals / CIP chemicals or auxiliaries for equipment	Only auxiliary chemicals are mentioned. No information available publicly.	n/a

	Tech 1: Integrated AD and tunnel composting for household, HORECA, and green biowaste streams	Tech 2: Integrated dry AD for biowaste and composting of dewatered sludge	Tech 4: Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration)	Tech 3: Integrated wet AD of biowaste and composting of dewatered digestate)	Tech 5: Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks)	Tech 6: Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendment)	Tech 11: Turning local industrial wastes into nutrient-rich fertilizer via AD)
waste generation	External utilization for metals and incineration of plastics/other foreign materials	0	Used active carbon for H2S removal from biogas: 0.025 kg/t input, Used RO membranes and filters: 0.05 kg/t input	Waste generation is mainly associated with pretreatment rejects, including heavy contaminants (e.g. stones, glass, metals), light contaminants (e.g. plastics, textiles, wood) and grit	Even though no publicly available data were identified, it is expected that reject streams containing heavy contaminants (e.g. stones, glass and metals), light contaminants (e.g. plastics, textiles and wood), and grit are generated.	Even though no publicly available data were identified, it is expected that reject streams containing heavy contaminants (e.g. stones, glass and metals), light contaminants (e.g. plastics, textiles and wood), and grit are generated.	Only a small quantity of heavy and light contaminant s is expected.

Table 1 shows three clear groups of AD-based systems. First, the municipal biowaste systems with composting/post-composting, generally deliver a moderate final fertiliser/compost yield, roughly in the range of 0.30–0.45 t product per t input, because a substantial share of the incoming mass is lost as biogas, water evaporation and stabilisation losses during post-treatment. Second, manure- and digestate-refining systems produce several product streams rather than one single fertiliser, so their "yield" is better understood as a product split into solid fraction, retentate and concentrated nutrient products. Third, wet co-digestion systems tend to preserve much more mass in the form of wet digestate, with the main product often being a liquid or wet fertiliser stream rather than a dry compost-like product.

Productivity depends on the scale of the systems. The systems presented here operate at scales ranging from 20,000 to 150,000 t/a of waste treated. Regarding water consumption, all systems are designed to recycle process water, so they generally do not use freshwater from the public water network except for limited secondary uses such as rinsing or steam production. Finally, waste generation mainly refers to impurities present in the feedstock. In some cases, these impurities are separated and sent for recycling, while in others they are directed to landfill.

2.2 N and P recovery – Anaerobic digestion technologies

The data in table 2 indicate that nutrient recovery from AD-based systems depends strongly on the downstream processing route and the nature of the final fertilising product, as well as the organic matter recovery. Compost-like products mainly contain nutrients in more stable organic forms, whereas liquid digestate fractions are generally richer in readily plant-available ammoniacal nitrogen and soluble potassium. More advanced post-treatment systems, such as membrane-based digestate refining, allow the production of fertiliser products with distinct nutrient compositions and functions.

Table 2: N and P recovery of the anaerobic digestion technologies

	Tech 1: Integrated AD and tunnel composting for household, HORECA, and green biowaste streams	Tech 2: Integrated dry AD for biowaste and composting of dewatered digestate	Tech 4: Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration	Tech 3: Integrated wet AD of biowaste and composting of dewatered digestate	Tech 5: Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks	Tech 6: Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendment	Tech 11: Turning local industrial wastes into nutrient-rich fertilizer via AD
Form of nutrient	Ntotal, Norg, K2O, P2O5, CaO-alkaline reaction substances	n/a	Solid fraction: DM=29% Most organic matter from digestate, P2O5=17 g/kg, N=11 g/kg (mostly organic N), K=6 g/kg RO-retentate: DM=4.2%, of which 50% is organic matter, N total=7 g/kg, NH4-N=5.6 g/kg, N-organic=1.4 g/kg, P_2O_5=0.6 g/kg, K=8.34 g/kg.	Nitrogen mainly as ammonium (NH4), and soluble K salts in liquid, P as inorganic phosphate (PO4), and organic matter in solid digestate.	Liquid digestate contains nitrogen mainly in ammoniacal form (NH4), while solid digestate is used mainly as an organic amendment supplying organic matter rather than as a fast-acting mineral fertiliser.	Typical characteristics of a biowaste derived digestate include an organic matter content of approximately 25-45% and a DM content ranging from 30%-60%. Total nitrogen is between 1-2%, while ammoniacal nitrogen remains low due to the stabilisation process. Phosphorus (expressed as P_2O_5) typically ranges from 0.5%- 1.5% of FM, and potassium (K_2O) from 0.5-2% of FM.	n/a
organic matter recovery from input	Almost all pure and suitable native organic matter is decomposed to biogas and recovered as compost material	n/a	Unknown. Part organic matter converted to CO2 and CH4	n/a	n/a	It includes an organic matter content of approximately 25-45%	n/a
quantity of	N total in compost:1.2-	n/a	same as yield (solid fraction:	n/a	Liquid fraction of digestate: Total	Total nitrogen generally falls	n/a

	Tech 1: Integrated AD and tunnel composting for household, HORECA, and green biowaste streams	Tech 2: Integrated dry AD for biowaste and composting of dewatered digestate	Tech 4: Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration	Tech 3: Integrated wet AD of biowaste and composting of dewatered digestate	Tech 5: Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks	Tech 6: Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendment	Tech 11: Turning local industrial wastes into nutrient-rich fertilizer via AD
nutrient	1.8% TM/P_2O_5 in compost: 0.,56-0.85% TM / K_2O in compost: 0,86 – 1.3% TM / CaO in compost: 2.70 - 5,35% TM / TM:65-77%		0.18 t/t manure, RO-retentate: 0.55 t/t manure, If RO is further processed: Ammonium bicarbonate:0.026 t/t manure, Kali-concentrate: 0.069 t/t manure)		N:4.0-5.1 kg/t of fresh matter, Total P:0.7-1 kg/t FM, total K: 3.5-5.2 kg/t FM/ Solid fraction of digestate: Total N:4.6-6.5 kg/t FM, Total P:2.0-2.5 kg/t FM, total K:3.4-4.8 kg/t FM	between 1-2%, while ammoniacal nitrogen remains low due to the stabilization process. Phosphorus (expressed as P_2O_5) typically ranges from 0.5- 1.5% of FM, and potassium (as K_2O) from 0.5-2% of FM	

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2.3 Treatment capacity – Anaerobic digestion technologies

Table 3: Treatment capacity of anaerobic digestion technologies

Treatment capacity (Operating capacity)	Tech 1: Integrated AD and tunnel composting for household, HORECA and green biowaste streams	Tech 2: Integrated dry AD of biowaste and composting of dewatered digestate	Tech 4: Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration	Tech 3: Integrated wet AD of biowaste and composting of dewatered digestate	Tech 5: Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks	Tech 6: Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil assessment	Tech 11: Turning local industrial wastes into nutrient-rich fertilizer via AD
permitted/ current capacity	Tunnel composting 50,000 t/a, within 20,000 t/a for digestion of biowaste, Green-waste composting 25,000 t/a	45,000 – 60,000 t input/a	262,500 t input/a	1.7 million t per year (70+ BTA Waste Pulpers and 90+ GRSs have been supplied and installed and more than 50 plants in over 15 countries)	60,000 t feedstock/a	25,000 t/a	150,000 t/a feedstock capacity
permitted organic/ inorganic input material (feedstock); the main mass flows	Green waste (25,000 t/a), Biowaste (50,000 t/a)	Municipal household waste (45,000 – 60,000 t/a), FVG (45,000 – 60,000 t/a)	Pig manure (slurry): 250,000 t/a, crude glycerine:12,500 t/a	25,000-55,000 t/a	Total organic input: 36,000 t/year agricultural waste	-	150,000 t of organic waste per year

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2.4 Equipment requirements – Anaerobic digestion technologies

The technical requirements of the equipment (Table 4) varies considerably among the examined systems, depending on the degree of process integration and the level of downstream treatment. In general, the core AD process is largely automated across all systems, including feedstock dosing, digester feeding, temperature and pH control, mixing, and gas production monitoring. However, manual or semi-manual operations are still needed in several cases, especially for feedstock unloading, storage management, tunnel loading/discharge, transport of solid materials, and certain maintenance tasks. Staffing requirements also vary, ranging from about 5 operators in more compact systems to around 15 technical and operational staff in larger integrated facilities. Land requirements differ substantially depending on plant capacity and the extent of composting or post-treatment, while lead times for delivery and installation of the main equipment typically range from several months to about two years. Overall, the table indicates that AD plants are highly automated in their biological core, but still require site-specific manual support, regular maintenance, and significant infrastructure, particularly when composting or nutrient recovery units are included.

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Table 4: Technical requirements of the equipment of the anaerobic digestion technologies

Complexity of the required equipment	Tech 1: Integrated AD and tunnel composting for household, HORECA and green biowaste streams	Tech 2: Integrated dry AD of biowaste and composting of dewatered digestate	Tech 4: Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration	Tech 3: Integrated wet AD of biowaste and composting of dewatered digestate	Tech 5: Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks	Tech 6: Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendsment	Tech 11: Turning local industrial wastes into nutrient-rich fertilizer via AD
automated and not automated process steps	Fully automatically running fermentation unit. Non-automated: Loading and discharge activities in/out of the tunnels with wheel loader/transportation of materials to storage boxes with wheel loaders	Automated: Feeding/extraction of digester. Composting depending on customer wishes. Non-automated: Depending on customer wishes	Automated: dosing of manure and glycerine from storage to digestors, whole digestate treatment Not automated: - Loading of solid fraction of digestate after separation with wheel loader	Automated: Feeding of digesters, temperature and pH control, mixing system, solid-liquid separation	Automated: feeding systems, temperature control, pH monitoring, mixing, biogas production monitoring/ Non-automated: storage management, pump maintenance, cleaning operations	Automated: temperature control, pH monitoring, gas production monitoring, mixing and agitation systems/ Non-automated process steps: waste collection and transport, unloading of organic waste	Automated: Feeding systems, temperature, pH, gas production rate control, mixing systems. Non-automated: transport of organic waste to the plant, unloading trucks
Number of operators	1 operation manager, 15 technical and operational staff	5-10 depending on the size of installation	5	4-8 operators per plant	n/a	n/a	n/a
Land used (area occupied by facilities)	About 55,000 m^2	9,440 – 44,520 m^2 depending on size and type of composting	33,440 m^2	n/a	n/a	n/a	n/a

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Complexity of the required equipment	Tech 1: Integrated AD and tunnel composting for household, HORECA and green biowaste streams	Tech 2: Integrated dry AD of biowaste and composting of dewatered digestate	Tech 4: Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration	Tech 3: Integrated wet AD of biowaste and composting of dewatered digestate	Tech 5: Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks	Tech 6: Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendsment	Tech 11: Turning local industrial wastes into nutrient-rich fertilizer via AD
Time required between ordering and manufacturing of the main process equipment	Mobile technique; wheel loader, shredder and sieving machines about 6 months, Stationary machine technique about 1 year and more if specifications apply. In addition, environmental permits are required. Required time of more than 1 year.	Installation takes up to 2 years		For industrial scale AD: design phase, fabrication of digesters, delivery mixers, pumps. Typical time: 12-18 months	The construction and equipment supply phase for AD plants typically requires several months to about 1 year, depending on plant scale and equipment manufacturing	6 -12 months	6-12 months. This period usually includes: fabrication of digesters and storage tanks, manufacturing of pumps, mixers, and feeding systems

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Complexity of the required equipment	Tech 1: Integrated AD and tunnel composting for household, HORECA and green biowaste streams	Tech 2: Integrated dry AD of biowaste and composting of dewatered digestate	Tech 4: Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration	Tech 3: Integrated wet AD of biowaste and composting of dewatered digestate	Tech 5: Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks	Tech 6: Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendsment	Tech 11: Turning local industrial wastes into nutrient-rich fertilizer via AD
Frequency of main equipment/ machines maintenance	Maintenance; daily controls	1 time/year	2 times/year	For pumps, mixers, compressors ever 3-6 months, for digester equipment, gas systems every 1-2 years	Weekly-monthly: inspection of pumps and mixers, lubrication of moving parts, checking sensors (pH, temperature, gas flow)/ every 3-6 months: servicing pumps and agitators, checking gas compressors and blowers/once a year: maintenance of engines or gas upgrading systems, structural inspection of digesters and piping	Daily-weekly: pumps and mixers, feedstock feeding system, gas pressure and flow, sensors (temperature, pH, gas composition)/Every 3-6 months: inspection of compressors and blowers, /Annually: maintenance of biomethane upgrading units, inspection of digesters and storage tanks	Daily-weekly (pumps and mixers, feeding systems, gas pressure and flow, sensors of temperature, pH, gas composition), every 3-6 months (servicing pumps and agitators), once per year (inspection of digesters and storage tanks)

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2.5 Operating Conditions – Anaerobic digestion technologies

The data (Table 5) indicate that the operating conditions of AD-based systems are largely determined by feedstock characteristics, process configuration, and regulatory hygiene requirements. While most of the examined installations operate continuously under mesophilic conditions, some systems apply thermophilic digestion or additional hygienization steps to ensure sanitisation of the treated material. The presence or absence of aerobic post-treatment further differentiates the systems, particularly where composting is integrated with anaerobic digestion.

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Table 5: Operating conditions of the anaerobic digestion technologies

Operating conditions	Tech 1: Integrated AD and tunnel composting for household, HORECA and green biowaste streams	Tech 2: Integrated dry AD of biowaste and composting of dewatered digestate	Tech 4: Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration	Tech 3: Integrated wet AD of biowaste and composting of dewatered digestate	Tech 5: Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks	Tech 6: Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendment	Tech 11: Turning local industrial wastes into nutrient-rich fertilizer via AD)
Feedstock quality requirements for acceptance in the installation	[3]nory	DM: 25% - 45% Pretreatment required: - Removal of plastics/inerts, - breaking the material: 60 mm - NH3 <5 g/L	No Cat. 1 materials. Only liquids/slurries can be handled and processed	n/a	n/a	n/a	n/a
plant run time	8,000-8,500 h/a	2,000-2,500 h /a	8,760 h/a	8,000-8,500 h/a	8,000-8,500 h/a	8,000-8,500 h/a	8,000-8,500 h/a
temperature	Thermophlic	Mesophilic	Thermophilic	Mesophilic	mesophilic	mesophilic	mesophilic
pH-range	7.7-9	7-9	pH 8.5	n/a	n/a	7-8	n/a
aerobic conditions	yes	yes (composting)	No	yes (composting)	no	no	no
anaerobic conditions	yes	yes (AD)	Yes	yes (AD)	yes	yes	yes
Hygienization process	[4] minimum 55°C for 2 weeks or 60°C for ~ 6 days and 65°C ~ 3 days in the material	yes	53°C in situ Solid fraction suited for export.	n/a	70°C, 1h	n/a	n/a

[3] German Biowaste Ordinance sets impurity and plastic limits with inspection

[4] According to national requirements set in the German Biowaste Ordinance requirements

3 Composting technologies

Composting represents a key biological treatment pathway within the circular bioeconomy. It enables the controlled biostabilisation of biodegradable materials and yields compost, a valuable soil improver and organic fertiliser that returns stable organic matter and plant nutrients r to soils. Composting contributes to climate mitigation and resource efficiency not only by diverting biowaste from landfill and thereby avoiding methane emissions, but also by substituting carbon-intensive products such as peat and mineral fertilisers. Therefore, it it transforms organic residues into a product with clear agronomic value, with benefits for soil structure, water retention, nutrient supply and soil biological activity. In addition, composting processes generally require little or no chemical additives and, depending on the technology applied, can be operated with relatively low energy demand.

Within the scope of the project, and after the selection made based on a Multicriteria Decision tool in the framework of task 2.2, four composting value chains were selected by the consortium for further assessment. These include one tunnel composting system, one open windrow system, and two semi-covered windrow configurations using a semipermeable membrane. The tables below summarise key operational parameters for the selected composting configurations.

3.1 Operation performance – Composting technologies

Table 6 includes yield, energy consumption, water use, productivity and waste generation. The yields of these four case studies have a wide range. This can be mainly attributed to the different composition of input (mixtures of food waste and green waste or only green waste). Energy consumption values also vary across systems, with different information on energy sources available per technology. Additional parameters such as water consumption, and waste outputs are also included in table 6.

Table 6: Operation performance of the composting technologies

	Tech 7: Tunnel composting combined with pre-treatment and refining	Tech 8: Open windrow composting for green waste	Tech 9: Composting system using semi-permeable membrane and forced aeration	Tech 10: Semi-covered windrow composting for green waste
Yield (t compost/ t of input)	0.17-0.2	0.5-0.6	0.65	0.4
Change of yield based on the feedstock composition*	No (the mixed input material is controlled to assure the quality and consistency of the final product)	Yes (depends on the quantity of wooden particles, and the diameter of cuttings)	No	Yes (the yield can change depending on the composition of the feedstock[5])
productivity	12,000 t fertilizer product/a (12,000/8,760) = 1.37 t/h	1.4t/h= 12,264 t/a	1.3 t/h=11,388 t/a	n/a
energy consumption per t of input	Electricity: 102.19 kWh/t, Diesel: 1.83 L/t, Natural gas: 27.77 kWh/t	7-8 kWh/t input (electricity)	~ 2.5 kWh /t (electricity only for the aerobic treatment)	1L of diesel[6], 30 kWh for size reduction screening[2]
water consumption	0.4 t/t input	use of separate collected rainwater	Approximately 100 L/t of input material, whereby most of it is covered by leachate from collection tank	Digestate when water is needed
chemicals consumption	no	no	no	no
waste generation	5,000 t waste/a	external utilisation for metals and incineration of plastics about 0.0007 t waste/t input	Inerts/foreign materials outward biomass (30%)- for energy generation (so not really waste)	n/a (inerts and other not compostable materials from screening are expected)[2]

[5] depending on the quantity of wooden particles, and the diameter of cuttings
[6] Database of Waste Management Technologies

3.2 N and P recovery – Composting technologies

Table 7 focuses on the nutrient content and organic matter recovery which are key indicators of fertilizer quality. The tunnel composting exhibits a well-defined composition and high organic matter recovery (53.2%). The compositional analysis has to be analyzed and is verfired by national quality assurance schemes. They can also meet FPR requirements. For the open windrow composting, the organic matter recovery is 0.3 t compost/t input. The quantity of nutrients is 0.02 t/t input. For the composting system using semi-permeable membrane and forced aeration, the only information is that it produces a certified finished compost. For the windrow composting system of green waste certain values are provided for the total nitrogen, phosphate, potassium, magnesium, and calcium.

Table 7: N and P recoveries of the composting technologies

	Tech 7: Tunnel composting combined with pre-treatment and refining	Tech 8: Open windrow composting for green waste	Tech 9: Composting system using semi-permeable membrane and forced aeration	Tech 10: Semi-covered windrow composting for green waste
Form of nutrient	Ntotal-2.3%, P2O5-1.2%, K2O-2.2%, MgO - 0.7%, CaO- 7.6%	Ntotal, Norg, K2O, P2O5, CaO-alkaline reaction substances	Finished compost (certified), Compost for organic farming (certified), compost as component for substrates (customer spec.), compost for soil amendments	n/a
Organic matter recovery from input	53.2	~0.3 t org. substance/t of compost	n/a	0. 233 t/t compost
quantity of nutrient	???	0.02 t nutrients (sum of N, P2O5, K2O, MgO, CaO)/ t input green waste, - 0.005 t N and P2O5/t input green waste	-	Total nitrogen: 6.36 kg/t, total phosphate (P2O5): 3.20 kg/t, K2O: 6.86 kg/t, MgO: 3.97 kg/t, CaO: 17.6 kg/t

3.3 Treatment capacity – Composting technologies

The capacity of the evaluated technologies ranges from 1,400 t input/a to 60,000 t input/a. The tunnel composting treats food waste, green waste, and cemeteries green waste, while the open windrow composting system and the semi-covered windrow composting systems treat only green waste.

Table 8: Treatment capacity of the composting technologies

	Tech 7: Tunnel composting combined with pre-treatment and refining	Tech 8: Open windrow composting for green waste	Tech 9: Composting system using semi-permeable membrane and forced aeration	Tech 10: Semi-covered windrow composting for green waste
permitted capacity	60,000 t input/a	25,000 t input/a	24000 t input/a	15,000 t of input/a
permitted organic /inorganic input material (feedstock); the main mass flows	Food waste (urban): 30,000 t/a, green waste (urban and small gardening companies): 25,000 t/a, Cemeteries Green waste: 2,500 t/a, Food waste (private companies): 2,500 t/a	Green waste: 25,000 t/a	biowaste: 11,600 t/a Green/Garden waste: 5,600 t/a	Green waste

3.4 Equipment requirements– Composting technologies

As for the complexity of the required equipment for the composting technologies, the tunnel composting system with pre-treatment and refining is a highly automated process, while the composting system with semi-permeable membrane and forced aeration is automated but with some non-automated parts, such as the mechanical pre-treatment, windrow formation. In the open windrow composting method for green waste some parts are automated and some parts are not. The tunnel composting occupies 36 operators, while the composting system with semi-permeable membrane has 3 full-time workers. The windrow composting system for green waste needs 1-2 operators per shift. The area occupied by the facilities ranges from 500 m^2 to 40,000 m^2. The time required between ordering and manufacturing the main equipment ranges from 3 to 24 months. Material maintenance ranges between daily (visual inspection of equipment), weekly (cleaning of filters), monthly (inspection of sensors), and annually (cleaning of reactor and heat exchanger).

Table 9: Technical requirement of the equipment for the composting technologies

	Tech 7: Tunnel composting combined with pre-treatment and refining	Tech 8: Open windrow composting for green waste	Tech 9: Composting system using semi-permeable membrane and forced aeration	Tech 10: Semi-covered windrow composting for green waste
Which process steps are automated and which are not automated	Automated: Mechanical pre-treatment, composting, tunnel loading, compost packaging and pelleted compost. Not automated: Unloading of the composting vessels	not automated	Automated: Treatment under semipermeable System (positive aeration controlled by T- and O2 content). Non-automated: Mechanical pre-treatment, Heap built up, Turning	Non automated
Number of operators	36	n/a	3 FTE	1-2 operators per shift may be sufficient
Land used (area occupied by facilities)	40,000 m^2	30,000 m^2	8,000 m^2 for the composting operations	
Time required between ordering and manufacturing of the main process equipment	24 months	n/a	3 months for the semi permeable membrane system, 6 months till start of operations due to delay in construction work	3 months for the semi permeable membrane system, 6 months till start of operations due to delay in construction work
Frequency of main equipment maintenance	Depends on the type of equipment: daily, weekly, monthly, for some parts of the equipment and annual maintenance at the whole system	Working day visual inspection and routine maintenance in accordance with the serving life of the machine components and in accordance with the manufacturer's specifications	Daily routine check, Equipment overhaul planned annually	Daily check of membrane.

Table 10: Operation performance of the composting technologies

Operating conditions	Tech 7: Tunnel composting combined with pre-treatment and refining	Tech 8: Open windrow composting for green waste	Tech 9: Composting system using semi-permeable membrane and forced aeration	Tech 10: Semi-covered windrow composting for green waste
Feedstock quality requirements	For food waste: admitted: fruit/vegetables, solid dairy products, bakery products,	Control value for impurities according to the German Biowaste Ordinance (2022)/ mandatory	< 0,5 % foreign materials/inerts There are no other requirements besides of the mentioned one since	General requirements for acceptance in the installation: the feedstock must generally be

Operating conditions	Tech 7: Tunnel composting combined with pre-treatment and refining	Tech 8: Open windrow composting for green waste	Tech 9: Composting system using semi-permeable membrane and forced aeration	Tech 10: Semi-covered windrow composting for green waste
for acceptance in the installation	biodegradable waste from kitchens and canteens, markets biowaste. Not admitted: ABP's (categories 1 and 2), large animal bones, entrails, wastewater sludge, manure, paper and cardboard, non-biodegradable waste (plastic bags and packaging), packaged food waste and inert material (sand, stones and glass). For green waste: Admitted: tree prunings with small trunks (up to 6 cm), untreated wooden logs (small size<50 cm), Foliage (without soil or sand), not admitted: wood logs with more than 50 cm. diam, invasive plant species, eucalyptus debris and palm trees. For cemeteries green waste (this material undergoes for a pre-treatment process where we sort these materials: admitted: target materials: flower and floral arrangement waste. non target materials: candle holders, packaging, metal lids, flowerpots, other plastics, paper and cardboard, scrap metal, glass, batteries and WEEE (Waste Electrical and Electronic Equipment). Not admitted: Hazardous waste: contaminants, solvents, tyres, syringes, waste from exhumations: coffin wood remains, clothing from the deceased, bones, sweeping	visual inspections obligation for pretreatment by exceeding the control value for impurities/plastics. Max 3% mass of impurities and max. 0.5% plastics in fresh mass above 20 mm	the waste stream is determined by contract; any seasonal variations (e.g moisture, structure, etc.) have to be considered by appropriate process management	organic biomass (green waste), suitable for carbonization, clean material (free of contaminants such as plastics, metals, stones, or treated wood). Typical technical quality requirements: moisture content: usually below 15-25%, particle size <50-100 mm after shredding, low contamination (minimal plastics, metals, glass or soil)

Operating conditions	Tech 7: Tunnel composting combined with pre-treatment and refining	Tech 8: Open windrow composting for green waste	Tech 9: Composting system using semi-permeable membrane and forced aeration	Tech 10: Semi-covered windrow composting for green waste
	waste, food waste, animal-origin waste, inert materials (stones, marble, glass), green waste (pruning's, gardening)			
other specifications for the process required	No	-	After mechanical pretreatment: - particle size: 0-100 mm, - foreign materials content < 0.5%, After standard pretreatment according to best practice for C:N ratio, moisture, porosity, as well a homogenous mix	Low oxygen conditions inside the reactor, controlled heating of biomass, controlled high temperatures for the carbonization of the biomass, gas management of the pyrolysis gases
plant run time	8760 h/a (24 h/365 days per year)	all working days of the year (open hours 8:00-18:00 Mo-Fr; Nov-March 8:00-16:00)	24/7; 8760 h	For similar biochar/pyrolysis plant, the usual operating schedule is: 24 hours per day, 330-350 days per year. If the plant works for 340 days per year then:8,160 hours/year
temperature	1st phase: 60°C/48 h + 50°C/7-10 days, maturation-pasteurization phase:70°C/1 h		65°C-75°C	typical biochar production temperatures are 400-700°C. Lower temperatures (400-500°C) tend to maximize biochar yield, while higher temperatures increase gas production
pH-range	5 (biowaste), 9 (compost)	-	-	Although the process itself does not have a defined pH, the resulting biochar typically has an alkaline pH commonly in the range:7-10. The exact value depends on the feedstock type (wood, green waste, agricultural residues), the pyrolysis temperature

Operating conditions	Tech 7: Tunnel composting combined with pre-treatment and refining	Tech 8: Open windrow composting for green waste	Tech 9: Composting system using semi-permeable membrane and forced aeration	Tech 10: Semi-covered windrow composting for green waste
aerobic conditions (yes/no)	yes	yes	yes	no
anaerobic conditions (yes/no)	no	no	no	yes
Hygienization process	yes	-	Yes (> 70°C for 3 days, 65°C for 7 days etc.) as well as german BioAbfV, Annex 2	The installation includes hygenization as part of the composting /biomass treatment process, ensuring safe use of the produced soil products.

4 Hydrolysis technologies

Hydrolysis technologies constitute a relevant category of processes for the conversion and upgrading of secondary raw materials into value-added fertilising products within the circular bioeconomy framework. These technologies involve the breakdown of complex organic compounds into simpler and more bioavailable forms through thermal, chemical, or combined physicochemical mechanisms. As a result, hydrolysis can enhance nutrient availability, facilitate downstream processing, and enable the production of fertilisers with tailored characteristics.

Depending on the specific process configuration and feedstock, hydrolysis technologies can be applied to a wide range of materials, including sewage sludge, anaerobic digestate, and specialised waste streams such as keratin-rich residues. In contrast to purely biological processes, hydrolysis often operates under controlled temperature and pH conditions, allowing for faster reaction rates and, in some cases, improved hygienisation of the treated material.

Within the scope of this deliverable, and following the selection carried out in Task 2.2, the identified hydrolysis technologies are assessed based on their key technical characteristics.

4.1 Operation performance – Hydrolysis technologies

The four processes aim to convert waste into fertilizer products. The highest yield was 0.886 t fertilizer/t input, while the lowest yield was 0.51 t fertilizer/t input. The last technology yield is 1, but that reflects more the material transformation rather than true production efficiency. As for the feedstock sensitivity, most technologies maintain stable yields despite variations in feedstock composition, but product quality can vary significantly.

The productivity of the technologies varies, indicating that two of the technologies (0.075 t/h and 0.02 t/h) are pilot or small-scale processes, while the one with productivity 10 t/h is industrial scale. Regarding the energy consumption of the technologies, two of them have low consumption (50 kWh/t and 52-58 kWh/t) and one of them is energy intensive (500 kWh/t). The biothermal treatment for efficient biosolids processing uses waste heat making it more sustainable. In reference to the technologies' water consumption, two of them are water-efficient (0.001 t water/t input and none), the hydrolysis of anaerobic digestate has moderate water consumption (0.2 t/t) and the hydrolysis of keratin waste has high water demand (1 t). The highest chemicals consumption comes from the two technologies that use multiple acids, bases, and trace elements, while the other two technologies use only KOH and NaOH. Two of the hydrolysis technologies do not generate waste, while the hydrolysis of anaerobic digestate generates 0.1 t of waste/t input.

Table 11: Operation performance of the hydrolysis technologies

	Tech 12: Biothermal treatment for efficient biosolids processing	Tech 14: Hydrolysis of keratin waste	Tech 15: Hydrolysis of anaerobic digestate	Tech 13: A physical-chemical hydrolysis process for the treatment of biosolids and organic waste
Yield t fertilizer/t of input	0.7/7500 = 9,33 *10^{-5} t fertilizer product /t input	0.886 t fertilizer product/t input	0.51 t fertilizer product/t input	1
Change of yield based on the feedstock composition*	-	no	The raw materials composition has a minor impact on fertilizer yield, but a significant impact on the quality characteristics of the product	The mass yield of the process remains approximately constant, as the process converts rather than separates material.
productivity	0.02 t fertilizer product/h	0.075 t fertilizer product/h	-	10 t/h
energy consumption	Not available (use of waste heat)	50 kWh/t input	500 kWh/t input	52-58 kWh per dry t
water consumption	0.001 t/t input	1 t	0.2 t/t input	no water consumption
chemicals consumption	KOH, quantities not available	H_2SO_4: 98.97 kg/t input, H_3PO_4: 98.97 kg/t input, KOH: 181.68 kg/t input, trace element salts (Cu, Co, Fe, Mn, Mo, Se, Zn):29.54 kg/t input	H_2SO_4: 23.40 kg/t input, H_3PO_4: 14.89 kg/t input, $CuSO_4$: 8.51 kg/t input, $ZnSO_4$: 8.51 kg/t input, lignosulphonate: 38.30 kg/t input, KOH: 65.96 kg/t input	KOH/NaOH (45-50% solution):80-90 kg/dry t
waste generation	no	n/a	0.1 t/t input	no

4.2 N and P recovery – Hydrolysis technologies

The Hydrolysis of keratin waste technology in Table 10 produces a fertilizer with nitrogen both in amino acids and in ammonium form. It also includes phosphorus, potassium, sulphur and micronutrients. The Hydrolysis of anaerobic digestate technology includes a granulated, neutralized product of chemical hydrolysis and in the physical-chemical hydrolysis process for the treatment of biosolids and organic waste technology the nutrients are in mixed forms (both dissolved and suspended). Nitrogen is present both as ammonium and as organic nitrogen. Phosphorus is present in both organic and inorganic form. Potassium is mainly present in soluble form. Regarding the organic matter recovery, most of the technologies are highly efficient in preserving organic matter, supporting soil health and carbon recycling. The highest nutrient recovery efficiency was achieved by the POIG hydrolysis technology (0.167 t nutrients/t input), while the Eranet technology had a nutrient recovery rate of 0.03 t/t input. The hydrolysis technology expresses the nutrient recovery differently (3.6-3.2-3.7 kg/m^3 N-P_2O_5-K_2O).

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Table 12: N & P recovery of the hydrolysis technologies

	Tech 12: Biothermal treatment for efficient biosolids processing	Tech 14: Hydrolysis of keratin waste	Tech 15: Hydrolysis of anaerobic digestate	Tech 13: A physical-chemical hydrolysis process for the treatment of biosolids and organic waste
Form of nutrient	Not specified, NPK liquid bio-fertilizer, rich in macro and micro nutrients and humic substances	Nitrogen: in organic form (aminoacids from keratin hydrolysate) and as ammonium. P2O5, K2O, SO3. Micronutrients: as soluble salts ($CuSO_4$, $CoSO_4$, $FeSO_4$, $MnSO_4$, $ZnSO_4$, Na_2SeO_4, H_3BO_3, $(NH_4)_6Mo_7O_{24}$)	Granulated, neutralized product of chemical hydrolysis	The nutrients in the product are present in mixed forms. Nitrogen is present as both readily available ammonium (NH4) and organic nitrogen (slow-release). Phosphorus is present in both organic and inorganic bound forms, with only partial immediate availability. Potassium is mainly present in soluble form (K^+). Overall, the product is a liquid biosolids-based fertilizer containing both dissolved and suspended nutrients
organic matter recovery from input	10% DM	100%	100%	The technology achieves near-complete recovery of organic matter, as it converts rather than removes solids. The fertilizer has high organic matter (59.9 kg/m^3)
quantity of nutrient	-	0.167 t/t input	0.03 t/t input	the hydrolysed sludge contains 20-40% Corg/DM and N-P_2O_5-K_2O:3.6-3.2-3.7 kg/m^3

4.3 Operating capacity – Hydrolysis technologies

The Biothermal treatment for efficient biosolids processing and Hydrolysis of anaerobic digestate technology in Table 11 have similar current capacities with 1 t output and 2.3 t output/a correspondingly, while the Hydrolysis of keratin waste technology has the highest capacity of 150 t input/a. As for the input, the biothermal treatment for efficient biosolids processing utilizes communal sewage sludge (7600 t/a), the hydrolysis of keratin waste uses *poultry* feathers (100t/a), the hydrolysis of anaerobic digestate uses
1.9 t/a of digestate, and the physical-chemical hydrolysis process uses 200,000 t dry matter sewage sludge annually.

Table 13: Operating capacity of the hydrolysis technologies

	Tech 12: Biothermal treatment for efficient biosolids processing	**Tech 14: Hydrolysis of keratin waste**	**Tech 15: Hydrolysis of anaerobic digestate**	**Tech 13: A physical-chemical hydrolysis process for the treatment of biosolids and organic waste**
permitted/ current capacity	1 t output/a	150 t input/a	2.3 t input/a	n/a
permitted organic/ inorganic input material (feedstock); the main mass flows	communal sewage sludge (7,600 t/a)	poultry feathers (keratin waste): 100 t/a, H_2SO_4:16.8 t/a, H_3PO_4:16.8 t/a, KOH: 30.8 t/a, Trace element salts (B, Cu, Co, Fe, Mn, Mo, Se, Zn): 5 t/a	anaerobic digestate: 1.9 t/a, Haemoglobin: 1.05 t/a, H2SO4: 0.11 t/a, H3PO4: 0.07 t/a, CuSO4: 0.04 t/a, ZnSO4: 0.04 t/a, lignosulphonate: 0.18 t/a, KOH: 0.31 t/a, peat: 0.56 t/a, Ash: 0.16 t/a, Water: 0.28 t/a	200,000 t DM/year of sewage sludge/ other organic waste such as food waste

4.4 Equipment requirement – Hydrolysis technologies

technical requirements of the equipment ranges from fully automated (hydrolysis of keratin waste) to fully manual (hydrolysis of anaerobic digestate). The number of operators varies from 1 to 4. The footprint of the facilities ranges from small (30 m^2 of land used for the hydrolysis of anaerobic digestate) to relatively large (150 m^2 of land used for the biothermal treatment for efficient biosolids processing). The time required between ordering and manufacturing the main process equipment can be around 6 months, while the frequency of the main equipment maintenance can be around 2 times per year.

Table 14: Technical requirements of the equipment for the hydrolysis technologies

	Tech 12: Biothermal treatment for efficient biosolids processing	Tech 14: Hydrolysis of keratin waste	Tech 15: Hydrolysis of anaerobic digestate	Tech 13: A physical-chemical hydrolysis process for the treatment of biosolids and organic waste
Which process steps are automated and which are not automated	-	Automated: loading, unloading, mixing. Non-automated: none	All processes are performed by the operator	"Automated operation, SCADA controlled, remote access available". This means that the core treatment process is highly automated including the control of temperature, alkali dosing, mixing. The non-automated process steps are the feedstock handling (sludge transport and feeding), product handling (storage tanks, transport, land application), maintenance (equipment cleaning, inspection)
Number of operators per shift	-	4	1	1 operator per shift is enough
Land used (area occupied by facilities)	150 m^2	n/a	30 m^2	800 ft^2=74 m^2 corresponding to a compact, containerized unit.
Time required between ordering and manufacturing of the main process equipment	-	n/a	6 months	The technology is described as a compact, modular package, suggesting relatively short periods compared to a conventional, site-built system
Frequency of main equipment/ machines maintenance	2 times/a	n/a	n/a	The system is described as automated and designed for easy operation, suggesting standard industrial maintenance requirements for mechanical, thermal and dosing components.

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4.5 Operating conditions – Hydrolysis technologies

For some technologies, the feedstock quality requirements are not specified. For some others, it is mentioned that the feedstock must be within a manageable solids range for pumping and mixing, or contaminants must be removed. The plant run time is around 2,000h/a and 24/7. Each technology is operating in different temperature. Hydrolysis of keratin waste operates at 80°C, hydrolysis of anaerobic digestate operates in less than 60°C, and the physical-chemical hydrolysis process for the treatment of biosolids and organic waste operates at 75°C. The pH range fluctuates a lot. In the hydrolysis of keratin waste, it is from 1 to 5.5. In the hydrolysis of anaerobic digestate it is from 0 to 8, and in the physical-chemical hydrolysis process for the treatment of biosolids and organic waste it is strictly 8.1. Some of these technologies operate in aerobic conditions while some others include hygienization, as it is seen in Table 15.

Table 15: Operating conditions of the hydrolysis technologies

	Tech 12: Biothermal treatment for efficient biosolids processing	Tech 14: Hydrolysis of keratin waste	Tech 15: Hydrolysis of anaerobic digestate	Tech 13: A physical-chemical hydrolysis process for the treatment of biosolids and organic waste
Feedstock quality requirements for acceptance in the installation	none	n/a	Contaminants are not removed during the process, therefore the feedstock must meet fertilizer requirements	The feedstock must be within a manageable solids range for pumping and mixing, and suitable for alkaline treatment (KOH) and thermal hydrolysis (75°C)
other specifications for the process required	-	no	no	Electricity (compatible with 600V or 460V), potable water, recyclable water, operating conditions (75°C, mixing), automated control (SCADA)
plant run time	24/7	2000 h/a	2000 h/a	It is a continuous, automated process (SCADA-controlled), indicating that it can operate on a 24/7 basis.
temperature	-	80°C	<60°C	75°C
pH-range	-	<1.0 to 5.5	0-8	8.1
aerobic conditions (yes/no)	microaerobic	no	yes	no
anaerobic conditions (yes/no)	none	no	no	no
Hygienization process	-	n/a	-	The process produces a Class A biosolids fertilizer, indicating effective pathogen reduction. Hygienization is achieved through the combined effects of elevated temperature (75°C), and alkaline conditions (KOH addition).

5 Physical technologies

Physical technologies represent an important group of processes for the recovery and concentration of nutrients from secondary raw materials, particularly from liquid streams such as digestate, centrate, and wastewater-derived effluents. In contrast to biological treatment pathways, these technologies rely mainly on physical separation and concentration mechanisms, including crystallisation, filtration, evaporation, and membrane-based processes, in order to produce fertilising products or intermediate nutrient-rich fractions. Depending on the technological approach applied, physical technologies may enable the selective recovery of specific nutrients, such as phosphorus in the form of struvite, or the broader valorisation of digestate into concentrated liquid and solid fertilising products. Their performance is strongly influenced by the composition and physicochemical characteristics of the input stream, as well as by the level of integration with upstream or downstream treatment steps. For the purposes of this deliverable, the selected physical technologies are assessed in terms of their main operational, product-related, and technical characteristics.

5.1 Operation performance – Physical technologies

Table 16: Operation performance of physical technologies

	Tech 17: Crystallizer for struvite production from nutrient-rich liquid streams	Tech 20: Liquid digestate valorisation through biological treatment and ultrafiltration technologies	Tech 18: Fluidized bed reactor for struvite production from municipal and industrial wastewater	Tech 19: Integrated solid-liquid separation, evaporation and reverse osmosis (RO) treatment for digestate valorisation
yield	varies	Almost 40% of the produced digestate quantity	0.69-1.67 kg struvite per m^3 of input[7]	245 kg fertilizer/t input[8]
Does the yield change based on the feedstock composition*	Yes, the yield depends on the input P load.	n/a	Yes, the yield strongly depends on the feedstock composition, especially phosphorus concentration. Higher nutrient concentration=higher fertilizer yield	Yes, the yield does change depending on the feedstock composition. The plant treats a mixture of different substrates (manure, industrial sludge, biowaste). Each of this has different nutrient and dry matter content
productivity	varies	30 t of liquid fertilizer/24 h ~ 1.25 t/h	(2 t/day)/ (24 h/day) = 0.083 t/day= 83 kg/h	2.5 t/h[9]

[7] The output is 2 t product/day=2,000 kg/day. The input flow is: 50-120 m^3/h= 1,200 m^3/day-2,880 m^3/day. So the yield is: at 50 m^3/h:2,000/1,200=1.67 kg fertilizer/m^3 input, at 120 m^3/h: 2,000/2,880 = 0.69 kg fertilizer/m^3 input. So the yield is 0.69-1.67 kg struvite per m^3 of input

[8] The digestate input to the NRR system is 245 t/day. The plant produces solid fertilizer and liquid fertilizer. The dried solid fraction is 30 t/day. The liquid fertilizer (evaporator concentrate) is also 30 t/day. 30 t/day + 30 t/day = 60 t/day. The yield is 60/245= 245 kg fertilizer/t input

[9] Evaporator concentrate:30 t/day. Solid fraction of digestate: 30 t/day. So, the hourly productivity is: evaporator concentrate: 30/24=1.25 t/h. The solid fraction stream:30/24=1.25 t/h. In total the fertilizers streams: 1.25+1.25=2.5 t/h

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	Tech 17: Crystallizer for struvite production from nutrient-rich liquid streams	Tech 20: Liquid digestate valorisation through biological treatment and ultrafiltration technologies	Tech 18: Fluidized bed reactor for struvite production from municipal and industrial wastewater	Tech 19: Integrated solid-liquid separation, evaporation and reverse osmosis (RO) treatment for digestate valorisation
energy consumption	varies	40 kWh/t of digestate	A realistic estimate of the energy consumption is 0.2-0.6 kWh/m^3 or 0.3-1.0 kWh/kg struvite=300-1000kWh/tn struvite	In 2020 the plant generated 21,313 MWh of electricity, of which 32% was consumed by the NRR system (32%*21,313=6,820.16 MWh). More specifically, 14% by the evaporator, 10% by the dryer, 5.8% by the aerobic treatment tank, 1.2% by the decanter centrifuges, 0.93% by the hygienisation tanks and 0.4% by the RO installation
water consumption	varies	equivalent to <10% of the incoming raw materials. Water is mainly used for steam generation, cleaning procedures etc.	Water is not consumed, it is treated and returned to the plant	no freshwater consumption is reported
chemicals consumption	MgCl2/Mg(OH)2: varies (depends on P load), NaOH: varies (depends on alkalinity)	$FeCl_2$-$FeCl_3$: ~ 1.4 kg/t input	The chemicals used are magnesium chloride ($MgCl_2$) (32%) and sodium hydroxide (NaOH) (25%)	Polymer flocculant in the decanter centrifuge, iron chloride in the aerobic treatment tank, sulfuric acid solution in the air scrubber
waste generation	No waste is generated. The only addition is from the source of Mg ion. If $MgCl_2$ is used, chlorides are added	Mixed plastics waste from depackaging process, transferred to landfill, are less than 0.5% of the total input quantity	The treated effluent is sent back to the WWTP for further treatment. The solid output is the struvite. So, technology does not generate waste	The dried solid fraction and the evaporate concentrate are used as fertilizers, and the RO concentrate is recycled back in the aerobic treatment tank, according to the PFD of the technology

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The assessment of the selected nutrient recovery technologies demonstrates that their technical performance and operational profile depend strongly on the targeted recovery pathway. Technologies based on struvite precipitation focus on the selective recovery of phosphorus from nutrient-rich liquid streams, whereas integrated digestate treatment systems aim at recovering larger fertiliser fractions through a combination of biological, thermal, and membrane-based processes. Consequently, product yield, productivity, and resource consumption vary considerably across the examined cases and are strongly influenced by feedstock composition, particularly nutrient concentration and solids content. In most cases, water use is limited through recirculation and internal reuse, while chemical consumption is mainly associated with precipitation reagents, conditioning chemicals, and separation aids. The analysed technologies also show limited waste generation, as most side streams are either reused within the process or further valorised, supporting the overall objective of nutrient recovery and circular resource management.

5.2 N and P recovery – Physical technologies

Table 17: N and P recovery of the physical technologies

	Tech 17: Crystallizer for struvite production from nutrient-rich liquid streams	Tech 20: Liquid digestate valorisation through biological treatment and ultrafiltration technologies	Tech 18: Fluidized bed reactor for struvite production from municipal and industrial wastewater	Tech 19: Integrated solid-liquid separation, evaporation and reverse osmosis (RO) treatment for digestate valorisation
Form of nutrient	MgNH4PO4*6H2O	-	MgNH4PO4*6H2O	Dried solid fraction of digestate and the evaporator concentrate with high K concentration
organic matter recovery from input	less than 3%	-	The technology targets inorganic nutriens (N,P,Mg), not organic matter	637 g/kg in the dried solid fraction of digestate, and 91 g/kg in the evaporator concentrate
quantity of nutrient	Very close to theoretical. 12.6% P, 5.7%N, 9.9% Mg	-	Struvite contains P_2O_5 (28.9%), N(5.7%), MgO (16%) (source same as below). Nutrients produced per day: Phosphorus (as P_2O_5):2000 kg *28,9%=578 kg/day. Nitrogen: 2000 kg* 5.7%=114 kg/day. Magnesium (as MgO): 2000 kg*16%=320 kg/day	In the dried solid fraction of digestate: dry matter:904 g/kg, organic matter:637 g/kg, Total N:29 g/kg, Total P:24 g/kg, Total K:15 g/kg, Total S: 10 g/kg in the evaporator concentrate: dry matter:187g/kg, organic matter:91 g/kg, Total N:13 g/kg, Total P:2.1 g/kg, total K: 22g/kg, total S:11 g/kg

The comparison of the selected nutrient recovery technologies shows that the recovered products differ significantly in terms of nutrient form and composition. Struvite-based systems produce a chemically well-defined mineral fertiliser, mainly targeting phosphorus recovery, with limited recovery of organic matter. In contrast, integrated digestate treatment systems recover nutrients in broader fertilising fractions, including solid and concentrated liquid products that retain both nutrients and part of the organic matter. Overall, the data indicate that the agronomic value of the recovered products depends not only on the quantity of nutrients recovered, but also on their chemical form and the extent to which organic matter is retained in the final product.

5.3 Operating capacity – Physical technologies

Table 18: Operating capacity of the physical technologies

	Tech 17: Crystallizer for struvite production from nutrient-rich liquid streams	Tech 20: Liquid digestate valorisation through biological treatment and ultrafiltration technologies	Tech 18: Fluidized bed reactor for struvite production from municipal and industrial wastewater	Tech 19: Integrated solid-liquid separation, evaporation and reverse osmosis (RO) treatment for digestate valorisation
permitted/ current capacity	There is no limit. Installation references between 1m^3/h to 833 m^3/h	permitted:36,000 t/a, current ~18,000 t/a (biogas plant input)	2 t/day of product	120 kt of feedstock per year
permitted organic/ inorganic input material (feedstock); the main mass flows	Nutrient load varies as per the kind of stream. There is no one number	pig manure: ~5000 t/a, chicken manure: ~3000 t/a, slaughter house waste/ meat processing by products: ~5000 t/a, expired food/food leftovers from hotels:> 3000 t/a, cheese whey: ~2500 t/a	liquor stream of sludge dewatering facilities	animal manure, industrial wastewater treatment sludge and biowaste

5.4 Equipment o requirements – Physical technologies

Table 19: Technical requirements of the equipment of the physical technologies

	Tech 17: Crystallizer for struvite production from nutrient-rich liquid streams	Tech 20: Liquid digestate valorisation through biological treatment and ultrafiltration technologies	Tech 18: Fluidized bed reactor for struvite production from municipal and industrial wastewater	Tech 19: Integrated solid-liquid separation, evaporation and reverse osmosis (RO) treatment for digestate valorisation
Which process steps are automated and which are not automated	Fully automated installation. The only part that might not be automated is exchanging of big bags for struvite harvest	-	The Nutrient Recovery facility consists of 2 groups of feed pumps, a crystallising reactor and its associated pumps, valves etc., a draining and drying product step, a product sorting and packaging step, a programmable logic controller (PLC) cabinet, an engine control centre, a MgCl2 storage tank and a NaOH storage tank.	Automated processes: feedstock pumping and pre-heating (to 40°C), anaerobic digestion (main digester and post-digestion), decanter centrifuge, Hydrogone dryer, aerobic treatment tank, evaporator (50°C-60°C), Reverse Osmosis unit/ Non-automated processes: Feedstock supply and mixing, composting (external process), transport/ export of products (to France and the Netherlands), Handling ammonia water
Number of operators	No additional operator is required. 3-4 hours/week is required for quick follow ups	-	For a small-medium plant (like 2 t/days) 1 operator is enough since the technology is highly automated	A typical plant of this size (120 kt/year) and complexity would likely be operated by roughly 4 staff in total, with perhaps 1-2 operators effectively covering the plant per shift plus day-support staff.
Land used (area occupied by facilities)	Varies depending on the project size. Could range between 121 m^2 to 576 m^2	~ 15,000 m^2 (biogas plant)	This system integrates into existing WWTP infrastructure, so the land used must be smaller than the WWTP area. The estimated occupied area is 50-200 m2	For a plant of this size (120 kt.year) it is estimated that the required area is 5,000-20,000 m^2
Time required between ordering and manufacturing of the main	6 months	-	For similar wastewater treatment equipment the time required between ordering and manufacturing of the main process equipment is 6 to 12 months	For similar equipment it is estimated that: digesters, evaporators, dryers require 6-12 months, and complex systems require up to 12-18 months

	Tech 17: Crystallizer for struvite production from nutrient-rich liquid streams	Tech 20: Liquid digestate valorisation through biological treatment and ultrafiltration technologies	Tech 18: Fluidized bed reactor for struvite production from municipal and industrial wastewater	Tech 19: Integrated solid-liquid separation, evaporation and reverse osmosis (RO) treatment for digestate valorisation
process equipment				
Frequency of main equipment/ machines maintenance	2 times/year	according to the daily, weekly, monthly etc maintenance schedule	Typical maintenance frequency is: routine inspection daily or weekly (check pumps, flow, sensors, monitor pH, dosing crystal formation), preventing maintenance monthly or quarterly (pump service, valve and piping inspection, cleaning of sensors and dosing systems) and major maintenance annually (reactor inspection, internal cleaning)	Daily-weekly (process checks - digesters, pumps, combined Heat and Power installation (CHP)), monthly-quarterly (pump service, centrifuge and dryer inspection, cleaning of pipes and heat exchangers), annually (digester inspection, evaporator and RO service)

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The assessment of the selected nutrient recovery technologies shows that required equipment and the associated operational needs vary considerably depending on the degree of process integration. Compact struvite recovery systems are characterised by a high level of automation, limited operator requirements, and relatively small space occupation, which makes them suitable as modular add-on technologies for nutrient-rich liquid streams. In contrast, more integrated digestate valorisation systems involve multiple treatment stages, including digestion, separation, drying, evaporation and membrane filtration, and therefore require more extensive equipment, larger installation areas, and more structured operational support. Overall, the assessment indicates that increasing process integration and product diversification are associated with higher technical requirements of the equipment and maintenance needs, even though a high degree of automation can still limit direct labour requirements.

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5.5 Operating conditions– Physical technologies

Table 20: Operating conditions of the physical technologies

	Tech 17: Crystallizer for struvite production from nutrient-rich liquid streams	Tech 20: Liquid digestate valorisation through biological treatment and ultrafiltration technologies	Tech 18: Fluidized bed reactor for struvite production from municipal and industrial wastewater	Tech 19: Integrated solid-liquid separation, evaporation and reverse osmosis (RO) treatment for digestate valorisation
Feedstock quality requirements for acceptance in the installation	For digestate applications: TSS of digestate needs to be less than 6%. For centrate applications: TSS of centrate needs to be less than 0.1%. As general rule, we only treat streams with PO4-P (soluble phosphate) concentrations of at least 60 ppm. There is no limit on higher concentrations. Ammonium nitrogen is also required (stichiometrically equivalent of PO_4-P)	TS content, VS content, Absence of toxicity C/N etc.	The feedstock must be a nutrient-rich liquid stream (e.g. sludge dewatering liquor) with sufficient phosphorus and ammonium concentrations	The plant accepts animal manure and solid fraction of manure, sludge from industrial wastewater treatment plants and other biowastes, glycerine and molasses, the feedstock is also mixed before the anaerobic digester to an optimal dry matter content, and the feedstock also contains sufficient nutrients (N, P, K) for recovery
other specifications for the process required	No	-	Chemical input: magnesium chloride 32% to supply Mg, sodium hydroxide 25% to control pH for crystallization. The controlled crystallization in the reactor requires stable hydraulic conditions. Inside the reactor struvite forms as crystals/granules. This requires proper mixing.	Temperature conditions (the feedstock must be pre-heated to 40°C before digestion), residence time (30 days in main digester, 10 days in post- digester)
plant run time	24 h/day with 330 workdays= 7920 h/a	8,700 h/a (biogas plant)	It is an automated struvite crystallization system, therefore it has typically continuous operation, about 24 h/day, 7 days/week. Therefore, the process operation corresponds to 8,760 h/y	the nominal time is 24*365=8,760 hours per year

	Tech 17: Crystallizer for struvite production from nutrient-rich liquid streams	Tech 20: Liquid digestate valorisation through biological treatment and ultrafiltration technologies	Tech 18: Fluidized bed reactor for struvite production from municipal and industrial wastewater	Tech 19: Integrated solid-liquid separation, evaporation and reverse osmosis (RO) treatment for digestate valorisation
temperature	35°C-10°C	-	The process treats anaerobically digested sludge streams/dewatering liquor. This implies that the process operates at ambient/wastewater temperature, therefore the typical temperature for the crystallization is 20°C-35°C	mesophilic conditions
pH-range	8-8.5	-	The typical pH range for struvite crystallization technologies is 7.5-9, while the most efficient precipitation occurs at 8-8.5	typical anaerobic digestion processes operate near neutral pH
aerobic conditions (yes/no)	Not relevant	No (digesters), Yes (post-digestate treatment)	it is not a biological process, it is a precipitation/crystallization process therefore it does not require oxygen	yes
anaerobic conditions (yes/no)	Not relevant. However, both digestate or centrate we treat are from anaerobic systems. However, the system does not have a similar dependence	Yes	It is not a biological process therefore it does not depend on oxygen conditions	yes (the feedstock is pre-heated to 40°C and mixed before pumped into the anaerobic digesters. The residence time in the digester is about 30 days and additional 10 days in the post-digester)
Hygienization process	Yes. Match with requirements under CMC12. They are under application process to get a CE mark	-	The system includes: crystallization reactor, washing, drying and packaging. No step related to hygienization is mentioned.	1 hour at 70°C

The comparison of the selected nutrient recovery technologies shows that their operating conditions are strongly influenced by the type and quality of the input stream, as well as by the underlying recovery mechanism. Struvite-based systems require nutrient-rich liquid streams with sufficient soluble phosphorus and ammonium concentrations, while maintaining appropriate solids content, pH conditions, and stable hydraulic operation to support controlled crystallisation. In contrast, integrated digestate valorisation systems can handle more complex feedstocks, but their performance depends on broader physicochemical characteristics such as solids content, biodegradability, and the absence of inhibitory compounds. The analysed technologies generally operate continuously or near-continuously, whereas temperature and oxygen requirements differ substantially depending on whether the system is based on physicochemical nutrient precipitation or biological treatment. Overall, the assessment indicates that feedstock acceptance criteria and operating conditions are highly technology-specific and closely linked to the targeted recovery pathway, the nature of the final product, and the required level of process control.

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6 Physicochemical technologies

Physicochemical technologies represent an important category of processes for the recovery and upgrading of nutrients from secondary raw materials, particularly from liquid streams such as wastewater, digestate, centrate, and manure-derived effluents. In contrast to purely biological treatment pathways, these technologies rely on controlled physicochemical mechanisms, including stripping, scrubbing, membrane separation, precipitation, and related conditioning steps, to recover specific nutrient fractions and convert them into fertilising products. Depending on the process configuration, physicochemical technologies may enable the targeted recovery of nitrogen, phosphorus, or combined nutrient streams, while also contributing to the concentration and purification of recovered products. Their technical performance is strongly influenced by the composition and quality of the input stream, as well as by operating parameters such as pH, temperature, and chemical dosing.

6.1 Operation performance– Physico-chemical technologies

Table 21: Operating performance of the physicochemical technologies

	Tech 21: Stripping and scrubbing system for ammonia recovery from wastewater streams	Tech 22: Membranes and stripping technologies: transforming livestock manure and digestate
yield	Very dependent on influent data, but a range of 23.5-35.3 kg fertilizer/t input can be expected	About 1.5%
Does the yield change based on feedstock composition	Yes, higher influent concentration, higher pH and higher carbonate buffer levels give higher yields	Yes, depending on N content in the input material: if lower N input, less fertilizer product yield in terms of total t per day
productivity	AMU I: 23,5 - 35,3 kg fertilizer/h, AMU II: 47-70 kg fertilizer/h, AMU V: 118 - 177 kg fertilizer/h, AMU X: 235 - 353 kg fertilizer/h	20 to 70 kg/hour depending on the installation size
energy consumption	AMU I: 5 kWhe/t + 5.8 kWhth/t, AMU II: 4 kWhe/t + 5.8 kWhth/t, AMU V: 2.6 kWhe/t + 5.8 kWhth/t, AMU X: 1.8 kWhe/t+5.8 kWhth/t	0.5 kWhe/t input of electricity, no other energy sources
water consumption	negligible (<0.0025)	0.08 t water/ t input for cleanings
chemicals consumption	antifoam (0.03-0.06 kg/t input), sulfuric acid 50% (13.2-19.8 kg/t input), other acids are possible	Sulphuric acid 50% (0.02% of input t, average per day), Caustic soda 30% (0.02% of input t, average per day), Chemicals for membrane cleaning recycled into the process
waste generation	-	0.015 kg/t input along a 3-year operation

The assessment of the selected ammonia recovery technologies shows that their performance is strongly influenced by the nitrogen concentration and physicochemical characteristics of the input stream. Both systems recover relatively limited product quantities compared with broader digestate valorisation technologies, as

they are designed to selectively recover nitrogen rather than total nutrients or organic matter. Their yield and productivity increase with higher influent nitrogen content, while energy and water requirements remain comparatively low. Chemical consumption is mainly associated with acid dosing for ammonia capture and, where applicable, alkali addition or membrane cleaning. Overall, the analysed technologies are characterised by targeted nitrogen recovery, moderate operational complexity, and limited waste generation, confirming their suitability as focused nutrient recovery solutions for nitrogen-rich wastewater or digestate streams.

6.2 N and P recovery– Physico-chemical technologies

Table 22: N and P recovery of the physicochemical technologies

	Tech 21: Stripping and scrubbing system for ammonia recovery from wastewater streams	Tech 22: Membranes and stripping technologies: transforming livestock manure and digestate
Form of nutrient	Basic: (NH4)2SO4 or NH4NO3. With further refinement: NH4OH or NH_4HCO_3	Ammonium sulfate solution: $(NH_4)_2SO_4$
organic matter recovery from input	0	None in the specific production of fertilizer
quantity of nutrient	Very dependent on influent data, but a range of 2.5-3.75 kgN/t input can be expected	5% to 6% in $N\text{-}NH_4$

6.3 Operating capacity– Physico-chemical technologies

Table 23: Operating capacity of the physicochemical technologies

	Tech 21: Stripping and scrubbing system for ammonia recovery from wastewater streams	Tech 22: Membranes and stripping technologies: transforming livestock manure and digestate
permitted/current capacity	AMU I: 8,000 t input/a, AMU II: 16,000 t input/a, AMU V: 40,000 t input/a, AMU X: 80,000 t input/a	30 to 120 t input/day, 10,950 to 43,800 t/a depending on the installation
permitted organic/inorganic input material (feedstock); the main mass flows	LF manure, LF digestate, LF leachate	Liquid pig manure, liquid cow manure, digestate of various inputs (from biogas, biomethane): one input per installation, depending on design, input quantity may vary

6.4 Equipment requirements– Physico-chemical technologies

Table 24: Technical requirement of the equipment for the physicochemical technologies

	Tech 21: Stripping and scrubbing system for ammonia recovery from wastewater streams	Tech 22: Membranes and stripping technologies: transforming livestock manure and digestate
Which process steps are automated and which are not automated	Automated: all, Non-automated: Filling acid storage tank (by truck)	All automated
Number of operators	1 (system is automated, so gives a warning in case of failure)	1
Land used (area occupied by facilities)	AMUI:21m^2, AMUII:32m^2, AMUV:45m^2, AMU X: 50 m^2 (excluding storage tanks)	150 m^2 to 300 m^2 depending on installation size
Time required between ordering and manufacturing of the main process equipment	2 months	8 months
Frequency of main equipment/machines maintenance	6 times per year (2 monthly check of the pumps and sensors)	3 times per year

The assessment of the selected ammonia recovery technologies indicates that these systems are generally characterised by a high degree of automation, low labour requirements, and relatively limited space occupation. In both cases, the core process is fully automated, while manual intervention is restricted to occasional support activities such as chemical supply and routine supervision. As a result, operator requirements remain minimal, typically around one person per installation. The required land area is also relatively small compared with more integrated nutrient recovery systems, although it varies with unit capacity and the need for ancillary storage. Overall, the table shows that ammonia stripping and membrane-based recovery systems can be implemented as compact and operationally efficient solutions, with moderate equipment lead times and maintenance requirements.

6.5 Operating conditions– Physico-chemical technologies

Table 25: Operating conditions of the physicochemical technologies

	Tech 21: Stripping and scrubbing system for ammonia recovery from wastewater streams	Tech 22: Membranes and stripping technologies: transforming livestock manure and digestate
Feedstock quality requirements for acceptance in the installation	Only liquid streams after liquid-solid separation by centrifuge, screw-press or similar techniques	Dry matter (total solids TS) max 9%, Total Nitrogen N max 5.0 kg/t
other specifications for the process required	-	no
plant run time	ca. 8,000 h/a	8,000 h/a

	Tech 21: Stripping and scrubbing system for ammonia recovery from wastewater streams	Tech 22: Membranes and stripping technologies: transforming livestock manure and digestate
temperature	55°C-60°C	5°C-35°C
pH-range	7-10	4-11
aerobic conditions (yes/no)	NA	yes
anaerobic conditions (yes/no)	NA	no
Hygienization process	No, but E. coli is eliminated after our process	no

7 Plasma technology

Plasma-based technology constitutes a specialised thermochemical treatment route based on the application of extremely high temperatures for the transformation and stabilisation of secondary raw materials. Such systems can enable extensive degradation of organic matter and the production of stable mineral-rich residues with potential for further valorisation. Their technical performance depends on feedstock characteristics and on key operational parameters such as temperature, residence time, and energy demand.

7.1 Operation performance – Plasma-based technology

Table 26: Operation performance of the plasma-based technology

	Tech 16: Plasma-based technology converting livestock slurry and biogas digestate into fertilizing products
productivity	During operation, the unit produced approximately 25 to 55 gallons of nitrogen enriched organic liquid per hour
energy consumption	1.25 kWh for every gallon NEO produced
water consumption	water is used in the absorber to produce nitric acid from nitrates and nitrites
chemicals consumption	-
waste generation	no waste generation

7.2 N and P recovery – Plasma-based technology

Table 27: N and P technology for the plasma-based technology

	Tech 16: Plasma-based technology converting livestock slurry and biogas digestate into fertilizing products
Form of nutrient	NEO - Nitrogen Enriched Organic Fertilizer
quantity of nutrient	The NEO had a total N content of 3407 mg l^{-1} consisting of 1480 mg l^{-1} $NH4^{+}$-N, 777 mg l^{-1} $NO2^{-}$-N, and 1150 mg l^{-1}NO3 $^{-}$-N and a pH of 5.3

7.3 Operating capacity – Plasma-based technology

Table 28: Operating capacity of the plasma-based technology

	Tech 16: Plasma-based technology converting livestock slurry and biogas digestate into fertilizing products
permitted/current capacity	expected processing capacity: 3560 gallons per day of liquid manure /the farm scale biogas plant treats around 730 t of cattle manure annually

7.4 Equipment requirements– Plasma-based technology

Table 29: Technical requirements of the required equipment of the plasma-based technology

	Tech 16: Plasma-based technology converting livestock slurry and biogas digestate into fertilizing products
Which process steps are automated and which are not automated	The stages that should be automatized are the plasma production, nitrogen capture from the air, plasma reaction with the slurry, energy supply control. The non-automated parts are the transportation of the manure/slurry to the system, the product storage and the application of the fertilizer to the field.
Land used (area occupied by facilities)	The N2 treating unit comes in a 20-foot container. This set up includes an air compressor, a plasma system, an absorption tank to mix slurry and gas, and a controlled unit.
Frequency of main equipment/machines maintenance	The unit requires regular maintenance to ensure optimal performance. One critical component is the plasma torch, which uses significant power to create a plasma of compressed ambient air injected into the manure. The torch's copper core degrades with use and needs refurbishment every 12 to 14 days. This process involves stopping the unit, refurbishing or replacing the copper core and restarting the unit, which incures downtime and maintenance costs.

7.5 Operating conditions – Plasma-based technology

Table 30: Operating conditions of the plasma-based technology

	Tech 16: Plasma-based technology converting livestock slurry and biogas digestate into fertilizing products
temperature	Temperatures were slightly higher than ambient temperature in tanks containing the NEO
pH-range	The pH of the manure was dramatically reduced by the treatment process from 6.70 to 5.26. During the first portion of the trial when the pH setpoint was 5.5, the resulting NEO pH was 5.45, while during the second portion of the trial when the pH setpoint was 4.5 to 5.0, the resulting NEO pH was 5.03
aerobic conditions (yes/no)	yes, it uses air
anaerobic conditions (yes/no)	no

8 Thermochemical technologies

Thermochemical technologies constitute an important group of processes for the treatment and valorisation of secondary raw materials through thermal conversion. Unlike biological pathways, these technologies are based on the application of heat under controlled conditions in order to transform the input material and recover nutrient-rich products or solid fractions with fertilising potential. Their performance depends strongly on feedstock properties and on operating conditions such as temperature and residence time. For the purposes of this deliverable, the selected thermochemical technologies are assessed on the basis of their main technical, operational, and product-related characteristics. It should also be noted that some of the parameters examined in previous technology categories are not included here to the same extent, as they are not always directly relevant to thermochemical conversion processes.

8.1 Operation performance – Thermochemical technologies

Table 31: Operation performance of the thermochemical technologies

	Tech 24: Biowaste to biochar and energy: integrated pyrolysis and biological methanation	Tech 23: Pyrolysis of biomass residues for biochar production	Tech 25: Pyrolysis of wood chips for the production of biochar
yield	0.6 t fertilizer product/t input	25%-35%	0.24-0.28 m^3 biochar/m^3 woodchips[10]
energy consumption	not available	25-35 MJ/kg	120-150 kWh

8.2 N and P recovery – Thermochemical technologies

Table 32: N and P recovery of the thermochemical technologies

	Tech 24: Biowaste to biochar and energy: integrated pyrolysis and biological methanation	Tech 23: Pyrolysis of biomass residues for biochar production	Tech 25: Pyrolysis of wood chips for the production of biochar
Form of nutrient	not available	biochar	biochar
quantity of nutrient	not available	biochar:100%, moisture<15%, carbon>60%, ash<15%, pH=8, electrical conductivity: 850 µS/cm	

[10] 600-700 m^3 biochar is produced from 2,500 m^3 wood chips. Therefore, the yield is 600-700/2,500=0.24-0.28 m^3 biochar/m^3 wood chips

8.3 Operating capacity – Thermochemical technologies

Table 33: Operating capacity of the thermochemical technologies

	Tech 24: Biowaste to biochar and energy: integrated pyrolysis and biological methanation	Tech 23: Pyrolysis of biomass residues for biochar production	Tech 25: Pyrolysis of wood chips for the production of biochar
permitted/current capacity	current pyrolysis capacity: 500 kW input material (approx. 130 kg/h)	input production capacity: 4000 kg/day	2,500 t/a wood chips
permitted organic/inorganic input material (feedstock); the main mass flows	wood chips (910 t/a)	n/a	n/a

8.4 Equipment requirements– Thermochemical technologies

Table 34: Technical requirements of the equipment of the thermochemical technologies

	Tech 24: Biowaste to biochar and energy: integrated pyrolysis and biological methanation	Tech 23: Pyrolysis of biomass residues for biochar production	Tech 25: Pyrolysis of wood chips for the production of biochar
Which process steps are automated and which are not automated	n/a	n/a	Highly automated process
Land used (area occupied by facilities)	1,500 m^2	n/a	54 m^2

8.5 Operating conditions – Thermochemical technologies

Table 35: Operating conditions of thermochemical technologies

	Tech 24: Biowaste to biochar and energy: integrated pyrolysis and biological methanation)	Tech 23: Pyrolysis of biomass residues for biochar production)	Tech 25: Pyrolysis of wood chips for the production of biochar
Feedstock quality requirements for acceptance in the installation	Max size 20 mm, max humidity 25%		Branch chips finely chopped and screened<20 mm
plant run time	up to 7,500 h/a		
temperature	-	500-600°C	500-700°C
anaerobic conditions (yes/no)	Yes		

9 Conclusion

Deliverable 3.1 presents a thorough technical assessment of the most representative nutrient recovery (NR) and bio-based fertiliser (BBF) production technologies, based on a structured set of Technical Assessment Indicators (TAIs). These indicators include key parameters such as operational performance, nutrient recovery (N and P), treatment capacity, yield and productivity, sensitivity to feedstock variability, equipment complexity, and operating conditions. The analysis covers a broad range of technology categories, including anaerobic digestion, composting, hydrolysis, physical, physicochemical, thermochemical and plasma-based processes, thereby ensuring a holistic representation of the current technological landscape.

The results highlight that there is no single “optimal” technology; instead, the performance of each system is strongly dependent on the type and quality of the input material, as well as on the targeted recovery pathway. Biological processes such as anaerobic digestion and composting demonstrate robustness and flexibility in handling heterogeneous feedstocks, while producing stabilised organic fertilising products. In contrast, physical and physicochemical technologies are more targeted, enabling the selective recovery of specific nutrients (e.g. phosphorus as struvite or nitrogen via stripping/scrubbing), often with higher product purity but stricter feedstock requirements. Hydrolysis and thermochemical processes offer additional pathways for material transformation, often achieving high conversion efficiencies but with increased energy or chemical inputs and, in some cases, higher process complexity.

Across all categories, a key finding is that feedstock composition plays a critical role in determining both process performance and product characteristics. Parameters such as nutrient concentration, solids content, and the presence of contaminants directly affect yield, productivity, and recovery efficiency. In addition, the level of process integration significantly influences system performance: more integrated systems (e.g. combined digestion–separation–concentration processes) can produce multiple value-added products, but typically require more complex equipment, higher capital investment, and more demanding operation and maintenance.

Another important observation concerns resource use and circularity. Most of the analysed technologies aim to minimise waste generation and water consumption through internal recirculation and reuse of process streams. At the same time, chemical consumption is often necessary in physicochemical processes to enable nutrient recovery (e.g. pH adjustment, precipitation reagents), highlighting a trade-off between recovery efficiency and input requirements. Furthermore, the form in which nutrients are recovered (organic vs mineral, liquid vs solid) is a determining factor for the agronomic value, practical use, and potential market uptake of the final products.

In terms of agronomic value, besides yield, the nutrient concentration also plays an important role determining how much product must be applied to meet a given crop nutrient demand. For example, technology 19 produces a dried solid fraction and a liquid evaporator concentrate from the same digestate, at an equal mass-based productivity (30 t/day for each stream), yet the two products differ sharply in composition — the solid fraction contains 24 g total P/kg and 637 g organic matter/kg, against only 2.1 g total P/kg and 91 g organic matter/kg in the liquid concentrate. At equal mass output, the solid fraction therefore delivers roughly eleven times more phosphorus and seven times more organic matter per tonne than the liquid fraction. In terms of practical use, dilute liquid products require larger volumes to deliver an equivalent nutrient dose, which increases storage, transport, and spreading requirements. On the contrary, concentrated solid or mineral products (e.g. compost, dried digestate, struvite) can be stored, bagged, and transported more efficiently relative to their nutrient content, and are more easily blended into standard fertiliser formulations. In terms of market uptake, mineral, slow-release forms such as struvite offer consistent, well-defined nutrient content and align more readily with existing fertiliser regulations (e.g. FPR), facilitating market entry, whereas organic-

bound or liquid fractions (e.g. digestate) face greater regulatory constraints, which can limit their scalability beyond local application.

Beyond technical performance, product safety is also important for market roll-out, particularly the hygienization and the management of contaminants and micropollutants. The assessed technologies handle hygienization in quite different ways. Several anaerobic digestion, composting, and hydrolysis systems apply clearly defined thermal treatment protocols, typically sustaining temperatures in the range of 53-75°C. Where durations are reported, they range from one hour to around two weeks. In some cases, these protocols are explicitly aligned with national requirements such as the German Biowaste Ordinance (BioAbfV), as reported for Technology 1 (Integrated AD and tunnel composting) and Technology 9 (Composting using semi-permeable membrane and forced aeration). Technology 13 (hydrolysis of biosolids and organic waste) achieves hygienization through combined elevated temperature and alkaline conditions (addition of KOH/NaOH), resulting in a Class A biosolids-grade product. Other technologies achieve hygienization through different process conditions. For example, technology 21 (physicochemical ammonia stripping/scrubbing) achieves pathogen control through the elimination of E.Coli as part of its process condition. For a number of technologies, particularly within the thermochemical category (Tech 23, Tech 24, Tech 25), no hygienization process is reported, consistent with the high-temperature nature of these processes.

Feedstock impurities are another issue that several technologies need to deal with. Physical contaminants such as plastics, glass, metals, and grit are usually removed through pre-treatment, thereby protecting both the equipment and the biological processes from foreign materials. Some of the technologies set specific limits for this. Technology 2 (integrated dry AD of biowaste) for example requires pre-treatment involving removal of plastics and inerts, with material broken down to 60 mm, while Technology 8 (open windrow composting) applies a control value of max. 3% mass of impurities and max. 0.5% plastics in fresh matter above 20 mm, in line with the German Biowaste Ordinance. In practice, the removal of such physical contaminants is important for market roll-out, as it determines whether the final product can meet basic quality and safety expectations.

Chemical micropollutants are another aspect of product safety. Heavy metals, pharmaceutical residues, and persistent organic substances can end up in the final product, while their presence depends largely on where the feedstock comes from. Limits for heavy metals and certain organic contaminants are set under the EU Fertilising Products Regulation. However, the data collected for this assessment did not cover micropollutants, and this is a candidate area for more detailed investigation in later stages of the project.

The yield values reported throughout this deliverable, expressed as fertilizing product per unit of input, may vary considerably depending on the extent to which water evaporation and other mass losses occur, which itself depends on the technology and the feedstock involved. In technologies where anaerobic digestion is followed by composting of the digestate as a post-treatment step (e.g., Tech 1, Tech 2, Tech 3), a substantial share of the incoming mass is lost through biogas formation, water evaporation, and stabilization losses, which can markedly reduce the reported yield compared to processes that preserve most of the input mass, such as wet digestate systems. As a result, yield figures are not always directly comparable across technologies. This distinction is also closely linked to the difference between liquid and solid fertilizing products. The data indicate that phosphorus and organic matter tend to concentrate preferentially in solid fractions, while liquid products, despite comparable or sometimes higher soluble potassium and nitrogen content, generally show substantially lower phosphorus and organic matter concentrations. Consequently, a liquid product with a relatively high mass-based yield may still deliver considerably less nutrient value per tonne applied than a solid product with a lower yield, underlining the importance of considering nutrient concentration, and not yield alone, when comparing the agronomic value of different fertilizing products.

It should also be noted that, for certain technology categories—particularly thermochemical and plasma-based systems—the availability of detailed technical data was more limited compared to more established technologies. As a result, some parameters included in other categories were not always available or considered relevant, reflecting both the emerging nature of these technologies and differences in data

reporting practices.

This deliverable constitutes the outcome of Task 3.1 (Analysis of key technical aspects of selected technologies), where the TAIs were defined and quantified in order to benchmark the selected technologies from a technical perspective. The dataset generated in this task provides a consistent and structured basis for further analysis. In particular, the results presented here will be directly used in Task 3.3 (Comparison of technical aspects, environmental impacts and resource efficiency), where the technical indicators (TAIs) will be combined with environmental assessment indicators (EAIs) developed in Task 3.2. This subsequent step will enable a comparative evaluation of NR and BBF technologies against conventional fertiliser production systems, using a harmonised scoring approach (e.g. 5-point scale and stakeholder-informed assessment), ultimately supporting the multi-criteria decision analysis (MCDA) framework of the project.

Overall, Deliverable 3.1 establishes a solid technical baseline for the comparative assessment of nutrient recovery technologies and provides critical input for the next phases of the project, contributing to the identification of best available techniques for fertiliser production from secondary raw materials.

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