D2.2. Multi-assessment of impacts, trade-offs and framework conditions

Assessment of technical aspects and conditions for industrialisation

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement N° 101060426.

List of Acronyms

CAPEX	Capital expenses
EU	European Union
FM	Feather meal
FMF	Feather meal fertiliser
FU	Functional unit
GHG	Greenhouse gas
IC	Impact category
IWW	Industrial waste water
IWW	Struvite from industrial waste water
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
NPV	Net present value
NRF	Non-renewable fertiliser
NVZ	Nitrate Vulnerable Zones
OFR	Organic Farming Regulation
OPEX	Operating expenses
p.e.	Population equivalent
SFD	Solid Fraction of Digestate
SMS	Spent Mushroom Substrate
SS	Stabilised sludge
US	United States
UWW	Urban waste water

Disclaimer

Table of Contents

Executive summary

Task 2.5 analysed key technical aspects for replacing conventional fertilizers. This included ensuring product compatibility with existing equipment, exploring combinations with conventional and organic fertilizers, and proposing blends for balanced fertilizers that met market demands. The task also benchmarked alternative fertilizer production technologies, discussed farming techniques and assessed the costs and environmental impacts of industrialization of LCA value chains.

Based on the analysis of the alternative fertilizers, it is concluded that they show promising potential for replacing conventional fertilizers. Each product offers unique benefits in terms of nutrient content and soil improvement properties. However, challenges remain regarding compatibility with existing machinery, and consistency in nutrient composition. Struvite and the solid fraction of digestate are particularly promising due to their nutrient profiles and ease of handling. Combining these products, such as through co-composting or blending with conventional fertilizers, could optimize their performance and facilitate the transition from conventional to alternative fertilizers. To fully realize their potential, further research on application rates, long-term soil impacts, and refinement of production processes is needed. Overall, these circular fertilizers represent a significant step towards more sustainable agricultural practices, aligning with the project's goal of transitioning from conventional to alternative fertilizer sources.

The technological benchmarking study highlights the complexity and variability in the costs and revenues associated with different technological routes for all alternative fertilizers. While some technologies, like anaerobic digestion in several value chains, offer cost advantages due to byproducts like biogas, others vary significantly based on operational conditions and by-product(s) processing. The findings underscore the importance of considering both economic and environmental factors when evaluating different technology variants for alternative fertilizers production, as well as the need for tailored approaches to optimize their use and market integration. This is however challenging due to the inconsistencies found in published literature. Additionally, for many alternative fertilizers, the primary commercial motivation behind the technological process is not the fertilizer itself. Instead, the fertilizer often serves as a valuable byproduct that may require additional refinement before it is market-ready.

For most alternative fertilizers, the highest damage costs were primarily due to particulate matter, followed by climate change. Other significant categories included marine eutrophication, fossil resource use, and non-cancer human toxicity. It is important to recognize that the monetization factors for characterized impact categories can differ significantly in terms of damage costs.. While particulate matter and non-cancer human toxicity had high monetization factors despite low

actual impacts, climate change had a low monetization factor but higher impact characterization results.

1 Objectives and Methodology

Task 2.5, which focused on the assessment of technical aspects and conditions for the industrialization of alternative fertilizers, was further divided into three sections. Each section has its own specific methodology, detailed below. Followed by results where the findings and outcomes of these assessments are discussed.

1.1 Assessment of technical aspects and conditions for industrialisation

1.1.1 Objectives

The task involved several critical targets aimed at enhancing the use of circular fertilizers. Firstly, it focused on identifying key technical aspects necessary for effectively replacing non-renewable fertilizers. This included assessing the applicability of circular fertilizers with existing machinery to ensure seamless integration. Additionally, the task investigated potential combinations of circular fertilizers with other circular substrates or non-renewable fertilizers to achieve a balanced and effective product. Market demand alignment was also a priority, with efforts to assess how well circular fertilizers met current market needs. Finally, the task included technical benchmarking to compare circular fertilizers with both organic and non-renewable alternatives, ensuring they met or exceeded industry standards.

1.1.2 Methodology

The methodology followed to address the specific aspects of machinery compatibility, substrate combination, and market alignment for circular fertilisers, while incorporating key elements from the search results to ensure a comprehensive technical assessment.

1. Physical characterisation:
   - Analysis of particle size distribution, bulk density, and flowability.
   - Assessment of moisture content and hygroscopic properties.
2. Compatibility testing:
   - Evaluation of spreading patterns using standard fertilizer spreaders.

- Testing of dissolution rates for liquid application systems.
- Assessment of potential for clogging or corrosion in equipment.
- Conducting small-scale field tests with existing machinery.
- Monitoring application uniformity and accuracy.

3. Combination with other circular substrates

   a. Nutrient profiling:

   - Analysis of nutrient content of circular fertilisers and substrates.
   - Identifying of complementary nutrient profiles for potential blending.

   b. Blending:

   - Conducting small-scale mixing trials of different circular fertilisers and substrates.
   - Evaluation of physical and chemical stability of blended products.
   - Optimisation ratios for balanced nutrient composition.

4. Market Demand and benchmarking:

- Gathering input on desired fertiliser characteristics and application methods (Farmer survey).
- Assessment of willingness to adopt circular fertilisers.

1.2 Benchmarking of fertiliser production technologies

To complement the assessment of technical conditions for industrialisation, the circular fertiliser production technologies under study were benchmarked following the methodology described below.

1.2.1 Scope and objective

The objective of benchmarking study for alternative fertiliser production technologies is to compare and contrast the life cycle assessment (LCA) modelled technologies with other available techniques. This will inform the stakeholders regarding several employed options and enable them with the help of economic and technical indicators allowing decision making towards successful industrialisation of the circular fertilisers.

1.2.2 Methodology

The methodology comprised the following points:

1. Collection of data: Priority was given to primary data collection from technology providers and Fer-Play consortium members. When data was not available through these sources, literature was explored for research within Europe and internationally.

2. Data processing: Collected data was analysed and made coherent with the seven LCA studies where possible to allow comparison. However, due to lack of comprehensive commercial data availability and inconsistencies in LCA system boundaries within literature, it was challenging.

3. Compilation of results: Results were combined via two approaches:

    a. Study of scales: where data for several case studies but for one particular technique was available, analysis was presented based on the reflection on economic feasibility due to varying system capacity.

    b. Technology comparison: where data was available for several technologies to produce an alternative fertiliser, the data was extracted and cited in terms of operational and capital finances or plain technological figures e.g. energy consumption. In most cases, data is not completely compatible for direct comparisons with the LCA.

1.3 Assessment of environmental impacts prevention and control costs

1.3.1 Objective

For the preliminary assessment of installation costs of environmental impacts prevention and control strategies for the alternative fertiliser production and application technologies, monetarisation factors were researched for the LCA impacts. The scope for the summed costs is equal to the boundary set in the LCA for the seven value chains. Additionally, it is important to understand that this study is just an estimation and not to be used as factual information.

1.3.2 Concept

Monetarisation factors can also be expressed as environmental/external costs. These costs can be used for specific LCA evaluation methodologies with their impact categories. The Product Environmental Footprint 3.1 (PEF) characterisation impact categories are employed in the Fer-Play project. Environmental Prices Handbook EU28 Version published by CE Delft uses characterisation adopted in ReCiPe methodology to publish these monetarisation factors. One report on external costs evaluated the compatibility in adapting these monetarisation factors from ReCiPe methodology to Environmental Footprint (External Costs: Energy Costs, Taxes and the Impact of Government Interventions on Investments: Final Report., 2020). Amadei et al, (2021) also summarised the monetarisation factors used by LCA practitioners and summarised averages for the EF methodologies. These three references are used for the selection of these factors and also a comparison is drawn in the difference between these resources.

There is also a distinction between valuation methods for estimation of external costs (External Costs: Energy Costs, Taxes and the Impact of Government Interventions on Investments: Final Report., 2020):

- Damage cost: Cost for all damage caused by externalities (impacts). The costs are typically monetised using the willingness to pay (WTP) or willingness to accept (WTA) principles which is the extent to which individuals are eager to pay to avoid damage or to which individuals are willing to accept the damage.
- Avoidance cost: Costs of externalities (impacts) based on the total costs required to reach a certain (policy) target. This approach assumes that a certain policy target reflects collective preferences with respect to the externality and, as such, it is a proxy for the collective WTP to avoid damage caused by an externality.
- The replacement cost: Costs of externalities (impacts) based on the total costs required to repair or replace the adverse impacts as a result of the externalities.

The evaluation in this study was done mainly based on the 'damage costs' as this has the most available conversion factors in the literature. Some contrasts are also drawn based on avoidance and replacement costs when available but these are limited.

The monetisation factors compiled in External Costs: Energy Costs, Taxes and the Impact of Government Interventions on Investments: Final Report (2020) are adopted for this study but they are adjusted to year 2022 as shown by **Table 1**. Additionally, factors employed by LCA practitioners in research as summarised by Amadei et al. (2021) (**Table 2**) are compared with the used factors.

Table 1: Monetisation factors EUR2022 used for FER-PLAY LCA impacts.

Impact category and unit	Monetisation factor EUR2018[a]	Monetisation factor EUR2022[b]	Valuation Method
Acidification [Mole of H+ eq.]	3.44E-01	3.87E-01	Damage and avoidance
Climate Change [kg CO2 eq.]	1.03E-01	1.15E-01	Avoidance
Ecotoxicity, freshwater [CTUe]	3.82E-05	4.30E-05	Damage
Eutrophication, freshwater [kg P eq.]	1.92E+00	2.16E+00	Damage
Eutrophication, marine [kg N eq.]	3.21E+00	3.61E+00	Damage
Eutrophication, terrestrial [Mole of N eq.]	N/A	N/A	Not quantified[c]
Human toxicity, cancer [CTUh]	9.03E+05	1.02E+06	Damage
Human toxicity, non-cancer [CTUh]	1.63E+05	1.84E+05	Damage
Ionising radiation, human health [kBq U235 eq.]	1.20E-03	1.35E-03	Damage
Land Use [Pt]	1.75E-03	1.97E-03	Not identified
Ozone depletion [kg CFC-11 eq.]	3.14E+01	3.53E+01	Damage
Particulate matter [Disease incidences]	7.84E+05	8.83E+05	Damage
Photochemical ozone formation, human health [kg NMVOC eq.]	1.19E+00	1.34E+00	Damage
Resource use, fossils [MJ]	1.30E-03	1.46E-03	Resource depletion
Resource use, mineral and metals [kg Sb eq.]	1.64E+00	1.85E+00	Resource depletion
Water use [m^3 world equiv.]	4.99E-03	5.62E-03	Resource depletion

a: Central values adopted from External Costs: Energy Costs, Taxes and the Impact of Government Interventions on Investments: Final Report., 2020 page 45-46.
b: Adjusted to from year 2018 to year 2022 with a fixed inflation rate of 3%. These values are employed for this study.
c: Eutrophication, terrestrial has not been identified by the source due to lack of quantification methodology.

Table 2: Monetisation factors EUR2022 in literature review by Amadei et al. (2021).

Impact category and unit	Monetisation factor EUR2019[a]	Monetisation factor EUR2022[b]	Valuation Method	Remarks on selection[c]

Acidification [Mole of H+ eq.]	3.50E-01	3.82E-01	Not identified	Only EF compatible coefficient
Climate Change [kg CO2 eq.]	2.72E-01	2.97E-01	Damage	Paper average
Climate Change [kg CO2 eq.]	6.38E-02	6.97E-02	Avoidance	Paper average
Ecotoxicity, freshwater [CTUe]	3.91E-05	4.27E-05	Not identified	All EF compatible coefficients averaged
Eutrophication, freshwater [kg P eq.]	1.96E+00	2.14E+00	Not identified	Selected EF compatible coefficients averaged
Eutrophication, marine [kg N eq.]	6.64E+00	7.26E+00	Not identified	All EF compatible coefficients averaged
Eutrophication, terrestrial [Mole of N eq.]				No value
Human toxicity, cancer [CTUh]	8.12E+05	8.87E+05	Not identified	All EF compatible coefficients averaged
Human toxicity, non-cancer [CTUh]	1.60E+05	1.74E+05	Not identified	All EF compatible coefficients averaged
Ionising radiation, human health [kBq U235 eq.]	2.13E-01	2.33E-01	Damage	Paper average
Land Use [Pt]	1.78E-04	1.95E-04	Not identified	Only EF compatible coefficient
Ozone depletion [kg CFC-11 eq.]	5.55E+01	6.06E+01	Damage	Paper average
Particulate matter [Disease incidences]	7.98E+05	8.72E+05	Not identified	Only EF compatible coefficient
Photochemical ozone formation, human health [kg NMVOC eq.]	3.51E+00	3.84E+00	Damage	Paper average
Resource use, fossils [MJ]	1.10E-02	1.20E-02	Market price	Paper average
Resource use, mineral and metals [kg Sb eq.]	1.66E+00	1.81E+00	Not identified	Selected EF compatible coefficients averaged
Water use [m³ world equiv.]	5.08E-03	5.55E-03	Not identified	Only EF compatible coefficient

a: Central values selectively adopted from Amadei et al. (2021).
b: Adjusted to from year 2019 to year 2022 with a fixed inflation rate of 3%. These values are used for comparison.
c: Explanation provided on the selection of monetisation factors. Only explicitly stated EF compatible factors were used. Where more than one EF factor for same impact category was provided, average value was used. Where the multiple EF factors for the same category had high variance, closest values were averaged for precision.

1.3.3 Comparison between monetarisation factors

Six out of the 16 PEF impact categories only vary by less than 2 % between the two resources. For all six categories: Acidification, Ecotoxicity freshwater, Eutrophication freshwater, Particulate matter, Resource use, mineral and metals and Water use, selected factors from Amadei et al.

(2021) are maximum 2 % less of what has been selected in **Table 1**. In Amadei et al. (2021), Human toxicity non-cancer, Human toxicity cancer, Climate change and Land use are 5 %, 13 %, 40 % and 90 % lower than considered values, respectively. Whereas, Ozone depletion, Eutrophication marine, Photochemical ozone formation human health and Ionising radiation, human health are higher in literature compared to this study by 42 %, 50 %, 65 % and 99 %, respectively. Resource use fossils cannot be compared as Amadei et al. (2021) report on market price and not on damage costs. Both studies do not report on Eutrophication, terrestrial but however it is reported as 1.71 € per mol of N equivalent in eco-costs 2023, which equals to 1.66 € for year 2022 (*Eco-costs Estimate EPDs - Sustainability Impact Metrics*, 2024). However, it is not considered in this study due to lack of references/understanding about its correct use. It is important to note that the summation cost will be per functional unit for each value chain i.e. per tonne of circular fertiliser.

2 Results: Technical aspects and industrialisation

2.1 Urban and industrial wastewater struvite

2.1.1 Introduction

The phosphate mineral struvite (magnesium ammonium phosphate; $NH_4MgPO_46H_2O$) is produced by the precipitation of P from urban waste water (UWW) or industrial waste water (IWW). Comparison between struvite from IWW and UWW is stated in **Table 3**. Struvite is a viable alternative to non-renewable rock phosphate that has the potential to address several existing agronomic and environmental problems. Struvite is a superior or comparable alternative to other chemical fertilisers in various parameters (such as nutrient content and environmental sustainability) (Erdal et al., 2023). Additionally, struvite is considered a better source of phosphorus compared to traditional phosphate fertilisers due to its slow phosphorus release characteristic (Gonzalez et al., 2007). Research indicates that struvite is an emerging, cost-effective, and potential alternative to commercially available phosphate fertilisers, highlighting its benefits in resource recovery (Nageshwari et al., 2022). Furthermore, struvite has shown effectiveness as a phosphate source in agriculture, with significant improvements observed in crop growth compared to other fertilisers like single superphosphate (SSP) (Nongqwenga et al., 2017). Overall, struvite is recognised as an interesting and sustainable alternative to non-renewable phosphate fertilisers, offering benefits while posing minimal environmental impact (Nongqwenga et al., 2017). **Table 4** summarises the technical parameters for IWW and UWW struvite.

Table 3: Comparison between IWW Struvite and UWW Struvite.

Characteristic	Waste water Struvite	Industrial Water Struvite
Composition	Magnesium ammonium phosphate (MAP) with a chemical formula of $NH_4MgPO_46H_2O$	Like waste water struvite, but can also include other nutrients like potassium (K) and other minerals
Formation	Struvite forms in waste water treatment processes, particularly in anaerobic digestion, when there is a	Struvite can be produced in industrial water treatment processes by controlling pH and adding magnesium and other nutrients

Characteristic	Waste water Struvite	Industrial Water Struvite
	mole-to-mole ratio of magnesium, ammonia, and phosphate	
Appearance	Can appear in various colours, from white to yellow to brown, depending on the MAP content	Can have different shapes and sizes depending on the process conditions
Primary Use	As a nutrient in agriculture, particularly as a slow-release phosphorus (P) fertiliser	As a raw material for macronutrients in industrial waste water treatment processes, reducing the need for primary raw materials
Other Uses	Can be used in various industries, such as in the production of fertilisers, animal feed, and even as a building material	Can be used in various applications, including as a fertiliser, animal feed, and in the production of other industrial products

Table 4: Technical parameters of IWW Struvite and UWW Struvite.

Technical parameter	Struvite (UWW)	Struvite (IWW)
N-P-K Balance	5,7:12.6:0	5,7:12.6:0
Market price	80-120 €/tonne	100 €/tonne
Raw material availability	70-120 m³/year	100-120 m³/h
Storage ease	Dry environment necessary	The storage needs to be in a dry environment - rainfall free
Applicability in organic farming	Permitted in EU but CE label required.	Permitted in EU but CE label required.
Considered as fertiliser in the European regulatory framework?	Yes, as CMC12	CMC12 compliant
Compatibility with existing machinery	Compatible with existing machinery	Compatible with existing machinery
Nutrients leaching	No	No
Nutrient Availability and Release	Slow release	Slow release

2.1.2 Morphology and recommendations

For different applications, different struvite granulometry is preferred. Smaller granule size i.e. less than desired 1 mm may hinder its direct consumption as a fertiliser, however smaller granules are still adequate for blending or granulation.

Typically, a fertiliser's ideal particle size range falls between 2 and 4.40 mm in diameter. This range makes sure that roughly 80% of the particles fit within these parameters, which is thought to be ideal for the fertiliser's spreading qualities and effectiveness. When it comes to nutrient delivery rate, segregation tendencies, and overall product quality, particle size is a major determinant of fertiliser efficiency.

The following are possible routes for employing struvite as a P-source in the production of fertilisers:

Blending: To make NPK fertilisers, spherical granules larger than 1 mm can be blended directly. In commercial N-P-K (nitrogen, phosphorus, and potassium) fertilisers, struvite can take the place of phosphate rock.

Micro pelletising: Micro pelletising is probably the best option for reprocessing granules smaller than 1 mm or granules that are not spherical. When organic acids have a substantial impact on the rate at which P dissolves from struvite, hence influencing P uptake and efficiency, compost and Spent Mushroom Substrate (SMS) may be a suitable substitute for chemical fertilisers when mixed with struvite.

A synergistic effect can be produced by combining polysulfides, a slow-release sulphur source, with struvite, a slow-release phosphorus source. The sulphur oxidation facilitates struvite dissolution and enhances plant nutrient uptake (Valle et al., 2022). Sulphur can be added to fertilisers containing phosphorus to increase the nutrient's solubility, availability, and uptake by plants. Sulphur is also a necessary nutrient on its own. When formulating fertiliser, the ideal ratio, and interactions between sources of sulphur and phosphorus are crucial factors to consider.

Phosphorus can become more soluble and bioavailable to plants when sulphur is present. The results of fertilisers with a phosphate to sulphur ratio of roughly 10:1 was superior to those with a 38:1 ratio.

2.1.3 Possible combinations

It is advised to blend struvite with other granules containing potassium and nitrogen when using it as a raw material for N-P-K fertilisers, as opposed to subjecting it to chemical processing, which could change its mineralogical makeup.

Struvite also could be a good candidate to be mixed with circular fertilisers like compost, Spent Mushroom Substrate (SMS) or solid fraction of digestate. These proposed combination grantees a good balanced nutrient content and improve soil structures while enhances the application efficiencies of the circular fertilisers into soil by increasing its content of P which struvite is rich in it and the high carbon content helps in making the soil acidic which facilitate the release of P from struvite.

Table 5: Struvite proposed combinations of non-renewable and alternative fertilisers.

Proposed non-renewable combinations	Proposed Organic Combinations
Sulphur	Compost
Ammonium Sulphate	Spent mushroom Spent (SMS)
Potassium calcium magnesium sulphate (Haspargit)	Solid fraction of digestate (SFD)
Instead of rock phosphate in NPK fertilisers	Instead of perlite or vermiculite

Table 6 proposes different combinations of struvite with non-renewable fertilisers. These combinations are recommended to boost the intrinsic properties of struvite, improve nutrient content and to add organic C to the soil.

Table 6: Combinations ratios of possible combinations with struvite.

Proposed combination	Matrix	Ratio	Observations
Combination 1	Str+Hu+Has	09:04:01	Hu 5%
Combination 2	Str+Has+NH4SO3	10:3:0.5	NH4SO3 7%
Combination 3	Str+Hu+S+Mo	5:0,25:0,50: 0,25	hu 5%-Mo5%
Combination 4	Str+NH4SO3+Kstru	5:0,5:0,5	NH4SO3 7%
Combination 5	Ben+Str+Has+Mo+Hu+S	5:5:1:0,5:0,5:0,5	Mo 10%-Hu5%
Combination 6	Str+S+Mo	10:1:0,5	Mo 10%
Combination 7	Str+Compost	1:100	(Dereszewska et al.,2021)
Combination 8	Str+SMS	1:100	(Dereszewska et al.,2021)
Combination 9	Str+SFD	1:100	(Dereszewska et al.,2021)

abbreviations Str =Struvite, Hu= humic acid, Has=Haspargit, Mo=Molasse, S=Sulphur, Kstru= K Struvite, Ben=Bentonite, SMS= Spent Mushroom Substrate, SFD= Solid fraction of digestate

2.1.4 Struvite benchmarking

The most competitive commercial fertilisers to struvite are rock phosphate which is like struvite in terms of insolubility in water and P content and single super phosphates (SSP). Compared to single super phosphate struvite has low solubility in water (neutral pH) while SSP is water soluble. This could be enhanced by mixing struvite with P solubilisation bacteria. Or sulphur mixing through sulphur oxidation with 10:1 ratio.

The potential risks associated with using single superphosphate (SSP) fertiliser include concerns related to natural radioactivity and radiation hazards. Recent studies have highlighted the presence of natural radioisotopes like 232Th and 238U in phosphate fertilisers, including SSP, which can contaminate agricultural soils and pose risks to human health and the environment (Suciu et al., 2022) (Khalf et al., 2021). These contaminants can accumulate in consecutive trophic levels, with urban areas posing a higher risk due to higher population densities.

Additionally, the production process of SSP involves reacting phosphate rock with sulphuric acid, which can disrupt the radioactive equilibrium between U, Th, and their decay products. This process can lead to the migration of radionuclides according to their solubility, with uranium isotopes forming highly soluble compounds while other radionuclides concentrate in phosphogypsum. The dispersion of these radionuclides over fields through inert gases like 222Rn can pose risks when using phosphate fertilisers like SSP (Khalf et al., 2021). Research indicates that struvite is significantly more soluble than calcium phosphates at alkaline pH levels, making it a potential phosphorus fertiliser for soils with specific characteristics. In summary, the application of struvite from soil to plants involves considerations of nutrient release, soil characteristics, heavy metal concentrations, and the overall impact on plant growth. Understanding these factors is essential for optimising the use of struvite as a sustainable fertiliser in agriculture.

When comparing the effectiveness of struvite to commercial fertilisers, studies have shown that using struvite as a phosphorus fertiliser can lead to comparable crop yields while offering additional benefits such as improved soil nutrient status and reduced environmental impact. Furthermore, the agrotechnical assessment of struvite as a fertiliser for maize hybrid P9241 revealed that struvite application showed effectiveness comparable to ammonium nitrate and carbamide fertilisers, highlighting its potential as a sustainable alternative in agriculture (Wei et al., 2018) (Valle et al., 2022).

Struvite appears to be effective at application rates of 50-80 kg P2O5/ha, which is comparable to the typical range for superphosphate, DAP and MAP of 50-150 kg P2O5/ha. The exact rate depends on soil test levels, crop requirements and other factors. Struvite's slow-release properties may allow lower application rates in some cases compared to highly soluble P fertilisers which make it more sustainable alternative (Perez et al., 2023)

2.1.5 Existing machinery compatibility and precision fertilisation techniques

Struvite from UWW is completely compatible with existing machinery of fertilisers spreaders and struvite of IWW is also suitable for existing fertiliser spreaders machines. Struvite is compatible with precision farming techniques and could be the optimal P source for fertilization due to:

- Precision Delivery of Nutrients: Struvite is a precision fertiliser that can be placed near the future roots of plants, ensuring that nutrients are delivered exactly where they are needed, reducing the quantity of phosphorus required (BIO-STRU FOR AGRICULTURE. (2022).
- Nutrient Efficiency: Struvite helps in reducing nutrient losses by ensuring that no nutrients are lost through surface runoff or leaching into waterways. This efficient nutrient delivery system ensures that phosphorus remains entirely available for plant uptake, optimising nutrient use efficiency (Vassileva et al., 2022).
- Environmental Protection: By using struvite, the risk of nutrient pollution in water bodies is minimised. Struvite does not dissolve easily, preventing phosphorus from entering waterways and causing imbalances in aquatic ecosystems (Vassileva et al., 2022).
- Sustainable Phosphorus Management: Struvite offers a slow-release fertilisation method that aligns with the plant's needs. This sustainable approach to nutrient management helps in maintaining soil fertility and plant health over time (Peeva et al., 2021).
- Alternative to Non-renewable fertilisers: Struvite serves as an alternative to non-renewable fertilisers that contain salts and can harm soil organisms. By using struvite, the soil remains healthy and fertile, promoting sustainable agricultural practices (BIO-STRU FOR AGRICULTURE. (2022).

These advantages highlight the importance of struvite in precision agriculture techniques, emphasising its role in optimising nutrient delivery, reducing environmental impact, and promoting sustainable farming practices.

Main types of organic fertiliser application machinery include:

- Organic Fertiliser Spreaders:

  Used to evenly distribute solid organic fertilisers over a large area. Examples include broadcast spreaders and manure spreaders.

- Liquid Organic Fertiliser Sprayers:

  Apply liquid organic fertilisers like compost tea or fish emulsion directly to the soil or foliage. Ensures efficient nutrient delivery to plants.

- Compost Spreaders:

  Designed specifically for spreading composted organic materials as fertilisers on agricultural land. Helps incorporate compost into the soil.

Main types of non-renewable fertilisers application machinery include:

- Broadcast Spreaders:

  Used to evenly distribute solid fertilisers over a large area. Examples include centrifugal spreaders and pendulum spreaders.

- Band Applicators:

  Apply fertilisers in narrow bands close to the seed or plant. Ensures direct nutrient delivery to the root zone.

- Liquid Fertiliser Sprayers:

  Used to apply liquid fertilisers directly to the soil or foliage. Provides efficient nutrient delivery to plants

- Placement Applicators:

  Place fertilisers close to the seed or plant.
  Supplies adequate nutrients to the roots of growing plants.

- Side-Dressing Applicators:

  Apply fertilisers between rows and around plants.
  Provides additional nutrients during the growing season.

- Fertigation Systems:

  Inject liquid fertilisers into irrigation systems.
  Allows for precise and targeted nutrient delivery.

Table 7: Struvite compatibility with non-renewable and organic machinery.

		Struvite	Struvite + proposed non-renewable fertilisers	Struvite + proposed circular fertilisers	Observations
Non-renewable machinery	Broadcast Spreaders	Compatible	Compatible		N/A
	Liquid Fertiliser Sprayers	Compatible with restrictions	Compatible with restrictions		It is recommended to be added in acidic medium due to low solubility in water
	Placement Applicators	Compatible	Compatible		N/A
	Side-Dressing Applicators	Compatible	Compatible		N/A
	Fertigation Systems	Compatible with restrictions	Compatible with restrictions		It is recommended to be applied in acidic medium to avoid the irrigation blocking slots by sedimentation
Organic Machinery	Organic Fertiliser Spreaders	Compatible		Compatible	N/A
	Liquid Organic Fertiliser Sprayers	Compatible		Compatible	N/A
	Compost Spreaders	Compatible		Compatible	N/A

2.2 Stabilised sludge

2.2.1 Introduction

Sewage sludge (SS), a by-product of waste water treatment, is increasingly being recognised as a valuable resource in the circular economy. When properly stabilised and sanitised, sewage sludge can be transformed into a nutrient-rich organic fertiliser. The stabilisation process, such as lime treatment, aerobic digestion, thermal drying and composting or anaerobic digestion, kills pathogens and reduces odours, making the sludge safe for beneficial use as a soil amendment or fertiliser (Jovičić-Petrović et al., 2021). The main biological stabilisation processes for producing agricultural-grade biosolids are composting and anaerobic digestion. Stabilised sewage sludge contains significant amounts of nitrogen, phosphorus, and organic matter that can benefit plant growth and soil health when applied as a fertiliser (Novosel et al., 2022). However, the carbon-to-nitrogen (C/N) ratio of raw sludge is often not ideal for direct use, typically being too low (less than 20:1). Adjusting the C/N ratio through co-composting with carbon-rich bulking agents like sawdust can produce a more balanced, stable soil amendment in the optimal 25-35:1 range (Głodniok et al., 2021). Benchmarking studies have compared the agronomic performance and environmental impacts of biosolids to other organic fertilisers like manure and compost.

While biosolids generally have higher nutrient content, they may also contain trace levels of heavy metals and organic micropollutants that require monitoring. Proper stabilization and management practices are critical to ensure the safety and sustainability of biosolids use. In summary, stabilised sewage sludge represents a promising circular fertiliser alternative that can help close nutrient loops, reduce waste, and improve soil fertility when managed responsibly. As the world faces increasing pressure on fertiliser resources, the recycling of nutrients from urban waste water will play an important role in future food production (Gusiatin et al., 2024). Combining it with other organic materials and precision application techniques can optimise its benefits while minimising environmental risks. Technical parameters for stabilised sludge are summarised in **Table 8**.

Table 8: Stabilised sewage sludge technical parameters. Source: FER-PLAY database project.

Technical parameter	Characteristics & values	Observations
N-P-K Balance	40:30:15	High and balanced nutrient content
Market price	1-15 €/tonne	N/A
Raw material availability	8.7 M tonnes dry solids/year (Europe)	N/A
storage ease	Stabilised sludge can be stored safely	N/A
Applicability in organic farming	No	N/A
Considered as fertiliser in the European regulatory framework?	Yes (if meeting the standards)	N/A
C/N Ratio	The C/N ratio of raw sewage sludge is often not ideal for direct use as a fertiliser, typically being too low (less than 20:1) (Jovičić-Petrović et al., 2021)	Studies have shown that the C/N ratio can be adjusted through various stabilization

Technical parameter	Characteristics & values	Observations
		and treatment processes, such as composting with sawdust or vermicomposting with earthworms (Wiater, J. (2020)
Application form	When powder, compatible with manure spreader	N/A
Application conformity	Compatible with existing machinery	N/A
Nutrients leaching	Yes, if application on the wrong soil or at the wrong period of time	N/A
Nutrient Availability and Release (Uptake speed)	slow release	N/A

2.2.2 Morphology and recommendations

Morphologically, stabilised sludge has a mud-like, semi-solid consistency with a high organic matter content, typically 30% or more. It contains significant amounts of nitrogen, phosphorus, and micronutrients that can benefit plant growth when applied to soils. However, the carbon to nitrogen (C/N) ratio is often not ideal for direct application as a fertiliser (Lim et al., 2021). Sludge-like materials (compost, solid fraction of digestate and Spent Mushroom Substrate (SMS)) also present handling issues, often requiring them to be conditioned to reduce the moisture content and/or stickiness of the material to improve handling. A unique approach to managing both dust and sludge wastes has been to mix the two materials prior to landfilling. For example, compost or solid fraction of digestate and sludge could be mixed to condition the two materials to mitigate their associated issues; dust issues are resolved, and the stickiness and moisture content of the sludge material is reduced.

We recommend if the stabilised sewage sludge (SSS) is in the form of powder to be undergo a process of micro pelletising for various advantages of this process like:

- Significant dust reduction/ elimination.
- Improved handling and transport.
- Improved application and use.

- More accurate application

Micro pellets can move through spreading equipment much more efficiently than powdered materials, making application more precise and reliable.

- More predictable results

Because micro pellets will not blow away like a powdered material might, applications stay where they are applied, delivering nutrients where they are needed, and nowhere else.

- Faster product breakdown

Smaller pellets are more quickly broken down than larger ones and thus, in the case of soil amendments, nutrients reach the soil sooner.

- Reduced visibility

Micro pellets sink between the grass blades quickly. This is beneficial because the application does not detract from the beauty of the turf, a valuable characteristic for applications such as golf courses and lawns. This is a common reason for choosing micro pellets over larger particle sizes.

2.2.3 Stabilised sludge benchmarking

In comparison to other fertilisers such as solid fraction of digestate or struvite, in terms of the homogeneity of stabilised sludge-based granulated fertiliser ensures consistent nutrient availability for plants, reduces nutrient leaching or runoff, and promotes even distribution of essential elements in the soil. This uniformity in nutrient content and physical characteristics enhances the effectiveness of stabilised sludge as a sustainable fertiliser option for improving soil fertility, supporting plant growth, and minimising environmental impact in agricultural practices.

The use of sewage sludge as fertilisers increases the organic matter content of the soil, the levels of total nitrogen and phosphorus, compared to mineral fertilisation. However, an excess of phosphorus in the soil can be harmful to the crop, so it is necessary to define what should be the limit in the phosphorus content in the soil from which the frequency of fertilisation with sludge must be changed to prevent the phosphorus content in the soil from increasing.

Benchmarking stabilised sewage sludge vs. other fertilisers:

- Studies have compared the agronomic performance and environmental impacts of stabilised sewage sludge (biosolids) to other organic fertilisers like manure, compost, and peat (Kazmierczak, 2012).

- Biosolids generally have higher nutrient content (N, P, K) compared to manure and compost, making them more efficient as a fertiliser per unit applied.
- Biosolids can improve soil properties like pH, organic matter, and cation exchange capacity similar to other organic amendments.
- However, biosolids may contain higher levels of heavy metals and organic micropollutants compared to some organic fertilisers, requiring monitoring and management (Lederer & Rechberger, 2010).

Overall, benchmarking has shown stabilised sewage sludge can be a valuable resource when managed responsibly but concerns around contaminants and public acceptance remain important considerations.

2.2.4 Existing machinery compatibility and precision fertilisation techniques

Existing machinery like manure spreaders and fertiliser injectors can be used to apply stabilised sludge, though precision may be limited compared to commercial fertilisers. Incorporating the sludge into the soil can reduce odours and nutrient losses (Lim et al., 2021).

- Stabilised biosolids can be applied using non-renewable manure spreaders, though the semi-solid consistency may limit even distribution compared to liquid or granular fertilisers (Jovičić-Petrović et al., 2021).
- Incorporating biosolids into the soil through injection or tillage can improve nutrient use efficiency and reduce odours, like practices for other organic amendments (Jovičić-Petrović et al., 2021).
- Precision application techniques like GPS-guided variable rate application are less commonly used for biosolids compared to commercial mineral fertilisers but can optimise nutrient placement (Jovičić-Petrović et al., 2021).

2.2.5 Concerns

Sewage sludge may pose the following concerns:

- Potential contaminants: Stabilised sludge may still contain trace levels of heavy metals, organic micropollutants, and other contaminants that could accumulate in soils over time with repeated application (Kunkel & Ternes (2014).
- Pathogen regrowth: There is a risk of pathogens regrowing during storage of stabilised sludge, so proper handling and application procedures are critical.

- Nutrient imbalance: The carbon-to-nitrogen ratio of stabilised sludge is often not ideal for direct use as a fertiliser, requiring blending with other organic materials.
- Public perception: Some public resistance exists to the use of sewage-derived products on food crops, despite the safety of properly stabilised biosolids (Jovičić-Petrović et al., 2021).

2.2.6 Possible combinations

Stabilised sludge can be applied to agricultural land, gardens, or used for land reclamation to improve soil fertility and structure in desertic farming areas. Combination with other organic materials like compost it is needed to optimise the C/N ratio and nutrient balance. The addition of calcium oxide/quicklime, dolomite flour, gypsum, cellulose fibres, Spent Mushroom Substrate (SMS) and/or struvite would help to improve the nutrient profile and physical properties of the stabilised sludge, making it a well-balanced and effective soil amendment (Głodniok et al., 2021). Finally, it is important to conduct soil tests to determine appropriate application rates based on crop needs and soil conditions.

Potential combinations with other fertilisers include:

- Mixing with non-renewable mineral fertilisers to provide a balanced nutrient supply.
- Blending with recycled phosphorus fertilisers derived from sewage sludge ash or other waste streams to create a circular nutrient loop.
- Composting the sludge with other organic wastes to produce a stabilised, nutrient-rich soil amendment (Kazmierczak, 2012).

Stabilised sludge could be used as soil improver, fertiliser, substitution for peat and in combination to other chemical materials as a complex fertiliser. The basic modification is the use of thermo-composting of separated sewage sludge with the addition of a structure-forming agent (straw pellet) (Kamizela et al., 2021). Due to its high content of nutrient, it is itself could be used as a complex fertiliser without any mixing with another chemical or organic fertiliser**.** Unlike chemical fertilisers that may have a limited nutrient range, stabilised sludge provides a comprehensive nutrient package that enhances crop productivity and soil fertility

2.3 Composted biowaste

2.3.1 Introduction

Compost made from food and green wastes offers a holistic approach to soil improvement by providing a wide range of nutrients, enhancing soil structure, and promoting environmental sustainability. On the other hand, circular organic fertilisers offer targeted nutrient solutions for specific plant needs with ease of application but may lack the comprehensive benefits of compost in terms of long-term soil health and environmental impact. compost is a natural soil amendment that promotes healthy soil by increasing organic matter, enhancing microbial activity, improving nutrient content, and aiding in moisture retention. It requires time to produce but offers numerous benefits for plant growth. Conversely, other organic fertilisers offer more rapid, targeted nutrient solutions for plant needs, but if applied incorrectly, they run the risk of overfeeding the soil or damaging the environment. Regarding application procedures, advantages and disadvantages for plant health and soil quality, compost and organic fertilisers are similar. Key technical parameters are summarized in **Table 9**.

Table 9: Technical parameters of compost. Source: FER-PLAY project database.

Technical Parameters	Characteristics & values	Observations
N-P-K Balance	1.99-0.44-1.19 In dry basis. With a dry matter of 75%	Balanced but very low nutrient content that is why it is considered as soil improver
Raw material availability	48-128 Mt	N/A
storage ease	No risk	Some issues come up when it is humid and when it is very dry
Applicability in organic farming	Have a look at Reg. (EU) 848/2018	Permitted in EU. Thresholds for biowaste compost
Considered as fertiliser in the European regulatory framework?	Yes, European Union Regulation 2019/1009	Considered organic soil improver in The EU Reg. 2019/1009 defines some Product Function Categories (PFCs
Application form	When pellet, compatible with granular chemical fertiliser spreader	N/A

Technical Parameters	Characteristics & values	Observations
Application conformity	When powder, compatible with manure spreader When pellet, compatible with granular chemical fertiliser spreader	When powder is not compatible and a certain problem of equal distribution and blow up in windy areas is probably associated with
Nutrients leaching	Low to none	N/A
Nutrient Availability and Release (Uptake speed)	Slow release	

2.3.2 Morphology and recommendation

Compost is ready for application when it has a dark, rich brown colour, crumbles easily, and has a sweet, earthy smell. It should not contain visible original ingredients and should be well decomposed. The optimal particle size for organic fertilisers to ensure efficient nutrient release is generally considered to be between 8-10 mm. This range allows for a balance between nutrient delivery and segregation during handling and spreading. Larger particles can take longer to break down, while smaller particles may become windblown or segregate unevenly, affecting application uniformity (Antille & Godwin., 2013). When handling and spreading organic fertilisers, it is essential to consider the particle size distribution and adjust the spreading width accordingly. Larger particles can be spread over wider areas, while smaller particles may require narrower spreading widths to prevent segregation.

Specification for optimal use:

Compost particle sizes are a balance of aesthetic and practical considerations. Screening compost through a 6.35 mm or 4.76 mm mesh creates a uniform appearance and is essential for reducing plastic contamination. Limiting the portion of compost finer than 6.35 mm to less than 50% helps prevent mulch from sealing.

Flemish Standards: In Belgium, more than 99% of the compost should be less than 40 mm. green composts are usually sieved to 20 mm, while finer sieving (10 or 15 mm) is possible for use in substrates and sieving to 30 mm is more common for arable field application (Amery et al., 2020).

Particle Size Distribution: Compost to be used in substrates has sometimes more strict regulations for certification than compost for soil application. The particle size distribution is important for the intended porosity and water holding capacity for plant growth in the substrates.

Large-Scale Organic Materials Composting:

Particle Size: The particle size for large-scale organic materials composting typically ranges from 3.175 mm to 50.8 mm in diameter, depending on raw materials, pile size, and/or weather conditions.

These specifications help ensure optimal fertiliser performance, efficient spreading, and uniform distribution for organic fertilisers, as well as suitable particle size distributions for composts used in different applications (Antille & Godwin., 2013).

Based on the provided data on the morphology of compost made from food and green wastes, we recommend undergoing a process of pelletising due to its various advantages, such as:

- Significant dust reduction/ elimination
- Improved handling and transport
- Improved application and use
- More accurate application. Micro pellets can move through spreading equipment much more efficiently than powdered materials.
- More predictable results
- Because micro pellets will not blow away like a low-density material might.
- Faster product breakdown
- Smaller pellets are more quickly broken down than larger ones.
- Reduced visibility
- Micro pellets sink between the grass blades quickly.
    - Mixing compost with struvite increases its density and its nutrient content.
    - Micro pelletising could be a good solution to the lower density and storage and transportation concerns.
    - Micro pelletising also can enhance the problem of size and compost variation
    - Mixing the compost with Spent Mushroom Substrate (SMS), feather meal or struvite decrease the C/N ratio and make it a relatively balanced combined fertiliser with sustainable improvement soil characteristics.

2.3.3 Concerns

While composting food and green wastes offer numerous benefits for soil health and sustainability, rather it includes drawbacks such as initial investments in equipment, dependence on waste quantity for effectiveness, unpleasant odours, attraction of pests, labour-intensive maintenance requirements, and the time-consuming nature of the process. These drawbacks highlight some challenges associated with implementing and managing a composting system effectively. Another barrier to the implementation of renewable raw materials in the production of fertilisers is the variability of the raw material. Production technologies should consider this.

In summary, while compost from food and green wastes offers significant benefits for soil health and sustainability, concerns such as nutrient variability, weed seeds, pathogens, heavy metal contamination need to be considered when comparing its application to other organic or non-renewable fertilisers. However, both pathogens and heavy metals have strict limits according to both EU Regulation 2019/1009 and national legislations. For compost to be marketed, it must comply with these limits. Proper management practices and quality control measures are essential to address these concerns effectively and maximise the benefits of using compost in agricultural settings.

The problems of using food and green waste compost in terms of application machinery include challenges related to the physical properties of compost, potential equipment clogging, and the need for specialised machinery to handle compost effectively. The application of food and green waste compost can pose difficulties due to its texture, moisture content, and potential for clumping, which may require machinery modifications or specialised equipment for efficient spreading. Additionally, the presence of organic matter in compost can lead to equipment clogging or blockages during application, necessitating regular maintenance and cleaning of machinery to prevent operational disruptions. Overall, the unique characteristics of food and green waste compost present challenges for traditional application machinery, highlighting the importance of using appropriate equipment designed to handle compost effectively in agricultural or landscaping settings (Ohio State University Extension, 2016).

The morphological status of food and green waste compost can affect its application machinery due to the physical properties of the compost. Compost with a high nutrient content may have a denser texture, making it more challenging to spread evenly using traditional application machinery designed for lighter materials. The nutrient-rich nature of the compost can lead to clumping, clogging, or blockages in machinery during application, requiring modifications or specialised equipment to handle the heavier and potentially more viscous compost effectively. Therefore, the nutrient status of food and green waste compost plays a crucial role in determining the type of machinery needed for efficient application to ensure uniform distribution and optimal utilisation of nutrients in agricultural or landscaping practices.

- The most usual problem of compost application is its lower density which hinders the homogenous distribution. A modification has been made with the existing machines to cope with this problem.
- Other problem of storage is being faced which is the water content which vary a lot from summer to winter and the compost easily absorbing or loosing air humidity in the uncovered storage places which is usually used for storage it
- Lower density causes high volume and high need for storage and transportation sites which cause logistic problems.
- Low C/N ratio of compost and low nutrient content put it in the pattern of soil improvers or soil amendment and make the peat is the most competitor

Key considerations

- Particle Size: Smaller particle sizes facilitate microorganism activity and decomposition.
- Temperature Control: Maintaining optimal temperatures (40-60°C) for a minimum of five days can significantly reduce pathogens and ensure the quality of the compost.
- Moisture Content: The ideal moisture content for composting is between 40% and 60%. This can be achieved through the addition of bulking agents or adjusting the amount of water added. This is not the ideal moisture content for storage and transportation which is around 25% (Kim et al., 2016).
- Automation: Fully automated composting machines can streamline the process and ensure consistent results.

2.3.4 Compost benchmarking

Since fish wastes, cattle dung, and urine are the best sources of liquid organic fertilisers that give soil and plants the nutrition they need, they are among the commercially competitive organic fertilisers of the compost of food and green wastes. (Dias et al., 2022). These organic materials offer valuable nutrients and microbial activity that can enhance soil fertility and promote healthy plant growth. Additionally, vermicompost is highlighted as a competitive organic fertiliser derived from earthworms that enhances the degradation of organic wastes, reduces environmental pollution, increases soil fertility sustainability, and protects environmental and human health (Toora et al., 2023).

Green waste refers to organic waste items, often produced from gardens and parks, such as grass clippings, leaves, branches, and other plant-based materials. the compost of green and food wastes could potentially be a good replacement for peat, but the evidence is not conclusive. The search results indicate that composting of green waste and food waste can produce a valuable organic fertiliser or "compost" that can be used as a soil amendment. This compost is described as "rich fertile compost" and a "premium grade compost product" that can be used by gardeners, farmers, and communities. The composting process breaks down the organic materials into a humus-like substance that can improve soil structure, water-holding capacity, and nutrient content (Dias et al., 2022). However, the search results do not directly compare the properties and performance of this compost to peat as a soil amendment. The suitability of compost as a direct replacement for peat is not explicitly stated. Some additional research would be needed to evaluate the specific physical, chemical, and horticultural properties of the compost produced from green and food waste, and how it compares to the characteristics and benefits of using peat.

The key differences between compost made from green and food waste compared to peat (while peat is not composted, it is extracted, prepared for the use, but not composted):

- Sustainability and environmental impact:

  Peat is a non-renewable resource that takes thousands of years to form, and its extraction destroys peat bogs which are important carbon sinks.

  Compost made from green and food waste is a renewable, sustainable resource that diverts organic waste from landfills and reduces greenhouse gas emissions (WRAP, (2016).

- Composition and properties:

  Peat-based soil improvers are more consistent in their physical and chemical properties.

  Compost from green and food waste can be more variable in quality and composition, depending on the source materials and composting process.

- Nutrient content and soil benefits:

  Peat-based soil improvers tend to be lower in nutrients compared to compost made from green and food waste (Royal Horticultural Society. (n.d.).

  The compost from green and food waste can improve soil structure, water-holding capacity, and provide a range of macro- and micronutrients.

- Suitability for plant growth:

  Peat-based growing media have traditionally been preferred by gardeners for seed starting and potting mixes due to their consistent quality.

With some adjustments, compost from green and food waste can also be suitable for many gardening applications, though it may require more monitoring and adaptation (Royal Horticultural Society. (n.d.).

In summary, the key differences are that compost from green and food waste is a more sustainable, nutrient-rich alternative to peat, but may be more variable in quality, while peat-based materials offer more consistent physical and chemical properties. The environmental benefits of the green/food waste compost are a major advantage.

2.3.5 Machinery compatibility and precision farming

Normally, there is no problem for compost of food and green wastes in terms of compatibility with existing application machinery although some general concerns should be considered when applying. The machinery used to apply compost into soil within precision farming systems includes several types of equipment designed for efficient and targeted application of composted materials. Here are some key points to consider:

Precision Compost Application Machinery

- Compost Distributors:

  Compost Distributors: These machines are designed to distribute compost evenly across fields or other areas. They are typically used in precision farming applications to ensure uniform application of compost.

- Forage Mixers:

  Forage Mixers: These machines are designed to mix compost with other materials like forage crops (green manure), manure, or other organic matter. They are used in agricultural applications to create nutrient-rich blends for crops.

The technical info provided highlights the importance of considering machinery factors when applying compost of food and green wastes to soils. Proper machinery selection and management are crucial for efficient and effective compost application.
The machinery for precision compost application involves various types of equipment designed to facilitate efficient processing and utilisation of composted materials. These machines are crucial for ensuring the quality and consistency of compost products, particularly in large-scale composting operations.

Here are some key points related to machinery considerations:

- Spreader Performance: Spreading machinery, such as side or rear discharge spreaders, plays a vital role in the even distribution of compost. Higher-end models can achieve an even spread of material within each pass, ensuring uniform application Rabaud. (n.d.).
- Calibration: Spreading machinery should be calibrated to accurately determine the amount of bulky organic fertiliser applied per hectare. This calibration process is essential for understanding the nutrients applied and optimising application rates (Agrolead. (n.d.).
- Sampling and Analysis: It is advisable to have bulky organic fertilisers analysed before use, especially when large volumes are being applied or when similar materials are used regularly on the farm. Knowing the nutrient content of compost helps optimise nutrient application, reduce fertiliser costs, and minimise environmental losses WorldWideScience.org. (n.d.).
- Application Rates: Machinery considerations are crucial for determining appropriate application rates based on site-specific factors, material properties, and intended land use following compost application. The application rate can vary depending on whether compost is used for soil forming, soil improvement, or as a top dressing (Rollett et al., 2015).

In conclusion, selecting the right machinery, calibrating spreaders, incorporating compost properly, analysing materials before use, and adjusting application rates based on specific needs are essential considerations when applying compost of food and green wastes to soils for optimal agricultural outcomes (WRAP, 2016).

2.3.6 Combinations with non-renewable and circular fertilisers

Compost of food wastes could be enriched by mixing with struvite or feather meal as good candidates from circular fertilisers and could be mixed with any complex of non-renewable ones.

Based on the data of value chains and literature reviews (Rollett et al., 2015; Ikenganyia et al., 2014), here are the ideal mixing ratios for various compost blends to raise the nutrient content:

- Compost and Spent Mushroom Substrate (SMS):

50% compost and 50% Spent Mushroom Substrate (SMS) for optimal nutrient retention and soil structure enhancement.

- Compost and Nutrient-Rich Materials:

Addition of 10-20% of nutrient-rich materials like struvite and K Struvite, feather meal, to the compost.

- Compost and Microorganisms:

Introducing beneficial microorganisms like phosphobacteria at a rate of 1-2% of the total compost mix.

- Compost and pH Adjustment:

Addition of lime or sulphur to adjust the pH of the compost as needed, typically 5-10% of the total mix.

The key is to maintain the right balance of carbon, nitrogen, and other nutrients, as well as proper aeration and moisture levels, to create a high-quality, nutrient-rich compost. Experimenting with different blending ratios may be necessary to achieve the desired results. (Ikenganyia et al., 2014).

2.4 Feather meal

2.4.1 Introduction

Feather Meal is indeed a valuable source of natural organic nitrogen, crucial for plant vegetative growth. Unlike blood meal, feather meal breaks down slowly in soil, providing a natural slow release of nitrogen. While it is potent and can potentially burn plants if over-applied, its slow-release nature helps mitigate this risk compared to blood meal. This slow breakdown allows for a steady supply of nitrogen to plants over time, making it an effective and sustainable fertiliser choice for organic gardening (Epic Gardening, n.d.), (Walt's Organic Fertilizer Co., n.d.), (North Country Organics, n.d.), (Wikipedia contributors, n.d.).

The utilisation of feathers that contain 11% nitrogen can be a source of not only macronutrient N, but also if the process is skilfully designed – this can be a source of amino acids, which are a chelating agent for micronutrient ions and a biostimulator of plant growth. Key technical parameters are summarised in **Table 10**.

Feather meal, a by-product of poultry processing, can be a valuable source of protein for plants when used as a fertiliser. However, there are several key considerations to keep in mind when applying it. First, the quality of the feather meal can vary, so it is important to assess its amino acid content and decomposition (Papadopoulos, 1985). Processing methods, such as pressure, time, and moisture, can affect the nutritive value of the feather meal (El Boushy, Van der Poel, & Walraven, 1990). Additionally, the pH and pressure during processing can impact the protein decomposition and sulphur amino acid content (Latshaw, 1990). Lastly, untreated feather meal may have limited nutritive value due to its insolubility and indigestibility (Naber & Morgan, 1956). Therefore, it is crucial to carefully evaluate the quality of the feather meal and consider its processing conditions before applying it to plants.

2.4.2 Morphology and recommendations

Feather meal has a very low C/N ratio, typically around 3.2 (Hardy & Barrows, 2003). This is much lower than other organic fertilisers like meat meal (C/N of 7) and stable manure (C/N of 10.6). The low C/N ratio of feather meal means it is a nitrogen-rich organic fertiliser (Seibersdorfer, n.d.). It contains around 14% nitrogen, which is higher than many other organic fertilisers. The low C/N ratio also means feather meal can provide a rapid release of nitrogen to plants, as the microbes in the soil can easily break down the organic nitrogen compounds (Hardy & Barrows, 2003) (Smith, n.d.). This makes feather meal a good source of immediately available nitrogen for crops. However, the very low C/N ratio also means feather meal may need to be blended with other organic materials that have a higher C/N ratio, in order to achieve a more balanced C/N ratio in the overall fertiliser mix. This helps synchronize nitrogen mineralisation with plant uptake (Smith, n.d.).

Feather meal can promote the formation of flowers and fruits, making it highly recommended for floral horticulture. It is also used as a fertiliser in organic crops and to aid decomposition in compost formation. Fermentation of feather meal using bacteria like Bacillus subtilis can increase its digestibility and nutritional value. Feather meal is considered a sustainable fertiliser option compared to energy-intensive synthetic fertilisers. Its use helps reduce waste and recycle nutrients. In summary, feather meal is a concentrated, slow-release organic fertiliser that is beneficial for promoting plant growth, flowering, and fruit production. Fermentation can further enhance its nutritional properties. As a by-product, it provides a sustainable alternative to synthetic fertilisers.

2.4.3 Feather meal benchmarking

Feather meal can be benchmarked against other common fertilisers in the following ways:

- Nitrogen content: Feather meal has a high nitrogen content, typically around 12-15% nitrogen. This is higher than many other organic fertilisers like compost (1-2% N) and manure (1-4% N), making it a more concentrated nitrogen source (Cultivers, n.d.).
- Slow-release nitrogen: The nitrogen in feather meal is released slowly over time, unlike fast-release fertilisers like urea. This slow-release property is beneficial for long-term plant nutrition and reducing nitrogen leaching (Cultivers, n.d.).
- Organic matter: Feather meal contains over 85% organic matter, which is higher than many synthetic fertilisers that are primarily inorganic salts. The organic matter in feather meal can improve soil structure and water-holding capacity (Cultivers, n.d.).

- Pricing: Feather meal prices have fluctuated alongside other commodity fertilisers like potassium chloride, diammonium phosphate, and urea. However, feather meal is generally more cost-effective than some synthetic fertilisers (Routray, n.d.).
- Sustainability: As a by-product of the poultry industry, feather meal is considered a more sustainable fertiliser option compared to energy-intensive synthetic fertilisers. Its use helps reduce waste and recycle nutrients (Routray, n.d.).

Overall, feather meal stands out as a high-nitrogen, slow-release, and organic fertiliser that compares favourably to many synthetic and other organic fertiliser options in terms of nutrient content, release characteristics, and sustainability.

2.4.4 Machinery compatibility and precision farming suitability

Based on the provided sources, there is a specific mention of modifications required for precision farming standard farm machinery to use feather meal fertiliser. In a research update from the Almond Board of California, it was noted that there were plugging problems in the applicator when trying to uniformly apply dry pelletised feather meal fertiliser in 2019, indicating challenges with application machinery compatibility (Bruno, Goodrich, & Sexton, 2021). This suggests that modifications or adjustments may be necessary in precision farming standard farm machinery to effectively apply feather meal fertiliser without encountering plugging issues.

When applying feather meal to soil, it is recommended to consider it as a good, fast-release source of nitrogen. Feather meal can be used as an OMRI amendment, but it is important to note that the product available at feed stores is likely a by-product of industrial chicken farming (Grow Abundant Gardens, n.d.)

2.4.5 Feather Meal Application

To apply feather meal effectively, it is advisable to follow best practices for organic fertilization, ensuring that the nutrients are released gradually to support plant growth and soil health. Feather meal is a fast or medium-release fertiliser, making it suitable for organic gardening and agriculture. It is not water-soluble and must be blended into the soil to start the decomposition process, making the nitrogenous compounds available to the plants. And must be put close by plant to be near by the roots for a proper absorption.

When applying feather meal to the soil, it is essential to mix it with the top 5cm (2") of soil to ensure proper decomposition and nutrient release. Feather meal is not suitable for top dressing due to its potent nitrogen content, which can potentially burn plants if over-applied. It is recommended to apply feather meal up to four times per year in the garden and up to once per month for top dressing or premixing soil.

Table 10: Technical parameters of feather meal. Source: FER-PLAY database project.

Technical parameters	Characteristics & values	Observations
N-P-K Balance	11:0.4:1.6	High N but low in P and K
Raw material availability	20,000 tonnes/year	Might face a shortage in case of industrial production however, the commercial production scale is much more than that amount
storage ease	Should be stored in a dry and cool environment	N/A
Applicability in organic farming	Yes, EU VO	N/A
Considered as fertiliser in the European regulatory framework?	Yes, European Union Regulation 2019/1009	N/A
C/N Ratio		Some commercial products have the percentage of 15% (Cultivers, n.d.).
Application form	Pellet	N/A
Application conformity	Compatible with existing machinery	N/A
Nutrients leaching		N/A
Nutrient Availability and Release (Uptake speed)	Fast Release	Some references say it is slow release some others say it is medium or fast release

2.4.6 Recommendations for use as an alternative fertiliser

Feather meal is recommended to be mixed with Spent Mushroom Substrate (SMS) to get a well-balanced fertiliser that could be competitive to many organic or even non-renewable fertilisers. Furthermore, the concerns of burnings to plants due to direct contact could be mitigated due to this mix. No special machinery is needed on the time of application where any manure spreaders or compost spreader could be used without problems. It is also recommended to granulate it or micro pelletising it for storage, use and transportation ease. Due to its slow-release properties, it is recommended to be added to soils of nutrient leaching or nutrients runoff concerns.

It is not synthetic or petroleum-based, making it a sustainable and environmentally friendly alternative to synthetic fertilisers (Epic Gardening, n.d.). Feather meal can be used to provide a natural slow-release nitrogen source for plants, contributing to the health and well-being of plants and soil ecosystems. Due to feather meal possible effect of increasing PH so it is not recommended to be mixed with struvite who needs an acidic media to be available to plants. In addition to it is not recommended in southern or eastern Spanish soils where an alkaline soil profile is widely existing.

2.4.7 Possible combinations

The relatively high content of N and low content of P and K in feather meal makes the blends of feather meal with K struvite is the best mix. Further experiments should be carried out to reach to the optimum ratios of mixed feedstocks. Another combination could get by blending the non-renewable complex of NPK fertiliser that might compete with already existing non-renewable unsustainable commercial fertilisers.

Here are some examples for possible combinations of feather meal with organic and non-renewable fertilisers:

Organic Fertiliser Combinations

- Feather meal + bone meal: Provides a balance of nitrogen (from feather meal) and phosphorus (from bone meal) for plant growth and flowering (Yeh et al., 2023) (McNeilan, 2008).
- Feather meal + kelp meal: Combines the nitrogen from feather meal with the potassium, micronutrients and plant growth hormones from kelp for a more complete organic fertiliser (McNeilan, 2008).
- Feather meal + rock phosphate: Adds phosphorus to the nitrogen in feather meal. Rock phosphate is a slow-release organic phosphorus source.
- Feather meal + greensand: Provides nitrogen from feather meal along with potassium and iron from greensand (McNeilan, 2008).

Non-renewable fertilisers Combinations

- Feather meal + urea: Combines the slow-release nitrogen from feather meal with the fast-acting nitrogen from urea for both immediate and long-term plant nutrition (McNeilan, 2008).
- Feather meal + ammonium sulphate: Provides nitrogen from both feather meal and ammonium sulphate. Ammonium sulphate also helps acidify the soil.
- Feather meal + superphosphate: Adds readily available phosphorus from superphosphate to the nitrogen in feather meal.
- Feather meal + muriate of potash: Combines the nitrogen from feather meal with potassium from muriate of potash for a balanced NPK fertiliser (McNeilan, 2008).

The key is to combine feather meal with other organic or non-renewable fertilisers that provide complementary nutrients like phosphorus, potassium, sulphur or micronutrients. This allows customizing the fertiliser to the specific needs of the crop and soil.

2.4.8 Concerns

Feathers are produced worldwide. According to FAO, about 24 billion chickens were produced in 2018. Assuming that a chicken weighs 2 kg and that the average percentage of feathers is 5%, the overall amount of chicken feathers in 2018 can be estimated to be 2.4 million t. Other poultry productions (ducks 1.12 billion heads, turkeys 466 million heads and geese 365 million heads) yield an additional 0.42 million t of additional feathers, resulting in a total amount of feathers up to 2.8 million metric tonnes in 2018 (Feedipedia, 2014). Out of the global annual consumption of nitrogen fertilisers which is around 195 million metric tonnes feather meal raw materials availability (3%) is considered a quite low to cover the global demand alone. However, depending on more circular N resource could be the solution for that issue.

Feather meal affects soil pH levels by increasing the pH when it is applied to soil. This is because feather meal contains a high amount of nitrogen, which can cause an increase in ammonia levels in the soil. Ammonia is alkaline in nature, and when it is released into the soil, it can cause the pH to rise. This can be beneficial for plants that prefer a slightly alkaline soil pH, but it can be detrimental for plants that prefer a more acidic soil pH. It is important to monitor soil pH levels when using feather meal as a fertiliser to ensure that the pH does not become too high for the plants being grown. Additionally, feather meal has a stronger effect on increasing electrical conductivity (EC) compared with blood meal, which can also affect soil pH levels and the availability of nutrients to plants (Smith, n.d.).

- Feather meal has a low solubility in water, which can make it difficult to mix with other fertilisers or water for application.

- The low solubility may also limit the availability of nutrients to plants, particularly in the early stages of growth when plants require more readily available sources of nitrogen.
- The organic matter stability is low in feather meal, which means that it is prone to decomposition and can break down quickly. This can lead to a loss of nutrients and a decrease in the overall fertility of the soil.

2.5 Solid fraction of digestate

2.5.1 Introduction

The Solid Fraction of Digestate (SFD) is the fibrous material that remains after the anaerobic digestion process that is used to produce biogas. SFD is separated from the liquid fraction through solid-liquid separation techniques like centrifugation, screw press or pressing (Tambone et al., 2017) (Czekała, 2022). The solid fraction of digestate is particularly important as a fertiliser due to its high nutrient content and organic matter. Studies have shown that it can contain up to 87% of the total nitrogen and 71% of the phosphorus present in the original digestate (Tambone et al., 2017) (Chojnacka et al., 2024).

The solid fraction is regarded as cost-effective to transport compared to the liquid fraction, which has limited market value due to its high-water content and lower nutrient density. When applied to soil, the solid fraction can increase soil stability and humification rates, improving overall soil health (Kovačić et al., 2022). Additionally, the solid fraction retains most of the digestate's phosphorus, making it a valuable source of this essential nutrient for plant growth. The average phosphorus to potassium ratio in digestate is around 1:3, further enhancing its fertiliser potential (Czekała, 2022). In summary, the solid fraction of digestate is a nutrient-rich, organic-matter-containing material that can serve as a valuable, cost-effective fertiliser for agricultural applications, contributing to sustainable soil management practices.

2.5.1.1SOLID FRACTION OF DIGESTATE FROM URBAN WASTE WATER

The solid fraction of digestate (SFD) derived from waste water is often viewed as more significant than that from manure or food waste due to several statistical and compositional factors:

- Nutrient Composition

  Phosphorus Concentration:

  Studies indicate that the solid fraction from waste water typically has a higher phosphorus content. For example, the solid fraction can contain significant amounts of phosphorus, which is crucial for soil fertility and often more concentrated than in manure or food waste digestates (Akhiar et al., 2015).

Organic Matter Quality:

The organic matter in waste water-derived digestate is often more stable and beneficial for soil health. Research shows that the solid fraction from waste water can improve soil structure and microbial activity more effectively than those derived from manure or food waste (Akhiar et al., 2017).

- Usage Statistics

Application Rates:

In regions where waste water treatment is prevalent, the application rates of solid fractions as fertilisers are increasing. For instance, the solid fraction from waste water is increasingly used in agricultural practices due to its nutrient density and lower pathogen levels compared to manure, which can pose health risks (Camilleri-Rumbau et al., 2021).

Regulatory Compliance:

Waste water digestates often meet stricter regulatory standards for contaminants and pathogens, making them safer for agricultural use. This compliance leads to higher acceptance and utilisation rates in agricultural applications compared to manure, which may require more treatment to meet safety standards (Beggio et al., 2021).

- Environmental Impact

Waste Management Efficiency:

The solid fraction from waste water treatment plants contributes to effective waste management strategies by recycling nutrients that would otherwise contribute to pollution. This contrasts with manure and food waste, which may not be processed as efficiently, leading to higher environmental risks (Akhiar et al., 2015) (Camilleri-Rumbau et al., 2021).

Nutrient Recovery:

The solid fraction from waste water allows for better nutrient recovery processes, enhancing its significance in sustainable agriculture. The ability to recover nutrients efficiently from waste water digestate can lead to reduced reliance on synthetic fertilisers, promoting a circular economy (Akhiar et al., 2017).

In summary, the solid fraction of digestate from waste water is statistically significant due to its superior nutrient profile, higher application rates in agriculture, regulatory compliance, and environmental benefits compared to those derived from manure or food waste. These factors contribute to its increased importance in sustainable agricultural practices and waste management strategies.

The solid fraction of digestate from urban waste water treatment plants has the following key characteristics:

It is rich in total solids (TS), organic matter, and still contains significant amounts of mineral nitrogen (3.6 to 12.9 mg N-NH4+/g TS) (Lu et al., 2021). Digestate can be separated into solid and liquid fractions to overcome transport constraints and facilitate handling. The solid fraction can be used as a soil improver. Mechanical separation reduces the total solids (TS) content by about 50% and decreases the phosphorus (P) content from 0.78-1.67 g/kg to 0.21-0.67 g/kg (Lyons et al., 2021). The solid fraction of digestate can be proposed as an NP-organic fertiliser due to its nutrient content and low heavy metal levels (Galamini et al., 2023).

In summary, the solid fraction of digestate from urban waste water treatment plants is a valuable resource that can be used as a soil improver, growing media substrate, or organic fertiliser after appropriate processing and blending with other materials to balance its nutrient profile. Key technical parameters are summarised in **Table 11**.

Table 11: Technical parameters of solid fraction of digestate (Source: FER-PLAY project database).

Technical parameter	Characteristics & values	Observations
N-P-K Balance	12-30:4-35:1-50	Very high variation in nutrients content depending on the feedstock and the processing techniques
Raw material availability	180 M tonnes/year	

Technical parameter	Characteristics & values	Observations
storage ease	Storage capacity between 6-9 months. Solid digestate is generally stored in covered, flat concrete areas or inside buildings. The storage must limit leachate and water pollution, and specific equipment might be made mandatory by the regulation (waterproof liners, leakage sensors, etc.). Stricter requirements are applied to digestate from ABP feedstock, especially concerning the protection of people and farm animals.	
Applicability in organic farming	Yes, if ingredients of the substrate do not originate from industrial livestock farming	With restrictions in some regions and areas if originated from waste waters
Considered as fertiliser in the European regulatory framework?	Yes, if EU Regulation for fertilising products 2019/1009 is met	
C/N Ratio		Should be declared as it is one of the most important indicators of organic fertilisers quality. The C/N ratio of 10:1 to 15:1 is considered optimal
Application form	Paste/pellet	
Application conformity	Commonly spread using muck spreaders or solid manure spreaders	It is recommended to be in the form of pellets or micro pellets
Nutrients leaching	Limited	N/A
Nutrient Availability and Release (Uptake speed)	slow release	N/A

2.5.2 Morphology and recommendations

According to the FER-PLAY database: The solid fraction of digestate has the following characteristics:

Moisture content (MC) of 15-25% and ash content of 5.23% for the pure solid fraction of digestate. The solid fraction can be blended with other materials like grain straw and sawdust to produce pellets with varying properties. For example, Blend 1 (66.7% DSF, 33.3% grain straw) has a MC of 23.96% and higher heating value (HHV) of 21,774 kJ/kg DM (Czekała, 2021). The particle size and shape are crucial factors that might affect the efficiency of SFD as a fertiliser. Micro pelletising might be a satisfactory solution for problems that might occurred with application into soil. So, pelletising of SFD is a recommendation for many advantages of application, transportation, and slow-release activities.

2.5.3 Solid fraction of digestate benchmarking

The effectiveness of the solid fraction of digestate compared to other types of fertilisers is notable due to its unique characteristics and benefits. The solid fraction of digestate, rich in essential nutrients like nitrogen, phosphorus, potassium, and trace elements, offers a balanced and diverse nutrient profile that supports steady plant growth and improves overall soil health. Digestates can be a beneficial alternative to mineral fertilisers, especially for heavier soils with high clay and carbon content, while manure or slurry from livestock may be more suitable for lighter, sandier soils with fewer organic carbon elements. Additionally, compost produced through aerobic microorganisms can be an alternative to digestates for soil enrichment and crop growth. Livestock slurry is another alternative that works effectively in certain soil types, providing nutrients for plant growth. These alternatives offer farmers a range of options to enhance soil fertility and crop productivity while managing nutrient inputs effectively.

- Digestates are richer in nitrogen (N) compared to other organic fertilisers like manure. Digestates can contain 4-5 kg of readily available N per tonne, compared to lower N content in raw manure. digestate contains a significant proportion of readily available ammonium-N and inorganic P, which can provide valuable nutrients for plant growth, but the nutrient ratios may need to be balanced through supplementation when using digestate as a fertiliser. The potassium (K) in digestate is primarily in inorganic, water-soluble forms that are readily available for plant uptake. The digestate can have different forms of P and K depending on the feedstock and the anaerobic digester system used. For example, digestates from fibrous feedstocks tend to have higher organic P fractions, while those from liquid manure tend to have higher inorganic P fractions. Labile P: Includes inorganic and organic P forms extracted by water and sodium bicarbonate ($NaHCO_3$). This fraction is available for plant uptake.

- Organic P: Includes forms extracted by sodium hydroxide (NaOH), such as phytate and other phosphates esters. This fraction can be mineralized to become available for plants.
- Inorganic P: Includes forms extracted by hydrochloric acid (HCl), which are sparingly soluble and less available for plants
- The form of potassium in digestate is typically expressed as potassium oxide (K_2O), which is a measure of the total potassium content.

These figures reflect that SFD provides a more balanced nutrient profile compared to some mineral fertilisers.

The N:P:K ratio in SFD is often more aligned with crop nutrient requirements than raw manure, reducing the risk of nutrient imbalances when applied (Nutrient Management and Nutrient Recovery Thematic Network. RECOVERED FERTILISER Fact Sheet (n.d)). SFD has a higher proportion of mineralised, plant-available nutrients compared to raw manure, making it more efficient as a fertiliser. For example, a pelletised digestate product from a mixture of pig manure, poultry manure, and straw had an N-P-K ratio of 10-4-4 (Nutriman (n.d). This balanced ratio is more suitable for many crops compared to raw manure, which often has an excess of phosphorus relative to nitrogen and potassium. By applying SFD with a more favourable N:P:K ratio, the risk of nutrient imbalances and potential environmental impacts (e.g., phosphorus accumulation in soils, nitrate leaching) can be reduced. This makes SFD a more sustainable fertiliser option compared to raw manure in many cases.

However, the exact nutrient content of SFD can vary widely depending on the feedstock and processing, so testing and analysis is important to understand the specific nutrient profile (Risberg et al., 2017).

SFD offers a more concentrated and balanced source of essential plant nutrients compared to raw manure or some mineral fertilisers, making them a valuable alternative fertiliser option for farmers. The readily available nutrient content is a key advantage of using digestates.

Research indicates that the solid fraction of digestate has a stronger impact on improving soil fertility compared to chemical fertilisers. Studies have shown that the application of digestate can lead to increased plant growth, improved soil microbial biomass, enhanced soil organic carbon levels, and better soil physical and chemical characteristics such as water-holding capacity and enzyme activities (Tambone et al., 2017) (Kovačić et al., 2022). (Czekała, 2022).

Additionally, digestate's slow-release nature minimises nutrient run-off, reducing the risk of water pollution and environmental harm associated with traditional fertilisers. Moreover, the solid fraction of digestate contributes to a circular economy approach by closing the nutrient loop through its application back to the land. By returning valuable nutrients to the soil, digestate promotes resource recovery and sustainability while reducing the need for separate fertilisers and soil amendments, leading to cost savings in agricultural practices. This sustainable approach not only improves agricultural productivity but also supports climate adaptation by enhancing soil health and crop resilience against environmental stresses like droughts, floods, and temperature extremes.

2.5.4 Combinations with non-renewable fertilisers and circular fertilisers

Unlike chemical fertilisers that may have a limited nutrient range, digestate provides a comprehensive nutrient package that enhances crop productivity and soil fertility. The effectiveness of digestate can be further enhanced when applied with K-struvite or split fertilisation methods. The combination of K-struvite with digestate can enhance the nutrient retention and release properties of the soil, leading to improved crop productivity. The use of K-struvite in combination with digestate can lead to a more efficient use of nutrients, reducing the environmental impact of agriculture while improving crop yields.

Split fertilization methods, which involve applying fertilisers at different stages of plant growth, can also enhance the effectiveness of digestate. By applying fertilisers at critical stages of plant growth, farmers can ensure that nutrients are available when they are needed most, leading to improved crop productivity, and reduced environmental impact. Therefore, to maximise the effectiveness of the solid fraction of digestate compared to commercial fertilisers, it is essential to apply it properly in a sustainable manner. This includes considering factors such as nutrient content, organic matter levels, application rates, timing, and potential synergies with other soil amendments or fertilisers. By adopting appropriate application methods tailored to specific agricultural needs, digestate can offer a cost-effective and environmentally friendly solution for improving soil health and crop productivity. The solid fraction of digestate, when applied correctly, can enhance soil health, crop productivity, and environmental sustainability. Studies have shown that digestate, as a nutrient-rich soil amendment, offers a balanced and diverse nutrient profile, including essential elements like nitrogen, phosphorus, potassium, and trace elements. Additionally, digestate contains significant amounts of organic matter that enhance soil structure, water retention, and drainage, promoting root growth and microbial activity for a healthier soil ecosystem.

The solid fraction can be used as a container media substrate to partially replace peat in growing media. Mixing digestate with peat strongly ameliorates chemical characteristics and balances bioavailable plant nutrients.

There are several benefits to mixing digestate with other materials such as:

1. **Improving handling and application:**

   Mixing digestate with drier materials like straw can reduce its moisture content, making it easier to handle, store, and apply to fields as a fertiliser. The blended material is less bulky and can be more evenly distributed.

Improved nutrient balance:

Mixing digestate with K-struvite could enhance the nutrient balance and provide a complete fertiliser and soil improver.

Enhanced soil conditioning:

Digestate contains organic matter that can improve soil quality over time when used as a fertiliser. Mixing digestate with other amendments rich in recalcitrant carbon, such as compost of food and green wastes, may further improve soil nutrients and health.

In summary, mixing digestate with other organic materials like straw, sawdust, or K-struvite can enhance its nutrient profile, soil conditioning properties, decomposition rates, and overall agronomic value when used as a fertiliser. The blended material is also easier to handle and apply to fields.

2.5.5 Concerns

Although further work is required to evaluate in detail the impact of digestate and treatments such as pre and post pasteurisation, which further sanitise the digestate, research indicates that digestion plants have the capacity to minimise the risk of any pathogens. The Nitrates Directive places strict limits and requirements on the application of digestates from manure to prevent water pollution from nitrates, with some flexibility for Member States to set higher limits under certain conditions.

Application maximum dose is 2-4 t/ha which could be exceptionally low for organic farming systems that depend only on organic fertilisers as a source for crop requirements (Redhead et al., 2020).

2.5.6 Existing machinery compatibility and precision fertilization techniques

If after composting, SFD still has a high-water content and is not solid enough to be used with normal solid manure spreader, muck spreaders could be the optimal option for application. Some attention should be given to the SFD when it is in the paste form and some research was done to change this form to a more applicable and easy handling form by transforming it into pellets

(Czekała, 2022). SFD is ideal fertiliser in precision farming systems due to its slow-release properties in addition to farming practices like split fertilisation it could be the optimal solution to some fertilisation problems such as nutrients runoff and leaching.

2.6 Spent mushroom substrate

2.6.1 Introduction

Spent mushroom substrate (SMS), also referred to as spent mushroom compost, is a by-product of mushroom cultivation. It is a mixture of *Agaricus Bisporus* mushroom substrate (horse manure, straw, chicken manure, gypsum, and water) and casing soil. The casing soil is composed of peat and lime, which helps to maintain optimal moisture levels for mushroom growth (Spent mushroom compost generated by mushroom production NUTRIMAN, n.d). After the mushroom cultivation process, the mushroom substrate and casing soil are directly loaded onto trucks and ready for disposal. Mixing SMS with chalk makes it very alkaline. It is made weed and disease-free by heating it to 70°C, which conforms to EU Regulation [EC] 1069/2009 and French NFU standard 44051. The moisture content of SMS can be brought back to around 20-30% to make it suitable for use in potted plants or as a biofuel (Our champost – Van Asseldonk Champignons, n.d). SMS is an easy-to-process soil improver that can increase the humus content in the soil. This helps to improve soil structure, water retention, and biodiversity. It can be used in arable farming, vegetable farms, fruit farms, and grasslands. SMS is a nutrient-rich fertiliser that can provide essential nutrients to plants. It can be used to improve soil fertility and support plant growth and it could be a good alternative for organic or non-renewable high fertilisers prices (Flanders Research Institute for Agriculture, Fisheries and Food - *ILVO Vlaanderen*, 2023). SMS contains beneficial microorganisms that can enhance microbial activity in the soil. This helps to improve soil health and support plant growth. it can be used to adjust the pH of the soil. The alkaline nature of SMS makes it suitable for use in acidic soils (Adeoluwa et al., 2011). In summary, SMS is a rich source of nutrients and can be added to soil directly or after composting because it contains little to no xenobiotic compounds and heavy metals. SMS characteristics are influenced by the type of mushroom, the cultivation method, and the raw materials used in the original substrate. As a result, using SMS as a soil conditioner or fertiliser has a variety of effects on crop growth and yield. It is noteworthy, though, that the species of the mushroom and the composition of the SMS are frequently omitted from relevant publications, which makes it challenging to make informed judgments regarding the mushroom's potential for exploitation. Improvements in soil fertility and structure were shown by the results, and these developments either enhanced crop productivity or helped restore degraded farmlands (Manici et al., 2013). Table 7 summarizes the technical parameters for SMS.

2.6.2 Morphology and recommendations

Table 12: Technical parameters of SMS (Source: FER-PLAY database project).

Technical parameter	Characteristics & values	Observations
N-P-K Balance	1.17: 0.59: 2.33 On dry matter bases	It considered a soil improver and a source of humus
Raw material availability	5384 tonnes/year	It seems low quantity in terms of industrial scale
storage ease	Solid	
Applicability in organic farming	Yes, organic SMS label possible	If ingredients of the substrate do not originate from industrial livestock farming
European regulatory framework?	Considered as animal manure	N/A
C/N Ratio	The ideal C/N ratio for good SMS is typically between 10:1 and 15:1. This range indicates that the SMS has undergone sufficient decomposition and stabilisation	Data missing in the FER-PLAY database
Application form	Solid	N/A
Application conformity	Compatible with standard manure spreaders	N/A
Nutrients leaching	N/A	more research is needed
Nutrient Availability and Release (Uptake speed)	Slow release	N/A

2.6.3 Possible combinations

SMS could be mixed with the following substrates and fertilisers to form a good mixture that needs further research in terms of effectiveness and marketing competitivity:

- Combinations of SMS with non-renewable fertilisers:

  SMS + Chemical Fertilisers: Studies have shown that combining composted SMS with chemical fertilisers can significantly improve soil nutrient availability and plant growth. The

SMS helps enhance nutrient cycling and promotes sustainable nutrient management in crops like apples, cauliflower, and grasslands (Raymond et al., 2021).

SMS + NPK Fertiliser: Applying a combination of SMS and NPK fertiliser has been effective in remediating crude oil-contaminated soils. The SMS helps bio-stimulate microbial activity and enhance the degradation of petroleum hydrocarbons (Chen et al., 2022).

- Combinations of SMS with organic fertilisers:

SMS + composted Animal Manure: Mixing SMS with composted animal manures, such as poultry waste, can create an effective organic fertiliser alternative to replace inorganic fertilisers in intensive vegetable production systems.

SMS + poultry waste compost: The combined application of SMS-derived from poultry waste and poultry waste compost has been shown to improve the growth and yield of crops like honeydew melon and onions.

SMS + cattle Manure (CM): Co-composting SMS with cattle manure, as well as other organic wastes like carnation and garden waste, can enhance compost quality and reduce greenhouse gas emissions during the composting process.

SMS + Bamboo Biochar: Incorporating bamboo biochar along with SMS and layer manure during co-composting can help conserve nitrogen and improve compost quality for soil amendment (Chen et al., 2022).

In summary, SMS can be effectively combined with non-renewable chemical fertilisers and various organic fertilisers and amendments to improve soil fertility, plant growth, and environmental sustainability. The specific combinations depend on the crop, soil conditions, and desired outcomes.

- Combinations with other circular and Non-renewable fertilisers

Feather meal is a concentrated organic nitrogen source that can be combined with SMS to provide balanced nutrition.

Other organic fertilisers like bone meal, kelp meal, and rock phosphate can be used in combination with SMS to create a more complete fertiliser system (Kwiatkowski et al., 2021).

Non-renewable fertilisers like urea, ammonium sulphate, and superphosphate can also be used in conjunction with SMS to leverage their different nutrient release characteristics (Kwiatkowski et al., 2021).

SMS may not provide phosphorus levels comparable to other organic fertilisers or commercial options, potentially limiting its effectiveness for crops with high phosphorus requirements which makes a combination of SMS and struvite a viable choice for such crops (Nuresys internal data).

2.6.4 Spent mushroom substrate benchmarking

Organic Matter and Nutrient Content:

- SMS contains beneficial microorganisms that can enhance microbial activity and improve soil health (OSU Extension Service, Kym Pokorny, 2023).
- The C:N ratio in aged SMS is higher compared to fresh SMS, indicating increased organic matter content over time (OSU Extension Service, Kym Pokorny, 2023).
- Organic fertilisers like SMS typically contain a wider range of nutrients compared to non-renewable fertilisers (Kwiatkowski et al., 2021).

pH Adjustment:

- The alkaline nature of SMS makes it suitable for use in acidic soils to adjust the pH to a more optimal range for plant growth (OSU Extension Service, Kym Pokorny, 2023).

Nutrient Availability:

- Organic fertilisers like SMS release nutrients more slowly as they need to be converted by soil microbes, unlike the more readily available nutrients in non-renewable fertilisers (Kwiatkowski et al., 2021).
- This slower nutrient release can be beneficial for long-term plant nutrition and reducing nutrient losses (Kwiatkowski et al., 2021).

Soil Improvement:

- Spent mushroom substrate, as an organic amendment, can improve soil structure, water movement, and overall soil health over time, unlike some non-renewable fertilisers.

In summary, SMS can be benchmarked as a beneficial organic soil amendment that improves soil health and provides balanced, slow-release nutrition. Its alkaline nature also makes it suitable for use in acidic soils. SMS can be effectively combined with other organic and non-renewable fertilisers to create customised, synergistic fertiliser solutions.

2.6.5 Drawbacks of SMS Compared to Competitive Fertilisers:

- Developing efficient processes for pressing the moisture out of SMS while minimising energy and treatment costs is crucial for its widespread adoption (Samagro, Products - CHAMPOST BIO, n.d).
- Market Demand: Encouraging the use of SMS as a fertiliser and ensuring that the humus content in the soil is restored are important steps towards creating a healthier and more sustainable environment (Kwiatkowski et al., 2021).
- The nitrogen mineralization potential of SMS may differ from other organic fertilisers like compost, affecting the timing and availability of nitrogen for plant uptake (Spent mushroom compost generated by mushroom production NUTRIMAN, n.d)
- Elevated levels of salts in the soil from SMS application can lead to nutrient deficiencies in and salt intolerance symptoms for susceptible crops (Samagro, Products - CHAMPOST BIO, n.d).
- Spent mushroom substrate may pose a risk of nitrogen loss through volatilisation compared to farmyard manure and compost, potentially impacting nutrient availability for plants (Spent mushroom compost generated by mushroom production NUTRIMAN, n.d)
- The alkaline effect of SMS may affect its use in large areas of alkaline soil in southern Europe and Mediterranean region.
- Should be taken its salt index and alkaline effect when mixing with other chemical fertilisers.

When comparing SMS to compost and other organic fertilisers, the physical handling and integration of SMS into the soil during agricultural practices might be of great concern and depends on various aspects:

- Soil Health Impact:

  The impact of SMS on soil health and microbial activity may vary compared to other organic fertilisers, potentially influencing overall soil quality and plant growth differently (Flanders Research Institute for Agriculture, Fisheries and Food - *ILVO Vlaanderen*, 2023).

- Physical Characteristics:

  Spent mushroom substrate, being derived from mushroom cultivation by-products, may have a different texture, moisture content, or composition compared to compost and other organic fertilisers. These differences can affect how easily SMS mixes with the soil when hoeing.

- Ease of Application:

  Spent mushroom substrate's specific properties may make it less uniform or clumpier compost, which can impact its distribution in the soil when hoeing. Uneven distribution can lead to inconsistent nutrient availability for plants. In some regions of Spain, SMS is also sold as pellets. It was not included in the LCA because we did not find information of this process being applied in other region, and because of its high energy consumption.

- Efficiency Concerns:

  The challenge in incorporating SMS into the soil when hoeing can affect its overall efficiency in providing nutrients to plants. Uneven distribution or incomplete mixing may result in localized nutrient availability, potentially impacting plant growth.

- Soil Structure Impact:

  Difficulties in incorporating SMS effectively can also influence soil structure. Inadequate mixing may lead to soil compaction or poor aeration, affecting root development and nutrient uptake by plants.

- Application Techniques:

  Farmers may need to adjust their application techniques when using SMS to ensure thorough incorporation into the soil. This could involve additional equipment or methods to achieve proper mixing and distribution.

- Overall Agricultural Practice:

  The ease of application and efficiency of SMS compared to compost and other organic fertilisers can influence farmers' decisions on which fertiliser to use based on their specific farming practices, equipment availability, and desired outcomes for crop production.

In summary, the challenge of incorporating SMS into the soil when hoeing highlights the importance of considering not just the nutrient content but also the physical characteristics and application methods of different organic fertilisers for optimal agricultural practices and crop yield.

To overcome the challenge of incorporating SMS into the soil when hoeing, several strategies can be implemented based on the information provided in the sources:

- Loosening the Soil: by loosening the top few inches of soil to create a more receptive environment for incorporating SMS effectively (Straatsma G., 2014).

- Superficial Application: SMS incorporation into the soil superficially, especially in orchards where soil organic matter content is typically low, to improve soil fertility and structure (Flanders Research Institute for Agriculture, Fisheries and Food - *ILVO Vlaanderen*, 2023).

- Consider Nitrogen Effect: When using SMS for basic fertilisation during cultivation, it is essential to consider its nitrogen effect and adjust application rates accordingly to limit nitrogen losses and ensure optimal nutrient availability for plants (Straatsma G., 2014).
- Integrate Crop and Animal Production: One comprehensive measure suggested is to integrate plant and animal production, optimising nutrient cycling and increasing soil fertility. This integration can enhance self-sufficiency in nitrogen and organic matter, reducing dependence on external fertilisers.
- Reduce Tillage: Implement reduced tillage practices to preserve overall soil quality, conserve plant nutrients, and promote better incorporation of SMS into the soil. Reduced tillage can also lead to energy savings during field work and improved soil moisture retention.

By following these strategies, farmers can effectively address the challenge of incorporating SMS into the soil when hoeing, ensuring proper nutrient distribution, improved soil health, and enhanced crop productivity.

2.6.6 Existing machinery compatibility and precision agriculture

If SMS has the proper water content will be No problems when applying SMS with the organic fertiliser existing machinery since it has the same physical characteristics as compost. However, some problems like less uniform or more clumpy SMS quiet expressed by farmers and technicians and a certain machines piece should be used to overcome these problems or some other substrates should be mixed with the SMS to adjust its physical texture making it compatible with the existing machinery and more evenly distributed in the field.

The recommendations for applying SMS to soil include spreading it over the surface without mixing it in, especially in soils with good texture, to avoid disturbing delicate mycorrhizal fungi that help plants access nutrients. Over time, natural processes like rain and earthworm activity will incorporate the SMS into the soil. (Lakaria et al., 2019)

Additionally, for making potting soil, a mixture of 1 kg SMS with 1 kg each peat, perlite, and topsoil is suggested. It is advised not to use more than 3 inches of SMS in vegetable gardens unless yard waste from the previous season has been incorporated. Ornamental beds generally require less SMS, while a fall cover crop of 1-3 inches can protect plant roots and retain moisture.

In general, the following are the most common application methods of SMS:

SMS can be applied in various ways depending on the specific needs and conditions of the soil. Here are some common methods:

- Bulk Delivery: SMS can be delivered in bulk using dump trucks or walking floors. This method is suitable for large-scale applications, such as agricultural fields or urban gardens.
- Spreading: SMS can be spread evenly over the soil to ensure uniform application and optimal nutrient availability. This method is suitable for smaller areas, such as flower beds or vegetable gardens.
- Mixing with Soil: SMS can be mixed with the top six to nine inches of soil to improve soil structure and health. This method is suitable for areas where the soil needs to be improved for plant growth.
- Mulching: SMS can be used as a mulch to retain moisture and suppress weeds. This method is suitable for areas where the soil needs to be protected from erosion and where weeds are a problem.
- Potting Mix: SMS can be used as a component in potting mixes to improve soil structure and nutrient availability. This method is suitable for indoor plants or container gardens.
- Tree Beds: SMS can be used to improve soil structure and health in tree beds. This method is suitable for areas where trees are planted and need to be supported.
- Window Boxes: SMS can be used to improve soil structure and health in window boxes. This method is suitable for areas where plants are grown in containers.
- Container Gardens: SMS can be used to improve soil structure and health in container gardens. This method is suitable for areas where plants are grown in containers.
- Lawn Care: SMS can be used to improve soil structure and health in lawns. This method is suitable for areas where the lawn needs to be improved for grass growth.
- Garden Beds: SMS can be used to improve soil structure and health in garden beds. This method is suitable for areas where vegetables, fruits, or flowers are grown.

These methods ensure that SMS is applied effectively to improve soil structure, health, and nutrient availability, ultimately supporting plant growth and development.

2.7 References

Adeoluwa, O. O., & Adeogun, O. O. (2011). Evaluation of the potential of feather meal as organic fertilizer in production of Amaranthus caudatus.

Agrolead. (n.d.). Matador Rear-Delivery Compost Spreader. Retrieved from https://agrolead.com/product/matador-rear-delivery-compost-spreader

Akhiar, A., Battimelli, A., Torrijos, M., & Carrere, H. (2017). Comprehensive characterization of the liquid fraction of digestates from full-scale anaerobic co-digestion. Waste management, 59, 118-128.

Akhiar, A., Torrijos, M., Battimelli, A., & Carrère, H. (2015). Characterisation of the liquid fraction of digestate after solid-liquid separation. In 2015; 14. World Congress on Anaerobic Digestion (AD14), Viña del Mar, CHL, 2015-11-15-2015-11-18,.

Amery, F., Vandaele, E., Körner, I., Loades, K., Viaene, J., Vandecasteele, B., & Willekens, K. (2020). Compost quality indicators. SoilCom. Aarslev, Denmark; Report, (5.1).

Antille, D. L., & Godwin, R. J. (2013). Determining the particle size range of organomineral fertilisers based on the spreading characteristics of the material. In 2013 Kansas City, Missouri, July 21-July 24, 2013 (p. 1). American Society of Agricultural and Biological Engineers.

Beggio, G., Peng, W., Lü, F., Cerasaro, A., Bonato, T., & Pivato, A. (2021). Chemically enhanced solid–liquid separation of digestate: suspended solids removal and effects on environmental quality of separated fractions. Waste and Biomass Valorization, 1-13.

Bio-Stru For Agriculture. (2022) https://bio-stru.com/bio-stru-for-agriculture/

Bruno, E. M., Goodrich, B., & Sexton, R. J. (2021). The outlook for California's almond market. Calif. Almond Acreage Rep, 24, 9-11.

Camilleri-Rumbau, M. S., Briceño, K., Fjerbæk Søtoft, L., Christensen, K. V., Roda-Serrat, M. C., Errico, M., & Norddahl, B. (2021). Treatment of manure and digestate liquid fractions using membranes: opportunities and challenges. International Journal of Environmental Research and Public Health, 18(6), 3107.

Chen, L., Zhou, W., Luo, L., Li, Y., Chen, Z., Gu, Y., & Deng, L. (2022). Short-term responses of soil nutrients, heavy metals and microbial community to partial substitution of chemical fertilizer with spent mushroom substrates (SMS). Science of the Total Environment, 844, 157064.

Chojnacka, K., & Moustakas, K. (2024). Anaerobic digestate management for carbon neutrality and fertilizer use: A review of current practices and future opportunities. Biomass and Bioenergy, 180, 106991.

Cultivers. (n.d.). Harina de pluma. Retrieved from https://cultivers.es/abonos/harina-de-pluma/

Czekała, W. (2021). Solid fraction of digestate from biogas plant as a material for pellets production. Energies, 14(16), 5034.

Czekała, W. (2022). Digestate as a source of nutrients: nitrogen and its fractions. Water, 14(24), 4067.

Dereszewska, A., & Cytawa, S. (2021). A proposal of low-cost technology for nutrient recovery from leachate of anaerobic digester at a biological wastewater treatment plant. In IOP Conference Series: Earth and Environmental Science (Vol. 642, No. 1, p. 012012). IOP Publishing.

Dias, N., Bandara, M. A. C. S., Munaweerage, T. P., & Shantha, W. H. A. (2022).COMMERCIAL ORGANIC FERTILIZER PRODUCTION.Ozturk, Munir, et al., eds. Introduction and application of organic fertilizers as protectors of our environment. Cambridge Scholars Publishing, 2022.

Diaz-Perez, Juan Carlos, et al. "Detrimental effects of blood meal and feather meal on tomato (Solanum lycopersicon L.) seed germination." HortScience 52.1 (2017): 138-141.

El Boushy, A. R., Van der Poel, A. F. B., & Walraven, O. E. D. (1990). Feather meal—A biological waste: Its processing and utilization as a feedstuff for poultry. Biological Wastes, 32(1), 39-74.

Epic Gardening. (n.d.). Feather meal: A high-nitrogen organic fertilizer. Retrieved from https://www.epicgardening.com/feather-meal/

Erdal, İ., Mejri, R., Yaylacı, C., & Türkan, Ş. A. (2023). Comparison of the effectiveness of struvite and some commercial fertilizers on the growth of lettuce. Bahçe, 52(2), 95-102.

Flanders Research Institute for Agriculture, Fisheries and Food - ILVO Vlaanderen, (2023). https://ilvo.vlaanderen.be/en/news/how-can-we-nourish-the-soil-under-strict-phosphate-norms-and-high-fertilizer-prices

Galamini, G., Ferretti, G., Rosinger, C., Huber, S., Medoro, V., Mentler, A., ... & Keiblinger, K. M. (2023). Recycling nitrogen from liquid digestate via novel reactive struvite and zeolite minerals to mitigate agricultural pollution. Chemosphere, 317, 137881.

Głodniok, M., Deska, M., & Kaszycki, P. (2021, May). Impact of the Stabilized Sewage Sludge-Based Granulated Fertilizer on Sinapis alba Growth and Biomass Chemical Characteristics. In Biology and Life Sciences Forum (Vol. 3, No. 1, p. 35). MDPI.

Gonzalez Ponce, R., & Lopez de Sa, M. E. G. (2007). Evaluation of struvite as a fertilizer: a comparison with traditional P sources.

Grow Abundant Gardens. (n.d.). Organic amendments user's guide. Retrieved from https://growabundant.com/organic-amendments-users-guide/

Gusiatin, M. Z., Kulikowska, D., & Bernat, K. (2024). Municipal Sewage Sludge as a Resource in the Circular Economy. Energies, 17(11), 2474.

Hardy, R. W., & Barrows, F. T. (2003). Diet formulation and manufacture. In J. E. Halver & R. W. Hardy (Eds.), Fish nutrition (pp. 505-600). Academic Press

Ikenganyia, E. E., Ndubuaku, U. M., Onyeonagu, C. C., & Ukonze, U. (2014). Influence of pelleted and unpelleted composted organic waste materials on growth, dry matter accumulation and yield of three varieties of cucumber (Cucumis sativus) in the greenhouse. American Journal of Experimental Agriculture, 6(3), 147-157.

Jovičić-Petrović, J., Mijačić, A., Lalević, B., Kljujev, I., Karličić, V., & Raičević, V. (2021). Stabilized sewage sludge-sanitary aspects and potential for conversion to biosolids. Acta Agriculturae Serbica, 26(52).

Kamizela, T., Lyng, K. A., Saxegård, S., Švédová, B., & Grobelak, A. (2021). Bionor sewage sludge technology–Biomass to fertiliser and soil addition. Journal of Cleaner Production, 319, 128655.

Kazmierczak, M. (2012). Sewage sludge stabilization indicators in aerobic digestion-a review. Annals of Warsaw University of Life Sciences-SGGW. Land Reclamation, 44(2).

Khalf, Y. S., & Mohammad, K. K. (2021, September). The effects of various types of phosphate fertilizers on the environment and their natural activity. In Journal of Physics: Conference Series (Vol. 1999, No. 1, p. 012046). IOP Publishing.

Kim, E., Lee, D. H., Won, S., & Ahn, H. (2016). Evaluation of optimum moisture content for composting of beef manure and bedding material mixtures using oxygen uptake measurement. Asian-Australasian journal of animal sciences, 29(5), 753.

Kovačić, Đ., Lončarić, Z., Jović, J., Samac, D., Popović, B., & Tišma, M. (2022). Digestate management and processing practices: a review. Applied Sciences, 12(18), 9216.

Kunkel, U., & Ternes, T. A. (2014). ROUTES “Novel processing routes for effective sewage sludge management Fate of emerging organic micropollutants in soils after the application of sewage sludge and/or the irrigation of treated wastewater. Factsheet, Koblenz.

Kwiatkowski, C. A., & Harasim, E. (2021). The effect of fertilization with spent mushroom substrate and traditional methods of fertilization of common thyme (Thymus vulgaris L.) on yield quality and antioxidant properties of herbal material. Agronomy, 11(2), 329.

Lakaria, B. L., Dotaniya, M. L., Meena, B. P., Wanjari, R. H., & Biswas, A. K. (2019). Soil health: Concept, components, management and opportunities. Advances in compost production technology, 95-103.

Latshaw, J. D. (1990). Quality of feather meal as affected by feather processing conditions. Poultry Science, 69(6), 953-958.

Lederer, J., & Rechberger, H. (2010). Comparative goal-oriented assessment of conventional and alternative sewage sludge treatment options. Waste Management, 30(6), 1043-1056.

Lim, S. M., He, L., Goh, S. H., & Lee, F. H. (2021). Strength of Chemically Stabilized Sewage Sludge—Some Inferences from Recent Studies. Geotechnics, 1(2), 573-587.

Lu, J., & Xu, S. (2021). Post-treatment of food waste digestate towards land application: A review. Journal of Cleaner Production, 303, 127033.

Lyons, G. A., Cathcart, A., Frost, J. P., Wills, M., Johnston, C., Ramsey, R., & Smyth, B. (2021). Review of two mechanical separation technologies for the sustainable management of agricultural phosphorus in nutrient-vulnerable zones. Agronomy, 11(5), 836.

Manici, L. M., Kelderer, M., Naef, A., Canet, R., Rühmer, T., Franke-Whittle, I., ... & Kaymak, S. (2013). Mid-term report for the CORE Organic II funded project."Innovative cropping Practices to increase soil health of organic fruit tree orchards" BIO-INCROP.

McNeilan, R. (2008, February 27). Here's the scoop on chemical and organic fertilizers. Oregon State University Extension Service. https://extension.oregonstate.edu/news/heres-scoop-chemical-organic-fertilizers

Naber, E. C., & Morgan, C. L. (1956). Feather meal and poultry meat scrap in chick starting rations. Poultry Science, 35(4), 888-895.

Nageshwari, K., & Balasubramanian, P. (2022). Evolution of struvite research and the way forward in resource recovery of phosphates through scientometric analysis. Journal of Cleaner Production, 357, 131737.

Nongqwenga, N., Muchaonyerwa, P., Hughes, J., Odindo, A., & Bame, I. (2017). Possible use of struvite as an alternative phosphate fertilizer. Journal of soil science and plant nutrition, 17(3), 581-593.

North Country Organics. (n.d.). Feather meal. Retrieved from https://norganics.com/index-12/index-11/fertilizers/feather-meal/

Novosel, B., Mislej, V., & Grilc, V. (2022). Basic Morphological, Thermal and Physicochemical Properties of Sewage Sludge for Its Sustainable Energy and Material Use in the Circular Economy. Recent Perspectives in Pyrolysis Research.

Nutrient Management and Nutrient Recovery Thematic Network. RECOVERED FERTILISER Fact Sheet (n.d): https://nutriman.net/sites/default/files/2021-08/264_INFO-SHEET-PRODUCT-liquid-and-dried-digestate_Agrogas.pdf project funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 818470

Nutriman (n.d): https://nutriman.net/farmer-platform/product/id_264

Ohio State University Extension (2016): https://ohioline.osu.edu/factsheet/fabe-5501

OSU Extension Service, Kym Pokorny, 2023 https://extension.oregonstate.edu/news/heres-scoop-chemical-organic-fertilizers

Our champost – Van Asseldonk Champignons. (n.d.). https://www.vanasseldonkchampignons.nl/en/our-champost/

Papadopoulos, M. C. (1985). Estimations of amino acid digestibility and availability in feedstuffs for poultry. World's Poultry Science Journal, 41(1), 64-71.

Peeva, G., Yemendzhiev, H., Koleva, R., & Nenov, V. (2021). Agrotechnical assessment of struvite application. Journal of Agricultural Chemistry and Environment, 10(2), 213-221.

Pérez-Piqueres, A., Ribó, M., Rodríguez-Carretero, I., Quiñones, A., & Canet, R. (2023). Struvite as a Sustainable Fertilizer in Mediterranean Soils. Agronomy, 13(5), 1391.

Rabaud. (n.d.). Compost spreader: FERTIDIS 3000. Retrieved from https://www.rabaud.com/en/materials/compost-spreader/compost-spreader-fertidis-3000

Raymond A., Ekemube, D., Dumkhana B., Beabu T., A., (2021). Combined Effects of Spent Mushroom Substrate (SMS) and NPK Fertilizer in the Remediation of Crude Oil Polluted Soil. International Journal of Academic Engineering Research (IJAER) ISSN: 2643-9085

Redhead, S., Nieuwland, J., Esteves, S., Lee, D. H., Kim, D. W., Mathias, J., ... & Hayhurst, E. (2020). Fate of antibiotic resistant E. coli and antibiotic resistance genes during full scale conventional and advanced anaerobic digestion of sewage sludge. PLoS One, 15(12), e0237283.

Risberg, K., Cederlund, H., Pell, M., Arthurson, V., & Schnürer, A. (2017). Comparative characterization of digestate versus pig slurry and cow manure–Chemical composition and effects on soil microbial activity. Waste management, 61, 529-538.

Rollett, A., et al. (2015). Guidance on suitable organic material applications for land restoration and improvement.

Routray, A., I. (n.d.). Feather meal: A sustainable solution for agricultural nutrient management. LinkedIn. Retrieved [Date], from https://www.linkedin.com/pulse/feather-meal-sustainable-solution-agricultural-nutrient-routray-4q3kf/Feedipedia. (2014). Cassava peels. Feedipedia, a programme by INRAE, CIRAD, AFZ and FAO. https://www.feedipedia.org/node/24893

Royal Horticultural Society. (n.d.). What are the alternatives to using peat-based compost? Retrieved from https://www.rhs.org.uk/science/gardening-in-a-changing-world/peat-use-in-gardens/peat-alternatives

Samagro, (n.d) https://www.samagro.com/en/products/compost/champost-bio-08-06-11-20-om/

Seibersdorfer. (n.d.). Feather meal. Retrieved from https://www.seibersdorfer.at/en/produkt/feather-meal/

Smith, R. (n.d.). Nitrogen fertility management in organic production. University of California Cooperative Extension. Retrieved August 13, 2024, from https://www.cdfa.ca.gov/is/docs/15-0522_Smith_FR.pdf

Spent mushroom compost generated by mushroom production (ID:1986) | NUTRIMAN. (n.d.). https://nutriman.net/farmer-platform/product/id_1986

Straatsma, G. (2014). Spent mushroom substrate, SMS;'livestock manure'according to the Nitrate Directive or compost? (No. 2006-12). Applied Plant Research.

Suciu, N. A., De Vivo, R., Rizzati, N., & Capri, E. (2022). Cd content in phosphate fertilizer: which potential risk for the environment and human health?. Current Opinion in Environmental Science & Health, 30, 100392.

Tambone, F., Orzi, V., D'Imporzano, G., & Adani, F. (2017). Solid and liquid fractionation of digestate: Mass balance, chemical characterization, and agronomic and environmental value. Bioresource Technology, 243, 1251-1256.

Toora, M. D., Javed, M. S., Malook, M. B., Sultan, Y., Ud Dine, M. M., & Aya, A. (2023). Exploring the role of vermicompost in mitigating environmental pollution: A review of its effects on soil contaminants and water quality. Journal of Soil Science and Plant Nutrition, 19(6), 9-16.

Valle, S. F., Giroto, A. S., Guimarães, G. G., Nagel, K. A., Galinski, A., Cohnen, J., ... & Ribeiro, C. (2022). Co-fertilization of sulfur and struvite-phosphorus in a slow-release fertilizer improves soybean cultivation. Frontiers in plant science, 13, 861574.

Vassileva, M., Mendes, G. D. O., Deriu, M. A., Benedetto, G. D., Flor-Peregrin, E., Mocali, S., ... & Vassilev, N. (2022). Fungi, P-solubilization, and plant nutrition. Microorganisms, 10(9), 1716.

Walt's Organic Fertilizer Co. (n.d.). Feather meal. Retrieved from https://waltsorganic.com/product/feather-meal/

Wei, S. P., van Rossum, F., van de Pol, G. J., & Winkler, M. K. H. (2018). Recovery of phosphorus and nitrogen from human urine by struvite precipitation, air stripping and acid scrubbing: A pilot study. Chemosphere, 212, 1030-1037.

Wiater, J. (2020). Changes in the C: N ratio in the sludge treated with natural methods. Journal of Ecological Engineering, 21(5), 240-245.

Wikipedia contributors. (n.d.). Feather meal. Wikipedia, The Free Encyclopedia. Retrieved August 13, 2024, from https://en.wikipedia.org/wiki/Feather_meal

WorldWideScience.org. (n.d.). Quality fertilizer vermicompost: Topics by WorldWideScience.org. Retrieved from https://worldwidescience.org/topicpages/q/quality%2Bfertilizer%2Bvermicompost.html

WRAP. (2016, March 17). Organics collection and reprocessing. WRAP. Retrieved from https://www.wrap.ngo/taking-action/collections-recycling/markets-materials/organics-collection-sorting-reprocessing

Yeh, R. H., Hsieh, C. W., & Chen, K. L. (2023). Two-stage fermented feather meal enhances growth performance and amino acid digestibility in broilers. Fermentation, 9(2), 128.

3 Results: Production technology benchmarking

3.1 Urban waste water struvite

3.1.1 Introduction

In the following study three of existing struvite recovery installations belonging to municipal waste water treatment plants (MWWTP) with their intrinsic flow and phosphate loads are analysed for the total costs per unit of recovered struvite. The selection of installations for analysis is based on the variability of their capacities in the range of 35 m³/h to 800 m³/h influent to struvite recovery installation. The phosphate load varies from 400 to 200 mg/L PO_4-P. In all cases, the feed to the struvite recovery installation is centrate from the dewatering of digestate. Furthermore, the data from the three installations is also simulated to calculate expected costs for all three regions of Europe. **Table 13** shows the flow and concentration characteristics of the three case studies.

Table 13: Case study UWW struvite installations and their characteristics.

	Case 1 (C1)	Case 2 (C2)	Case 3 (C3)
Flow (m³/h)	35	75	800
Mass of PO_4-P converted into struvite (kg/day)	265	360	3,600
Struvite (kg/m³)	2.5	1.6	1.4

Consideration for operational costs

Unit prices for chemicals and electricity is adopted from the life cycle inventories prepared in the project. For operational costs, only chemical and electricity cost are taken into account as these are the most significant contributors. These unit costs are the average for the countries with a region and thus do not necessarily equal to the exact costs of utilities for the three selected installations. Also, it is important to note that the unit processes for all the installations are not exactly the same and thus the overall electrical consumption differs. However, the primary technology is precisely the same in all and thus the quality of the produced struvite.

Considerations for the capital costs

Capital cost per tonne of struvite is calculated with the same interest rate and life span as in the life cycle costing for the value chain of struvite from urban waste water. The total capital cost takes into account the administrative, maintenance and end of life costs.

Cost calculations do not take into account the generated revenue from struvite sales or from savings in maintenance costs.

3.1.2 Results and discussions

The capital cost per tonne of struvite is the lowest for C3 with the highest mass load of phosphates, while 1.40 times higher for C2 and 1.50 times higher for C1. Even though C2 is twice the capacity of C1 in terms of flow, the difference in capital cost per tonne of struvite is almost negligible due to similar mass load of PO_4-P. Hence, cases with a higher mass load of PO_4-P have more positive return on investment.

In all cost categories: capital and operational, the largest share for all cases in all three regions are the chemical costs for struvite precipitation process and are in the range of 170 to 430 € per tonne of recovered struvite (/tS).

As shown by **Figure 1**, the lowest cost is observed for the simulated northern region of C1 with the most concentrated PO_4-P flow and north among other regions having the lowest chemical unit prices. The most chemical costs are observed for simulated central C3, where central region of EU with the highest chemical unit costs and C3 having the most PO_4-P mass load.

First figure shows the operational costs, and the second figure shows the overall costs. Cost values are not shown due to corporate confidentially purpose.

Overall, the total operational costs (chemical and energy) are the highest for C3, followed by C2 and C1 in all regions and among EU regions peak for the central region of EU. The difference is the operational costs between C1 and C2 for all regions is in the range 13 - 34 €/tS and the difference in the operational costs between C2 and C2 for all regions is in the range of 26 – 41 €/tS.

C1 and C2 installations originated from the central region of the Europe, and thus the trend reflects that a similar sized installation would have less operational costs in Mediterranean or northern Europe solely due to cheaper provision of chemicals.

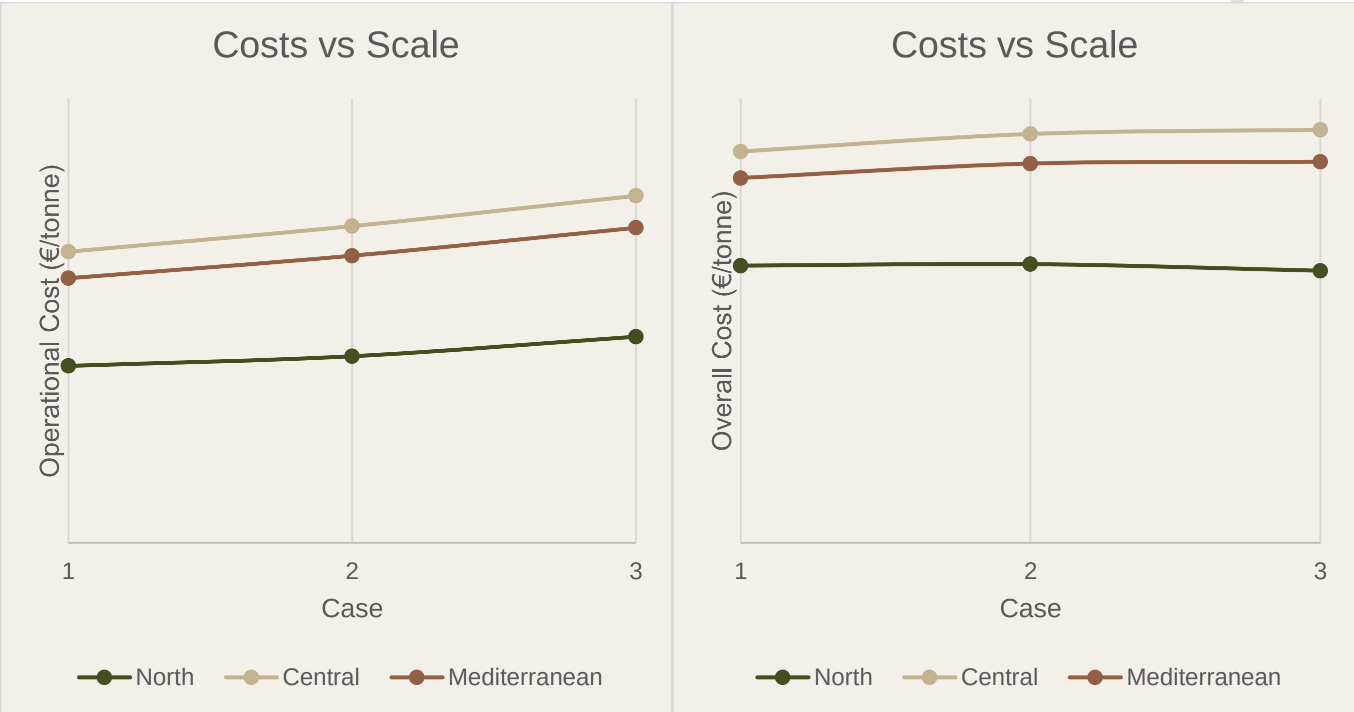

Figure 1. Operational and overall costs for the three struvite UWW installations in the three EU regions.

When the trend for total costs for the three cases in the three EU regions is examined, the overall conclusion is similar to operational costs: central Europe has the highest costs and northern region has the lowest. However, the trend in increase of costs between cases for a region changes. Within the northern region, C3 has the lowest cost compared to C1 and C2. The total cost per tonne of struvite is approximately the same for C1 and C2, and C3 is lower by 9 €/tS. Within central and Mediterranean regions, the difference in total costs between C1 and C2 is in the range of 20 - 24 €/tS which is reduced to 2 - 6 €/tS between C2 and C3. This reflects that with increasing size the cost per unit product is becoming stable as the difference is declining and even gets lower for the largest capacity as observed for northern Europe.

In order to see the effect of higher input PO_4-P concentration, simulation of total costs is conducted assuming the concentration of 400 mg/l PO_4-P as for C1 used for C2 and C3 as exhibited by **Figure 2**. The capital costs have reduced by the factor of 1.1 to 1.9 times lower, the lowest cost is observed for C3 reduced up to 46 €/tS. In line with the existing situation, the most dominating cost category is the total chemical costs, however reduced to the range of 165 – 393 euro per tonne of recovered struvite. Generally, the overall costs have reduced, the difference is the most prominent for C2 and C3 with an average reduction of 96 €/tS and for C1 reduction was only up to 24 €/tS.

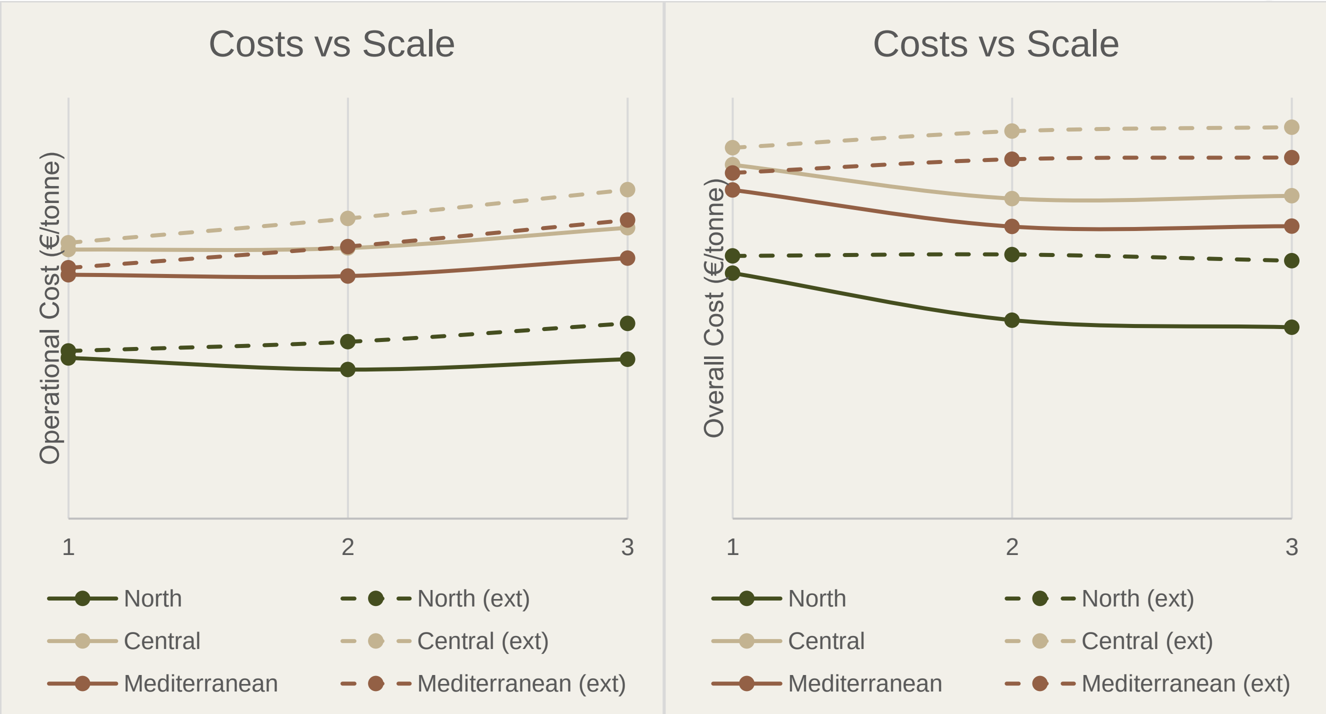

Figure 2. Simulated operational and overall costs for three struvite UWW installations in the three EU regions having an assumed concentration of PO_4-P equal to 400 ppm.

First figure shows the operational costs (line = simulation results, dotted line = existing installation results. The second figure shows the overall costs (line = simulation results, dotted line = existing installation results. Cost values are not shown due to corporate confidentially purpose.

Analysing further the simulation for higher concentration for the three cases, the results show that the operational costs are similar for C1 and C2 for central and Mediterranean regions and increase by 30 €/tS for C3. For the northern region, C1 and C3 have similar costs, however C2 has lower operational cost by 16 €/tS. This shows that increasing the size 23 times, increases the costs by factor 1 (30 €/tS) where per unit chemical costs have the highest share. However, with lower chemicals costs, the increase in operational costs by a factor of 0.5. For the overall costs, they are reduced by an average of 50 € per tonne of struvite going from a capacity of 35 m³/h to 75 m³/h and evens out from 75 m³/h to 800 m³/h for all three regions, reflecting capacity wise, further increase will not decrease total costs per tonne of struvite.

Waste water treatment plants with strategies to concentrate phosphorus loads in sludge which if efficiently converted to soluble phosphate can enable improved recovery efficiencies in the form of struvite. The study reflects a positive correlation with decreased per unit costs for increased PO_4-P concentration and flow rates. The higher the flow and/or more the PO_4-P load, more promising the economies. Unit cost of chemicals play a vital role in definition of overall costs upon having more than % weight in all cost categories. In a lot of European countries, MWWTP are now legally bound to recover nutrients like P and N from their waste water. Thus, a focus on concentrated P flows shall enable higher quantities of recovered struvite for which a certified EU Fertiliser product regulation CE mark can be obtained.

3.2 Industrial waste water struvite

3.2.1 Introduction

In the following study three of existing struvite recovery installations belonging to industrial waste water treatment plants with their intrinsic flow and phosphate loads are analysed for the total costs per unit of recovered struvite. The selection of installations for analysis is based on the variability of their capacities in the range of 120 m^3/h to 340 m^3/h influent to struvite recovery installation. The phosphate load varies from 70 to 120 mg/L PO_4-P. In all cases, the feed to the struvite recovery installation is effluent from the UASB reactor. Furthermore, the data from the three installations is also simulated to calculate expected costs for all three regions of Europe. **Table 14**: Case study IWW struvite installations and their characteristics. shows the flow and concentration characteristics of the three case studies.

Table 14: Case study IWW struvite installations and their characteristics.

	Case 1 (C1)	Case 2 (C2)	Case 3 (C3)
Flow (m^3/h)	120	200	340
Mass of PO4-P converted into struvite (kg/day)	187 (65 ppm)	456 (95 ppm)	408 (50 ppm)
Struvite (kg/m^3)	0.5	0.8	0.4

Consideration for operational costs

Unit prices for chemicals and electricity is adopted from the life cycle inventories prepared in the project. For operational costs, only chemical and electricity cost are taken into account as these are the most significant contributors. These unit costs are the average for the countries with a region and thus do not necessarily equal to the exact costs of utilities for the three selected installations. Also, it is important to note that the unit processes for all the installations are not exactly the same and thus the overall electrical consumption differs. However, the primary technology is precisely the same in all and thus the quality of the produced struvite.

Considerations for the capital costs

Capital cost per tonne of struvite is calculated with the same interest rate and life span as in the life cycle costing for the value chain of struvite from urban waste water. The total capital cost takes into account the administrative, maintenance and end of life costs. Cost calculations do not take into account the generated revenue from struvite sales or from savings in maintenance costs.

3.2.2 Results and discussions

The capital costs are in the range of 130 – 300 €/tonne of struvite (/tS) for all the three cases. The highest cost is for C1, followed by C3 and the lowest for C2. This reflects that low flow and less concentration has superior costs, and the costs becomes attractive upon increasing flow, however the most interesting upon increasing the PO_4-P load (concentration and flow).

In overall costs, the highest share is of chemicals. This is demonstrated by the lowest operational (chemicals and electricity) and overall costs for the northern region, followed by the Mediterranean and the highest for central EU regions. **Figure 3** compares the three regions for the three case studies. The difference in operating costs between north and other two regions is the around 200 €/tS, whereas between central and Mediterranean is only about 35 €/tS. The lowest operational costs are observed for all regions in C2, followed by C3 and the highest for C1. The difference in operating costs between C2 and C1 is around 165 €/tS, whereas between C3 and C2 is 36 €/tS. This strongly suggests that a bigger capacity (flow) influences per unit costs more than the concentration at these scales, since the concentration of C3 is lower than that of C1, and C2 has the highest concentration.

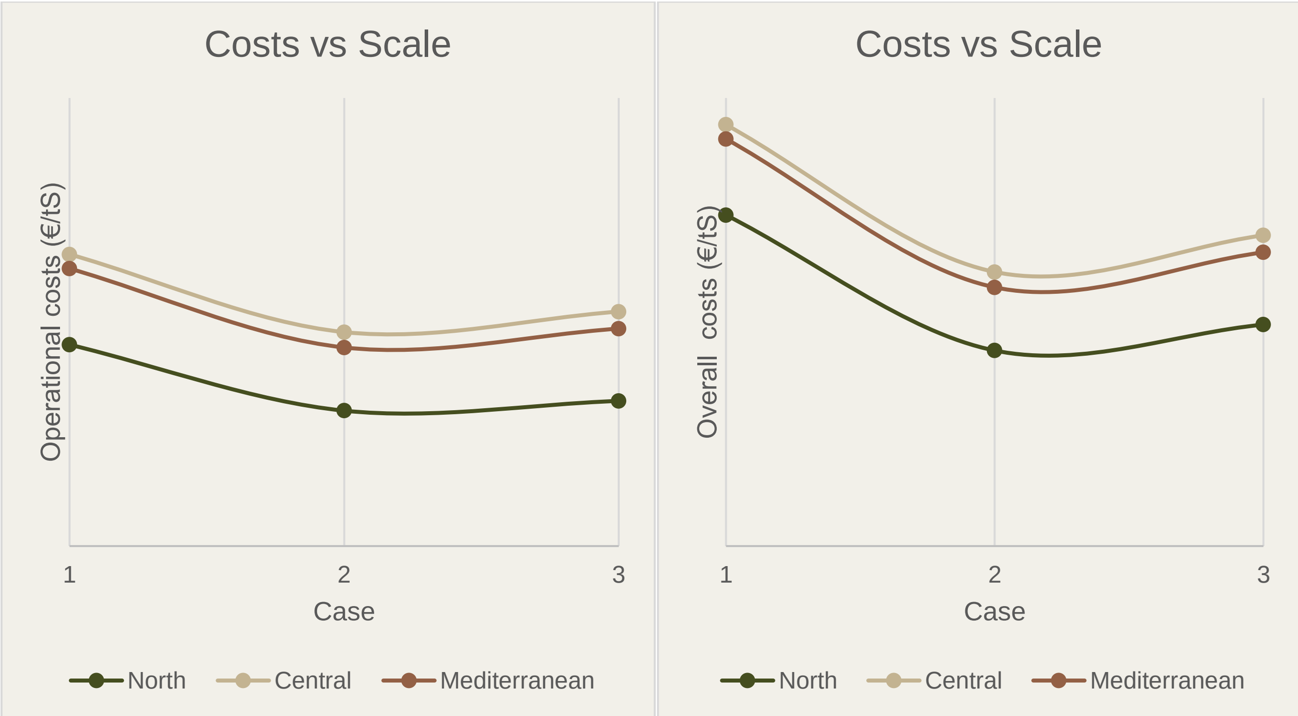

Figure 3. Operational and overall costs for the three struvite UWW installations in the three EU regions.

First figure shows the operational costs, and the second figure shows the overall costs. Cost values are not shown due to corporate confidentially purpose.

The overall costs for the three regions and the three case studies shares the same trend as of the operational costs: C1 and central EU region have the highest figures. The variation in cost between north and the other two regions is the range of 175 - 202 €/tS and between Mediterranean and central it is the range of 31 – 38 €/tS. C1 and C3 have a difference of 250 €/tS for all regions while having similar PO_4-P concentrations but a capacity difference of factor 2.8. C2 and C3 differ in the range of 73 €/tS, where C3 has double the flow, but similar PO_4-P load.

The results reflect a convincing correlation with decreased per unit costs for increased PO_4-P load or just increased hydraulic capacity for a low concentration of PO_4-P having the same effect. Unit cost of chemicals play a vital role in definition of overall costs upon having a significant portion in all cost categories. However, it is important to note that use of chemicals is dependent on the initial load of PO_4-P, and thus is expected to increase linearly with increasing loads. Although, other operational costs like electrical consumption is a function of hydraulic load rather than the PO_4-P mass load. Differences solely due to hydraulic load are camouflaged in this study due to high chemical costs.

For industrial struvite installation, faster return on investment (ROI) are expected compared to urban waste water treatment plants. Moreover, in most cases, fertiliser production is also not the main driver for the installation of struvite production unit. Recovery of P as struvite replaces use of conventional coagulants e.g. ferric chloride, which precipitates out P forming chemical sludge which is then required to be disposed of. The combination of coagulants costs and disposal of sludge alone makes the option of P recovery via struvite recovery very economical, and the added revenue from CE marked recovered fertiliser further enhances the cost-effectiveness.

3.3 Stabilised sludge

3.3.1 Comparison of technological routes

LCA for stabilised sludge took into account five routes to produce stabilised sludge from sewage sludge of urban waste water treatment plants for three EU regions. The five routes were: anaerobic digestion, aerobic digestion, thermal drying, alkaline treatment and composting, all of these routes were combined with either a pre or a post dewatering. Overall, the most energy is consumed by aerobic digestion and net zero energy is consumed by anaerobic digestion (offset by intrinsic energy production via biogas), thus the highest overall operational costs belong to aerobic digestion of sewage sludge. For the three EU regions, the cost of aerobic digestion is in the range of 2,400 – 2,700 €/wtSS (per wet tonne stabilised sludge). Composting technological route has the second most operational costs in the range of 117 - 151 €/wtSS. Alkaline and thermal dryer technologies are (operational) cost competitive, however thermal drying being slightly more expensive. The costs for thermal drying are in the range of 32 – 23 €/wtSS and alkaline treatment in the range of 19 – 25 €/wtSS. Anaerobic digestion route has the operational costs in the range of 23 – 36 €/wtSS, however the possible net energy sales are approximately equal to 40 €/wtSS, which shifts the net operational to 0, making it the most cost-effective route for the production of stabilised sludge.

Discussion on studies below are not directly comparable with the LCA results as system boundaries are different for all. The dryness content for each unit is also different and thus the stated information is to be treated independently, however the technologies can be compared within their own reference.

Ranking the sewage sludge treatment technologies from a study with similar treatment routes in China (Murray et al., 2008) based on operational costs (from year 2006) results in the most to least costly technique: dewatering at $424 per dry tonne of treated sewage sludge (/dtS), composting at $1,044 /dtS, aerobic digestion and heat drying at $881 /dtS, lime stabilisation at $587 /dtS and anaerobic digestion at net positive income stream of $359 /dtS. Total costs were in the order of $2,446 /dtS for aerobic digestion, $1,566 /dtS for heat drying, $1,174 /dtS for anaerobic digestion, $1,402 /dtS for compost, and $1,043 /dtS for lime stabilisation.

Another study by Hong et al, (2009) comparing anaerobic digestion, composting, and drying showed least electrical consumption by composting (70 kWh/dtS), drying (118 kWh/dtS) and the most by anaerobic digestion (223 kWh/dtS). However, anaerobic digestion was reported to produce 73 kWh/dtS from biogas, and drying required an additional 1,600 kWh/dtS of heat energy. The life cycle costs (inclusive of equipment, construction, operation, maintenance, disposal and reuse) were equal to compost at 409 €/dtS, and drying at 536 €/dtS and their combination with (pre) anaerobic digestion combination resulted in costs equal to 247 €/dtS anaerobic digestion + compost and for anaerobic digestion + drying equal to 311 €/dtS (currency exchange rate for year 2008, 1 EUR = JPY 152.35). The costs with combination with anaerobic digestion were lower than without due to more extensive independent composting or drying processes, and within these processes lower for compost then drying.

Suh & Rousseaux, (2002) reported 5 kWh electricity consumption for mixing 200 kg of lime per tonne of dry matter to sewage sludge, about 30 kWh/dtS and 8.4 kg/dtS of diesel for composting and for anaerobic digestion electricity consumption was 50 – 100 kWh/dtS with biogas production. Using LCA inventory data for 2022, these consumptions would translate into operational costs as 21 €/dtS for composting, 70 €/dtS for lime stabilisation and 14 €/dtS for anaerobic digestion.

Teoh & Li, (2020) analysed the volume or weight reduction effectiveness and pollutant reduction effectiveness of some of these technologies. Anaerobic digestion reduces TSS between 66 – 86 %, pharmaceuticals = 30 % and PCBs after 21 days 12 - 32 %. Composting/aerobic digestion reduces TSS up to 57 – 76 %, and organic pollutants up to 13 – 89 %. Lime stabilisation is recognised to reduce heavy metals between 6 – 23 %.

Sections below discusses these technologies further.

3.3.2 Anaerobic digestion

There can be different types of anaerobic digestion processes: it can be based on differences in operational temperature i.e. mesophilic or thermophilic, it can be differentiated based on configuration i.e. two or one stage reactors, or otherwise they can differ based on flow regime and moisture content (Chen & Neibling, 2014; Lanko et al., 2020). Many commercially available digestors employ combinations of these types within their design for market competitiveness.

A study comparing thermophilic, mesophilic and temperature phased anaerobic digestion reflected most electricity consumption by thermophilic, followed by mesophilic and the least by temperature phased digestion per unit of produced methane. In terms of environmental impacts, best technology was thermophilic concerning all categories, besides Climate change and Human toxicity (Lanko et al., 2020). Ferrer et al. (2024) suggest shift from mesophilic systems to thermophilic digestors allow better valorisation of by-products.

Li et al, (2017) compared digestion of sewage sludge by different technologies: mesophilic digestion (35 °C, TS 3 – 6 %), high rate anaerobic digestion (35 °C, TS 10 – 15 %), thermophilic anaerobic digestion (55 °C, TS 3 – 6 %), thermophilic high-solids anaerobic digestion (55 °C, TS 10 – 15 %), and pre-treatment step of thermal hydrolysis. Assessment based on capital and operational costs ranked the technologies from the most economical to least: thermophilic high-solids anaerobic digestion, thermal hydrolysis anaerobic digestion + thermophilic digestion + high rate anaerobic digestion, and the least scoring was mesophilic digestion. This was concluded based on higher organic content in the feed resulting in higher biogas generation which delivered the most revenue. However, authors suggest that thermal pre-treatment and thermophilic digestion are most suitable for high-organic-content sludge. In terms of environmental impacts, thermophilic and thermophilic high-solids anaerobic digestion preformed the best due to higher production of biogas. Thermal hydrolysis also generates competitive quantities of biogas however, it also has a higher share of electricity consumption. The mesophilic low and high rate systems were the last in terms of environmental performance. This study concluded in the favour of thermophilic high-solids anaerobic digestion as the best option overall, nevertheless, these technologies provide various benefits and thus the choice is dependent on the needs.

Liu et al. (2018) additionally emphasise on addition of a pre-treatment, co-digestion with other feedstocks, high-rate anaerobic digestion and phased digestion can improve the efficiency of anaerobic digestion of sewage sludge. Paranjpe et al. (2023) concluded in the favour of anaerobic digestion being the most competent technology for removal of sewage sludge by generating energy. The research pointed out co-digestion can increase the biogas generation by modified the C/N ratio. Research conducted by Balasundaram et al. (2024) analysing the advantages of a thermal pre-treatment before thermophilic and mesophilic digestion highlights that thermally pre-treated sludge generated 143 % more methane in mesophilic and 96 % more in thermophilic digestion. Moreover, the use of the pre-treatment resulted in the solubilisation of heavy metals, and that thermal mesophilic digestion and solely thermal digestion are competitive in terms of pathogen removal. Various commercially available low-temperature thermochemical hydrolysis full-scale technologies as a pre-treatment for anaerobic digestion can reduce sludge and increase biogas production up to 75 % and 50 %, respectively (Ferrentino et al., 2023).

3.3.3 Aerobic digestion

Ghazy et al. (2011) reported 222 thousand USD/dtS average capital cost for an aerobic digestion process, where 1 to 30 t/dtS are estimated to cost around 122 to 933 thousand USD (year:2009). The cost of energy (electricity) equals to 226.4 €/dtS (simulated for year 2022 using LCA inventory data). Tomei et al. (2011) used aerobic polishing for anaerobically digested sewage sludge and reported on energy consumption for aerobic stage at 0.0104 € per kg total solids under the assumption 1 kWh electric demand per kg volatile solids. Since the research was coupled with anaerobic digestion, a waste water treatment plant with 500,000 residents can potentially save 920,000 € annually based on cost savings of 0.10 € per kg total solids per kg total solids. Using autothermal thermophilic aerobic digestion technology for sewage sludge stabilisation can increase degradation rate of volatile solids, and improve pathogen inactivation, which makes digested sludge more favourable for land application (Liu et al., 2011). Cho et al. (2013) explained the advantages of having a combined anaerobic-aerobic digestion as mesophilic anaerobic digestion produces methane and reduces major part of soluble organic matter, whereas thermophilic aerobic digestion solubilised organic matter making it available for energy liberation.

3.3.4 Alkaline treatment

Alkaline treatment of sludge is rather a technique and not a technology. Thus, in most reported cases lime is used for stabilising sewage sludge. In Europe addition of lime is practised to raise pH greater than 12 for a minimum period of two hours for direct use (Fytili & Zabaniotou, 2008). Kalderis at al., (2010) reported on installation costs 1,572, 1,254, 2,278, 972 k€ for capacities 36, 20, 61, and 10 m³/day of sewage sludge. Additionally, reported operational cost in euro per m³ of treated sewage sludge was 68, 95, 53, and 162 €, respectively. The average operational cost was 95 € per m³ of sewage sludge (year:2010). Teoh & Li, (2020) report to use addition of 20 – 40 % CaO/dtS.

3.3.5 Composting

Ghazy et al. (2011) reported capital costs for mechanically turned windrow composting at average equal to 98,000 USD per tonne of dry solids composted (year:2009). The total capital costs reduce exponentially from 1,100 to 100 thousand USD till 20 tonne per day of dry solids, and stabilises between 20 - 50 tonne of dry solids composted. For the composting process, the cost of energy (fuel and electricity) equals to 26 €/dtS (simulated for year 2022 using LCA inventory data).

Song and Lee, (2010) used a fermenter and static pile composting for sewage sludge with the total cost of 52 USD per tonne of compost (year:2010). Albtoosh et al. (2024) composted anaerobically digested sewage sludge via windrow composting in horizontal reactors (forced aeration). Their cost simulation upon scale up resulted in capital and operational costs per tonne of (wet) sewage sludge treated equal to 41.4 and 76.9 €, respectfully. The annual revenue was 110.3 € per tonne of (wet) sewage sludge treated (exchange rate: 1 JD = 1.306 EUR), the generated compost complied with Class B of Jordanian Standard (1145: 2016). Kalderis at al. (2010) suggest a tunnel composting system would cost 125 and 600 € per tonne of dried sludge.

Wei et al. (2001) conducted a comparative study for windrow, aerated static pile and horizontal agitated solid bed composting systems. Various studies reported windrow composting systems had total cost (year:2001) between 11, 81 - 22, 36, 15 – 87 USD/dtS, for aerated static pile costs were between 135, 187, 35-120, 138, 95 USD/dtS, and one tunnel reactor reported for operational cost at 250 USD/dtS. Wei et al, (2001) concluded that initial moisture content of the sewage sludge is one of the vital factors defining the costs, and the composting cost were generally in the range of 55 – 174 USD/dtS. For moisture content between 70 – 85 %, the windrow systems were reported to have costs between 55-123 USD/dtS, for aerated static pile between 81 - 159 USD/dtS and for horizontal agitated solid bed between 89-174 USD/dtS. Even though in comparison windrow composting costs the least however the research proposed that land and bulking agent cost significantly impact the use of windrow system in small and mid-scale waste water treatment plants. Another important consideration is the reduction in moisture content increases overall costs.

3.3.6 Thermal drying

Schnell et al. (2020) summarise the thermal drying technologies as disc, thin film, drum, fluidised bed, bed and solar drying as presented in table below. These techniques depend on heat transfer through direct contact, convection drying, radiation and a mixture of these. Analysing the thermal and electrical energy demand for thermal drying techniques listed in **Table 15**, the most energy efficient technology Solar drying having the least consumption, whereas belt drying seems to be the highest consumer of energy. Disc, thin film and fluidised bed systems have more or less the same energy consumption per kg of water evaporated.

Table 15: Thermal and electrical energy demand for thermal drying techniques.

Technology	Disc or Thin-film	Drum	Fluidised bed	Belt	Solar
Heat transfer medium	Contact	Contact, convection	Contact, convection	Convection	Convection, radiation
Energy demand thermal (kWh/kg water)	0.8–0.85	0.85–1.00	0.8–0.85	0.95	0

Energy demand electrical (kWh/kg water)	0.05–0.08	0.04–0.12	0.07	0.05–0.08	0.03

Kalderis at al. (2010) compared thermal drying and solar drying. The reported installation costs for thermal drying was 1580, 668, 2727, 370 k€ and for solar drying at 1379, 962, 1884, 627 k€ for capacities 36, 20, 61, and 10 m³/day of sewage sludge, respectively. The average cost was lower for solar drying than thermal drying. The stated average operational cost per m³ of treated sewage sludge for thermal drying was 104 € and for solar drying at 34 € which is in line with the **Table 15**, where solar drying has the least energy demand.

3.4 Composted biowaste

3.4.1 Introduction

Composting technologies can be divided into two general categories: windrow and in-vessel systems. In windrow systems the material is collected in elongated piles where it is either mechanically turned or air is forced through the static piles. In-vessel systems can also be referred as bioreactors and are either vertical or horizontal. Vertical systems can be some type of cylinders or tanks in height and horizontal systems can be channels, cells, containers and tunnels in length. (Bruni et al., 2020).

For the alternative fertiliser 'Compost', confined windrow composting along with an additional pre-treatment is what has been modelled within Fer-Play. It is composed of dry anaerobic digestion (with CHP) as a pre-treatment step, followed by closed aerated static windrows which are periodically mechanically turned. For the alternative fertiliser 'Spent Mushroom Substrate', the composting technology is also confined windrow composting.

This study aims to compare the two broad composting technologies based on the LCA inventory data and in online available research. First part will compare solely the composting technologies and the second part will discuss the combination of dry anaerobic digestion as a pre-treatment to composting.

3.4.2 Operational data composting technologies

The energy cost from the LCA confined windrow composting stage for the three European regions lies in range of 46 - 51 €/tC, which is very similar to a confined windrow in Catalonia, Spain (Cadena et al., 2009) treating source separated OFMSW having a total of 52 €/tC simulated energy costs. However, when comparing the reported distinct electricity and diesel consumption, the confined turned windrow in Catalonia, Spain consumes 2.66 times more diesel than LCA confined static windrow system but 1.6 times less electricity per tonne of produced compost. This can be explained by the detail that LCA confined windrow is static and the windrow in Catalonia, Spain is turned. Both the inventories report to reuse some source of water on site or nearby, thus fresh water consumption is assumed negligible. Another composting plant in Catalonia, Spain (Cadena et al., 2009) using composting tunnels technology has approximately 5 times higher calculated energy cost of 271 €/tC, predominantly because of a higher electricity consumption. This plant also had a significantly higher refuse ratio in the collected OFMSW as well which can suggest the elevated calculated energy costs per tonne of produced compost. If the electricity consumption per tonne of treated OFMSW from both the plants in Catalonia, Spain are compared, composting tunnels have 1.20 times lower electricity consumption than confined windrow.

A case study in Ireland (Murphy & Power, 2006) using a combination of two weeks in vessel composting and 8 weeks of aerated static piles composting reported on calculated total operational costs of 150 €/tC for a plant capacity of 10 kt of biowaste treated which decreases to 94 €/tC for a 10 times higher plant capacity of 100 kt of treated biowaste. If the plant size data from composting tunnels technology from Catalonia, Spain (Cadena et al., 2009) is simulated for its scale of 6 tonne of compost per year using the formulation used for composting tunnels from Murphy & Power, (2006) and normalised to year 2022, the resulting operation cost would be equal to 166 €/tC. On the contrary, another study using a PROMETHEE ranking method gave the highest operational costs score to aerated windrow, followed by composting tunnel as relatively high, and the low score to turned windrow, furthermore, the operational costs in the ranking method had a wider scope than in the other studies (Makan & Fadili, 2020).

A food waste composting facility in Qatar (Al-Rumaihi et al., 2020) using turned windrows reflects a very low energy cost of 12 €/tC when calculated using average EU unit costs data for electricity and diesel. On the contrary, similar calculation done for a facility in Malaysia using turned windrow (Abu et al., 2021) resulted in energy costs equal to 45 €/tC. However, all the electricity consumed is during screening and shredding of waste, and not during the composting process itself. This may reflect that a significant portion of total energy consumed is due to pre-screening of waste.

Study using rotating drum composter treating food waste in UK (Slorach et al., 2019) reported a relatively high average electricity consumption and thus the calculated energy cost for this in-vessel system equals 58 €/tC which is not in line with the PROMETHEE ranking study giving rotating drum composting technology half a score than composting tunnels in accumulative operational costs (Makan & Fadili, 2020).

3.4.3 Environmental impacts of composting technologies

Comparing composting technologies based on their environmental impacts from different case studies would be challenging with a high risk of misleading comprehension as numerous factors come into play. Serafini et al., (2023) published a comprehensive systematic review and meta-analysis of various LCA to comprehend the environmental impacts composting processes could entail. According to the results, in-vessel composting in other composting methods had the least impacts in all analysed categories suggesting it to be the best environmental option. The following points are of significance when a comprehension is drawn for technologies/techniques:

- Having a treatment technique in a closed area that can include a system to collect and treat off gases.
- Better managed collection systems and transport of waste as it directly dictates the energy consumption.
- Composting technology differences also reflect into their specific environmental impacts, which can highlight the areas to advance on in the composting system.
- Agricultural use of compost only marginally reduces some of the impact categories in the use phase compared to non-renewable fertilisers.
- Combination of anaerobic digestion and composting can be more competitive compared to other waste management systems like landfilling compared to individual composting system.

Most of these points are further validated by another study that compares six composting systems (Makan & Fadili, 2020). Their results reflect reactor technologies are more sustainable than enclosed technologies and the least sustainable are open technologies mostly due to better management of air emissions and odour. Rotating drum composting technology was ranked the best among the rest in each criterion of economical, technical, environmental and social while turned windrow scored the worst.

3.4.4 Operational data dry anaerobic composting

LCA result for cumulative operational costs for a combined dry anaerobic digestion and composting treatment for the three European regions lie in range of 175 – 187 €/tC, where the fixed operational costs are almost double (factor of 1.90) the variable operational costs. Murphy & Power, (2006) in their economical evaluation for a comparable system simulated total operational costs of 155 €/tC for a plant capacity of 5 kt of biowaste treated which decreases to 58 €/tC for a 20 times higher plant capacity of 100 kt of treated biowaste (these costs have been adjusted to year 2022). According to this correlation, the proposed operation costs for the LCA study having an annual capacity of 48 kt of food and green waste treated would approximately equal 77 €/tC, which is nearly equal to the average variable operational cost of 63 €/tC calculated for the three regions.

If electricity consumption and production data for three dry anaerobic digestion and composting plants operating at 45 kt/y, 48 kt/y and 50 kt/y of bio-waste (Jensen et al., 2017, LCA study and Murphy & Power, 2006, respectfully) are compared, all three plants produce surplus of electrical energy (some plants have excess heat as well) which is further sold in the market generating additional income. However, the quantity of the surplus electrical energy varies depending on the total biogas production (difference in biogas generation potential), efficiency of energy conversion and internal energy use. A considerable amount of internal electricity use can be associated with 'pre-treatment' of waste received, as Jensen et al. (2017) with no pre-treatment of collected biowaste has only 13 kWh of total energy use per tonne processed waste (while others with pre-treatment are around 80 kWh/tonne) inclusive of energy used for forced aeration for 5 - 7 days during composting stage.

Apart from advantages related to energy self-sufficiency and an overall positive economic balance (surplus energy and smaller area requirements), combining anaerobic digestion with composting also ensures high stabilised organics, better emissions control and reduced nutrient load to compost hence low risk associated with nutrient runoff (Cucina, 2023). The integration also reduces the potential pathogens from digestate, improves rate of degradation, and generally improves the benefits of the final product compared to composting alone (Lin et al., 2018).

Xiao et al. (2022) found out that in their comparative study that within anaerobic digestion systems, dry anaerobic digestion has higher operational capacities (25% more) compared to wet-anaerobic digestion which reflected into less capital costs. On the contrary, another study comparing nine AD plant operating in the UK and Europe, found no prominent distinction in the plant design capacity between the two (Angelonidi & Smith, 2015). Moreover, the study showed wet anaerobic digestion to have an edge over dry on the basis of higher biogas productivity, and further on lower capital cost per tonne of treated waste.

3.4.5 Environmental impacts of anaerobic digestion and composting

Distinctively for anaerobic digestion process, emissions majorly come from improper storage (5 to 31% of the total CH4 produced) and application of digestate compared to digestion process (10% of the total CH4 produced) itself (Lin et al., 2018). Whereas in composting the emissions are majorly produced during the composting process as discussed in the section above.

In a comparative study, dry AD showed better environmental performance compared to wet AD sites, however for the post treatments compost preformed the least compared to incineration and landfill (Xiao et al., 2022). Anaerobic digestion preceding composting resulted in considerable reduction in LCA impact categories: eutrophication potential, global warming potential, acidification potential, and ecotoxicity potential when compared to just composting or anaerobic digestion (Li et al., 2018). However, when the integration of both is compared to incineration for the organic fraction of municipal solid waste, the latter reflects more environmental gains primarily due to more quantities of recovered energy. This conclusion was inclined due to gained environmental benefit for avoiding emissions from fossil fuels-based energy production (Di Maria & Micale, 2015). An UK based study (Slorach et al., 2020) for household FW simulating future scenarios for varying share of waste management techniques showed most environmental positive results for scenarios with anaerobic digestion (inclusive of energy sales) prioritised followed by incineration (with energy sales) and composting between 4 and 3% respectively, whereas landfills being the least favourable technique and 44% share of in-vessel composting being the least favourable scenario. The study also emphasised on reduction of FW production to be the most prominent way of saving environmental costs.

3.5 Feather meal

3.5.1 Introduction

Three kinds of treatment can be used for hydrolysis of feathers: hydro-thermal, chemical and biological methods. Hydro-thermal treatment involves ‘steam cooking’ at 275 - 415 kPa for 30 - 60 min. Chemical treatment involves using alkaline, acidic or/and organic solvents for hydrolysis. Biological treatment is composed of employing keratinolytic microbes under mild conditions to complete hydrolysis. Combination of these treatments can be beneficial at times for improving effectiveness (Muduli et al., 2019; Bhari et al., 2021).

3.5.2 Treatment cost analysis

The operational costs for the three European regions from the life cycle costing of feather meal (rendering and fertiliser production phase) for year 2022 were: north at 840 €, central at 920 € and Mediterranean at 926 € per tonne of feather meal.

Campos et al. (2020) reported rendering plant using steam and pressure hydrolysis at 113 °C, 3 atmospheric pressure for 20 min. Afterwards the hydrolysate was dried in a disk dryer to lower the moisture content below 10 % on weight basis and then sifted (to remove large fragments). In the study the hydrolysed feather meal was sold as a protein source for animal feed at 490 €/tonne. It is stated that to produce 1 tonne of hydrolysed feather meal, 3574 tonnes of feathers and blood are required. Translating the provided data by Campos et al. (2020) (using the LCA inventory) equals to operational (energy, packing material and waste water treatment) costs at 213 € per tonne of hydrolysed feather meal (year:2022). Simulating these costs for a production capacity of 2463 tonne annually, would equal to 524.6 k€ per year (year:2022). Assuming the feather meal for fertiliser is sold at 87 €/tonne (FER-PLAY database), the overall costs are higher than selling price.

Solcova et al. (2021) used physicochemical hydrolysis of feather waste at a scale of 8 m³ using malic acid, pressurised steam at 200 °C and 0.26 MPa for 6 hours. These conditions were followed by cooling at 100 °C for 10 h. The costs for this process were: material and energy OPEX equal to 344 €/tonne feather feed, direct labour OPEX at 323 €/tonne feather feed and CAPEX was set at 520 €/tonne feather feed. The total cost per tonne of feather feed would be 1188€. Assuming one tonne of feather meal is made from 3 tonne of feed (adopted from LCA), cost per tonne of feather meal would be 396 € (year: 2021).

Kim et al. (2002) compared chemical treatment (1.0 N reagent grade NaOH) and enzymatic treatment (614 mg of INSTA-PRO enzyme per 1 g of feathers) for hydrolysis of feather meal. Highest costs were reported for the combination of both treatments at 23 USD/kg of N solubilised with N solubility at 50 %. The 24-hour enzymatic treatment cost 10 USD/kg at N solubility 2.5 %, two-hour NaOH treatment cost 12 USD/kg at N solubility 30 %, and the cheapest treatment cost was for 24-hour NaOH at 5 USD/kg at N solubility 79 %. Assuming a N content of 130 kg nitrogen per tonne of feather meal (adopted from LCA) and no N loses upon conversion to feather meal, the cost for 24-hour NaOH treatment would translate into an optimistic 611 USD per tonne of feather meal (year:2002).

For environmental impact of the process using steam and pressure hydrolysis, rendering process contributes to 56 % global warming and 72 % abiotic depletion of total impacts in these categories. Transportation from the slaughterhouses to the rendering plant and for the final preparation as feather meal account for less than 10 % of the total impacts. Feather and blood as poultry by-products contribute to 69 % acidification and 72 % eutrophication marks the total impacts of these categories (Campos et al., 2020).

3.6 Solid fraction of digestate

3.6.1 Life cycle costing results for the solid fraction of digestate from the three feedstocks

Life cycle assessment (LCA) considers wet anaerobic digestion for sewage sludge as well as manure, and for food waste it is dry anaerobic digestion. Mesophilic digestion is assumed for all three feedstocks.

Average capital and operational costs in Europe for food waste is 150 and 82 € per tonne of solid fraction of digestate (/tSFD), respectively. For sewage sludge, it is 27 and 36 €/tSFD, respectively. Lastly for cattle manure, it was 402 and 139 €/tSFD, respectively. Operational costs are the highest for cattle manure, followed by food waste and the least for sewage sludge per functional unit. For food waste and manure, a considerable portion of the operational costs is a reflection of the maintenance and conservation costs, which is assumed at 2 % of the capital costs. Thus, a higher capital cost is influencing the sum of fixed operational costs. For sewage sludge, where the initial investment is the lowest, the highest cost portion is resulting from the use of consumables (polymer and ferric chloride) in variable operational costs.

In all cases, there is a net gain in electricity from biogas in the production phase, and the electricity is sold. Both sewage sludge and food waste have a higher energy consumption for the production phase of around 700 MJ/tSFD and for manure, it is 210 MJ/tSFD. In manure processing, electricity is only consumed during digestion process and dewatering. For food waste, electricity is additionally consumed for pre-treatment, and for sewage sludge, electricity is similarly consumed for mixing and thickening of primary and secondary waste sludge. The excess of electrical energy sold to the grid is 350, 715, and 1,100 MJ/tSFD for sewage sludge, food waste and manure, respectively. The difference in the net energy production is originating predominantly from the difference in energy consumption between all three feedstocks. The least yield of energy is from sewage sludge at 1,145 MJ/tSFD and highest from food waste at 1,340 MJ/tSFD.

3.6.2 Anaerobic digestion process for different feedstocks

Generally, there can be different types of anaerobic digestion processes: it can be based on differences in operational temperature i.e. mesophilic or thermophilic, it can be differentiated based on configuration i.e. two or one stage reactors, or otherwise they can differ based on flow regime and moisture content (Chen & Neibling, 2014; Lanko et al., 2020). Many commercially available digestors employ combinations of these types within their design for market competitiveness.

A study comparing thermophilic, mesophilic and temperature phased anaerobic digestion reflected most electricity consumption by thermophilic, followed by mesophilic and the least by temperature phased digestion per unit of produced methane. In terms of environmental impacts, best technology was thermophilic concerning all categories, besides Climate change and Human toxicity (Lanko et al., 2020). Ferrer et al. (2024) suggest shift from mesophilic systems to thermophilic digestors allow better valorisation of by-products.

Xiao et al. (2022) found out that in their comparative study that within anaerobic digestion systems, dry anaerobic digestion has higher operational capacities (25 % more) compared to wet-anaerobic digestion which reflected into less capital costs. On the contrary, another study comparing nine AD plant operating in the UK and Europe, found no prominent distinction in the plant design capacity between the two (Angelonidi & Smith, 2015). Moreover, the study showed wet anaerobic digestion to have an edge over dry on the basis of higher biogas productivity, and further on lower capital cost per tonne of treated waste.

Bhatt and Tao, (2020) emphasised on the essential aspects for investing in anaerobic digestion systems through a cost study of sewage sludge, food waste and swine manure digestion. The composition of the feedstock greatly influences the biogas yield and thus the overall process economics. The composition of methane content in biogas is a function of the feed's fermentable fraction and the operating conditions within the digestor. The chemical oxygen demand (COD) reduction in anaerobic digestion process for sewage sludge, food waste and pig manure were reported as 56, 65 and 55 %, respectively. For food waste, this value could go as high as 90 % due to the waste composition. Study states biogas yield for sewage sludge from 54 – 60 %, for food waste between 45 – 72 %, and for manure ranging from 36 – 65 %. It is also stressed that the yield can be boosted beyond the theoretical estimates (from fixed COD) by using pre-treatment technologies, or by use of inoculum or process optimisation with focus on increasing biogas production. The cost study modelled flow of waste water sludge between 1 – 300 million gallons per day, food waste at 1 – 250 wet tonne/day, and swine manure at 1 – 250 wet tonne/day. For sewage sludge, the modelled result shows a decrease in production costs upon increase of scale, and for larger facilities (greater than 150 million gallons per day), literature suggests the cost of biogas production can reduce to 1 USD per giga joules. For the food waste, the study model is rather optimistic compared to studied literature, and reports on highest reduction of costs up to 30 USD per giga joules between the scale of 10 to 250 wet tonnes/day. For pig manure, one of the fits is in satisfactory agreement with the literature, and the reduction in costs is about up to 22 USD per giga joules from the range of 10 to 250 wet tonne/day (year: 2016).

Liu et al, (2018) emphasise on addition of a pre-treatment, co-digestion with other feedstocks, high-rate anaerobic digestion and phased digestion can improve the efficiency of anaerobic digestion of sewage sludge. Paranjpe et al. (2023) concluded in the favour of anaerobic digestion being the most competent technology for removal of sewage sludge by generating energy. The research pointed out co-digestion can increase the biogas generation by modified the C/N ratio. Research conducted by Balasundaram et al. (2024) analysing the advantages of a thermal pre-treatment before thermophilic and mesophilic digestion highlights that thermally pre-treated sludge generated 143 % more methane in mesophilic and 96 % more in thermophilic digestion. Moreover, the use of the pre-treatment resulted in the solubilisation of heavy metals, and that thermal mesophilic digestion and solely thermal digestion are competitive in terms of pathogen removal. Various commercially available low-temperature thermochemical hydrolysis full-scale technologies as a pre-treatment for anaerobic digestion can reduce sludge and increase biogas production up to 75 % and 50 %, respectively (Ferrentino et al., 2023).

Li et al, (2017) compared digestion of sewage sludge by different technologies: mesophilic digestion (35 °C, TS 3 – 6 %), high rate anaerobic digestion (35 °C, TS 10 – 15 %), thermophilic anaerobic digestion (55 °C, TS 3 – 6 %), thermophilic high-solids anaerobic digestion (55 °C, TS 10 – 15 %), and pre-treatment step of thermal hydrolysis. Assessment based on capital and operational costs ranked the technologies from the most economical to least: thermophilic high-solids anaerobic digestion, thermal hydrolysis anaerobic digestion + thermophilic digestion + high rate anaerobic digestion, and the least scoring was mesophilic digestion. This was concluded based on higher organic content in the feed resulting in higher biogas generation which delivered the most revenue. However, authors suggest that thermal pre-treatment and thermophilic digestion are most suitable for high-organic-content sludge. In terms of environmental impacts, thermophilic and thermophilic high-solids anaerobic digestion preformed the best due to higher production of biogas. Thermal hydrolysis also generates competitive quantities of biogas however, it also has a higher share of electricity consumption. The mesophilic low and high rate systems were the last in terms of environmental performance. This study concluded in the favour of thermophilic high-solids anaerobic digestion as the best option overall, nevertheless, these technologies provide various benefits and thus the choice is dependent on the needs.

Sillero et al. (2023) compared anaerobic co-digestion of sewage sludge, wine vinasse and chicken manure in mesophilic, thermophilic and temperature phased system. The highest production of biomethane and lowest cost of manufacturing were of temperature phased, followed by mesophilic and then for thermophilic process, respectively. Whereas, the higher consumption of energy was by temperature phased, followed by thermophilic process and least for mesophilic digestor. The results suggested a strong correlation between manufacturing costs and the biogas yield, as observed above. Overall annual electricity, heat and fertiliser sales were highest for temperature phased, followed by mesophilic and least for thermophilic digestion.

Cano et al. (2014) conducted a feasibility study for integration of thermal hydrolysis as a pre-treatment for anaerobic digestion for multiple waste sources including biological sewage sludge and cow manure. Sludge had an increase of more than 50 % of biogas production after thermal hydrolysis, and for manure, it was 30 %. However, the overall net benefit per tonne of feed substrate did not increase for sewage sludge due to low volatile solids, thus the total methane generation was lower. Nevertheless, cow manure had net benefits of 10 euro per tonne of feed compared to without thermal treatment. The study concluded in the favour of thermal pre-treatment due to the potential increase in biogas generation and the resulting profitability.

3.6.3 Sewage sludge anaerobic digestion

Murray et al, (2008) reported on a net gain in electricity of about 920 kWh per dry tonne of sewage sludge, and total operational and capital costs per dry tonne of sewage sludge were 359 and 1,174 USD, respectively for mesophilic anaerobic digestion (from year 2006). Hong et al, (2009) stated 223 kWh per dry tonne of sewage sludge of electrical consumption and production was at 73 kWh per dry tonne of sewage sludge. Another study from Suh & Rousseaux, (2002) stated electricity consumption was 50 – 100 kWh per dry tonne of sewage sludge for anaerobic digestion, and upon using LCA inventory data for 2022, the consumption would translate into energy cost of 14 € per dry tonne of sewage sludge. Fersi et al. (2015) report on energy consumption as the highest contributor to overall operational cost of 75 € per year per dry tonne of sewage sludge, followed by consumables. The capital costs and total costs were stated as 151 and 226 € per year per dry tonne of sewage sludge, respectively (year:2013). In general, Fersi et al. (2015) summarised to a potential of 2.4 MWh of renewable energy from 1 MWh of energy consumption, thus a positive energy balance for sewage sludge.

3.6.4 Food waste anaerobic digestion

Huiru et al. (2019) simulated medium scale food waste two-stage anaerobic digestor operating at mesophilic conditions with a final pasteurisation temperature of 70 °C. Pasteurized solid fraction of digestate was 3300 tonne per year which was land applied. The total capital was 321,836 € for the input feed of 14,615 tonnes per year. Operational costs and revenue per tonne of solid fraction of digestate were 14.4 and 23.8 €, respectively (year: 2018, exchange rate September 2018: 1 EUR = 8.08 CNY). The research highlighted that the electricity export rate is a vital factor for shorter payback periods.

Sahoo & Mani, (2019) compared wet, dry and integrated anaerobic digestion for food waste, dairy-manure and miscanthus biomass. Highest investment costs were observed for integrated system at 13 million USD, followed by 10 and 9 million USD for dry and wet anaerobic digestors, respectively. The products were digestate and upgraded bioCNG. The operational costs were also the highest for integrated system at 230 USD per tonne of digestate. For dry and wet digestion, the operational costs were 83 and 33 USD per tonne of digestate, respectively (year: 2018). Energy consumption was the lowest for dry anaerobic digestion and highest for wet. Study concluded lowest economic performance for integrated anaerobic digestion due to significant reduction in volumetric methane yield compared to other two systems. however integrated system has some operational advantages. Overall, the market cost of BioCNG was the lowest amongst all three systems, and additionally lower than the fossil CNG market price making it market competitive. BioCNG from dry digestion can be financially feasible with financial incentives associated with recovered products.

3.6.5 Manure anaerobic digestion

Nasir et al, (2012) conducted a review of anaerobic digestion technologies for livestock manure. They concluded that anaerobic bioreactors had simple design and were operated below their design organic loading rates to get a stable performance. Cattle manure has low biodegradability and thus co-digestions can improve the nutrient balance and consequently the biogas production (up to 15 – 20 % increase). A separation of process phases: hydrolysis and the methanogenesis can achieve better process stability and optimum operation. The methane yield of cattle manure was in the range of 0.1 - 0.37 m^3 per kg of volatile solids added (LCA assumed 0.33 m^3/kg of volatile solids) and volatile solids destruction up to 78 % (45 % for LCA), for pig manure it was 0.1 – 0.44 m^3 per kg of volatile solids added, and 95 % volatile solids destruction and for poultry manure methane yield was at 0.01 – 0.5 m^3 per kg of volatile solids added.

Tan et al. (2022) compared three scenarios for anaerobic digestion of cow manure: mono-digestion of cow manure, its co-digestion with maize silage and its co-digestion with sewage sludge, food waste and returned dairy product. The capital costs were 984 k€ (digestor volume = 1,850 m^3), 822 k€ (digestor volume = 2,750 m^3), and 491 k€ (digestor volume = 600 m^3), respectively. The operational costs per tonne of digestate (unseparated) were 984, 2615 and 242 €, respectively (year:2021, exchange rate: 1 MR = 0.20 EUR). Most biogas production was observed in co-digestion with sewage sludge, food waste and returned dairy product, thus the least OPEX, and the lowest yield was for co-digestion with maize silage.

3.6.6 Outline

Anaerobic digestion is a promising technology to liberate energy from waste and convert it a usable form while simultaneously producing digestate with market potential as a recovered fertiliser. Many promising studies have been discussed in this document, with varying materials and process designs for system optimisation, all signifying the biogas sales as the major economic gain of anaerobic digestion process, and thus any technological or operational alteration boosting methane generation for a particular scenario makes the entire finances more favourable.

1.1. Spent mushroom substrate

3.6.7 Introduction

Spent mushroom substrate analysed in life cycle assessment (LCA) originated from cultivation of *Agaricus bisporus* on manure-based substrate. The confined windrow composting technology has been simulated in LCA study. In literature there is a lack of segregated information on different phases that leads to the production of the fertiliser. Additionally, mushroom cultivation is the major motivation for the process and spent mushroom substrate (SMS) is a by-product, which is composted, it being the most feasible technique to effectively and economically recycle SMS

(Othman et al., 2020). Comparison of composting technologies can be found in section **Error! Reference source not found.**.

3.6.8 Life cycle costing SMS

The average capital cost in Europe for the complete value chain was in the range of 250 - 362 per tonne of spent mushroom compost (/tSMC), where for re-composting stage was between 94 -126 €/tSMC. The highest operational costs are resulting from mushroom cultivation phase, followed by re-composting and substrate production. The re-composting average operational costs sum to 66 €/tSMC and the overall average operational costs equal 1,140 €/tSMC for the three regions, respectively. Approximately 2.17 tonnes of SMS were converted to 1 tonne of SMC in the LCA during the re-composting stage while using 22 kWh of electrical energy and 1.87 kg of diesel per tonne of SMC.

3.6.9 SMS processing technologies

Domínguez-Gutiérrez et al. (2022) compared turned windrow composting and closed vessel vermicomposting. Both methodologies stabilised SMS by reducing the volume, and the nutrient content. However, they recommended regulated use of SMC based on existing ecological conditions of the soil. Vermicompost was stabilised faster than the turned windrow composting and had more available nutrient content due to the earth worm population. Including other composting techniques, Ahlawat et al. (2011) analysed three composting techniques: natural static pits (natural), passively aerated pits (aerobic) and soil covered static pits (anaerobic). It was concluded that anaerobic technology was the most superior amongst others based on yield and disease incidence, and a minimum 9-month period is required for ensuring the quality.

Maher et al. (2000) highlighted the need for economically efficient and environmentally viable of combined management of SMC, including transport away from the mushroom farms due to the risks to the mushroom production and lack of land for SMC application for Ireland. They modelled a centralised SMC management facility for one of the county's within Ireland. Such a facility will receive SMC bags, and store them during the cold months where the SMC will be further composted. This facility was also distributing the final product to end-users. The projected capacity of SMC management plant was 650 tonne per week, where two composting technologies were employed: bunkers with odour treatment by biofilters and aerated piles with mechanical turning. The facility and the machinery would cost £ 1,080,000 and £ 625,000 for bunker system and aerated pile, respectively. Annual operating costs were projected at £ 250,000 for SMC collected from 100 farms, which would equal to £ 7.69 per tonne of feed SMC. It was assessed that a mushroom grower with four mushroom tunnels, this strategy (annual cost of £ 2,500 per mushroom producer) would be very cost effective compared to their current management (year:2000).

A study was conducted in Australia which investigated cost effectiveness of different technologies for mushroom waste management in Australian mushroom industry (Hort Innovation, 2019). The study compared recycling of SMS for mushroom production, pelletiser system for dewatering for energy and fertiliser markets, anaerobic digestion, mushroom powder for high value market, exotic mushroom production, insect cultivation on SMS, CO2 recycling and as edible shelf extender. Among these only recycling of SMS for production, pelletiser system and mushroom powder were feasible with potential future opportunities. In relevance to SMS as a fertiliser, pelletiser option was the most relevant. Dewatering costs were predicted at 395 thousand Australian dollars as capital and 6 thousand Australian dollars annually for operation with a pay back of 5 years, where SMS is brought to 25 - 35 % moisture content allowing long term storage on-site and sales at a higher price as soil additive. For further palletisation, capital of 1.8 - 2.4 million Australian dollars and operational expenditure at 27 thousand Australian dollars annually was estimated with a payback of 14.4 years. The moisture content will the drop to less than 15 %. In terms of viability, the option to dewater and sell SMS as a soil additive was regarded as directly financially viable. Palletisation was recommended for bigger stakeholders with no current financially rewarding SMS waste management in place. Mixes with the SMS for example with other fertilisers can optimise the elemental composition for SMS and enhance off-site sales. A payback of 5 years is simulated with co-inputs.

Further information in the study reflects that dewatered SMS was ought to achieve a practical payback if sold around 35 - 40 Australian dollars per tonne of SMS. Assuming a 5-year payback for the investment, predicted dry SMS sale price reduces from 41.2 to 3.3 Australian dollars per tonne of SMS if production is increased from 25 tonne of mushroom production per week to 100 tonnes. In the case of palletisation, in order to achieve a 5-year payback, mixed SMS with a co-product pellet cost decreases from 188.2 to 42.5 Australian dollars per tonne SMS if production is increased from 25 tonne of mushroom production per week to 100 tonnes.

3.7 References

Abu, R., Ab Aziz, M. A., Hassan, C. H. C., Noor, Z. Z., & Abd Jalil, R. (2021). Life cycle assessment analyzing with gabi software for food waste management using windrow and hybrid composting technologies. *Jurnal Teknologi*, *83*(6), 95-108.

Ahlawat, O. P., Manikandan, K., Sagar, M. P., Raj, D., Gupta, P., & Vijay, B. (2011). Effect of composted button mushroom spent substrate on yield, quality and disease incidence of Pea (Pisum sativum). *Mushroom research*, *20*(2).

Albtoosh, A. F., Alnsour, M. A., Hajar, H. A., & Lagum, A. A. (2024). Techno-Economic and Environmental Sustainability Assessment of a Sewage Sludge Composting Plant: A Case Study. *Waste and Biomass Valorization*, 1-18.

Al-Rumaihi, A., McKay, G., Mackey, H. R., & Al-Ansari, T. (2020). Environmental impact assessment of food waste management using two composting techniques. *Sustainability*, *12*(4), 1595.

Angelonidi, E., & Smith, S. R. (2015). A comparison of wet and dry anaerobic digestion processes for the treatment of municipal solid waste and food waste. *Water and environment journal*, *29*(4), 549-557.

Balasundaram, G., Gahlot, P., Tyagi, V. K., Kannah, Y., Banu, J. R., & Kazmi, A. A. (2024). Mesophilic, thermophilic and thermal hydrolysis process coupled anaerobic digestion of sewage sludge: Biomethane potential, pathogen removal and energy feasibility. *Sustainable Chemistry and Pharmacy*, *37*, 101397.

Bhari, R., Kaur, M., & Sarup Singh, R. (2021). Chicken feather waste hydrolysate as a superior biofertilizer in agroindustry. *Current Microbiology*, *78*(6), 2212-2230.

Bhatt, A. H., & Tao, L. (2020). Economic perspectives of biogas production via anaerobic digestion. *Bioengineering*, *7*(3), 74.

Bruni, C., Akyol, Ç., Cipolletta, G., Eusebi, A. L., Caniani, D., Masi, S., ... & Fatonnee, F. (2020). Decentralized community composting: past, present and future aspects of Italy. *Sustainability*, *12*(8), 3319.

Cadena, E., Colón, J., Artola, A., Sánchez, A., & Font, X. (2009). Environmental impact of two aerobic composting technologies using life cycle assessment. *The international journal of life cycle assessment*, *14*, 401-410.

Campos, I., Valente, L. M. P., Matos, E., Marques, P., & Freire, F. (2020). Life-cycle assessment of animal feed ingredients: Poultry fat, poultry by-product meal and hydrolyzed feather meal. *Journal of Cleaner Production*, *252*, 119845.

Cano, R., Nielfa, A., & Fdz-Polanco, M. (2014). Thermal hydrolysis integration in the anaerobic digestion process of different solid wastes: energy and economic feasibility study. *Bioresource technology*, *168*, 14-22.

Chen, L., & Neibling, H. (2014). Anaerobic digestion basics. *University of Idaho extension*, *6*.

Cho, H. U., Park, S. K., Ha, J. H., & Park, J. M. (2013). An innovative sewage sludge reduction by using a combined mesophilic anaerobic and thermophilic aerobic process with thermal-alkaline treatment and sludge recirculation. *Journal of environmental management*, *129*, 274-282.

Cucina, M. (2023). Integrating anaerobic digestion and composting to boost energy and material recovery from organic wastes in the circular economy framework in Europe: A review. *Bioresource Technology Reports*, 101642.

Di Maria, F., & Micale, C. (2015). Life cycle analysis of incineration compared to anaerobic digestion followed by composting for managing organic waste: the influence of system components for an Italian district. *The International Journal of Life Cycle Assessment*, *20*, 377-388.

Domínguez-Gutiérrez, M., Gaitán-Hernández, R., Moctezuma-Pérez, I., Barois, I., & Domínguez, J. (2022). Composting and vermicomposting of spent mushroom substrate to produce organic fertilizer. *Emirates Journal of Food & Agriculture (EJFA)*, *34*(3).

Ferrentino, R., Langone, M., Fiori, L., & Andreottola, G. (2023). Full-scale sewage sludge reduction technologies: a review with a focus on energy consumption. *Water*, *15*(4), 615.

Ferrer, I., Passos, F., Romero, E., Vázquez, F., & Font, X. (2024). Optimising sewage sludge anaerobic digestion for resource recovery in wastewater treatment plants. *Renewable Energy*, *224*, 120123.

Fersi, S., Chtourou, N., Jury, C., & Poncelet, F. (2015). Economic analysis of renewable heat and electricity production by sewage sludge digestion—a case study. *International Journal of Energy Research*, *39*(2), 234-243.

Fytili, D., & Zabaniotou, A. (2008). Utilization of sewage sludge in EU application of old and new methods—A review. *Renewable and sustainable energy reviews*, *12*(1), 116-140.

Ghazy, M. R., Dockhorn, T., & Dichtl, N. (2011). Economic and environmental assessment of sewage sludge treatment processes application in Egypt. *International Water Technology Journal*, *1*(2), 1-17.

Hoang, S. A., Bolan, N., Madhubashani, A. M. P., Vithanage, M., Perera, V., Wijesekara, H., ... & Siddique, K. H. (2022). Treatment processes to eliminate potential environmental hazards and restore agronomic value of sewage sludge: A review. *Environmental Pollution*, *293*, 118564.

Hong, J., Hong, J., Otaki, M., & Jolliet, O. (2009). Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan. *Waste Management*, *29*(2), 696-703.

Hort Innovation. (2019). Mushroom production waste streams: novel approaches to management and value creation. In *https://www.horticulture.com.au/growers/help-your-business-grow/research-reports-publications-fact-sheets-and-more/mu17005/*. Retrieved August 22, 2024, from https://www.horticulture.com.au/globalassets/laserfiche/assets/project-reports/mu17005/ms190---final-report---public.pdf

Huiru, Z., Yunjun, Y., Liberti, F., Pietro, B., & Fantozzi, F. (2019). Technical and economic feasibility analysis of an anaerobic digestion plant fed with canteen food waste. *Energy Conversion and Management*, *180*, 938-948.

Jensen, M. B., Møller, J., & Scheutz, C. (2017). Assessment of a combined dry anaerobic digestion and post-composting treatment facility for source-separated organic household waste, using material and substance flow analysis and life cycle inventory. *Waste management*, *66*, 23-35.

Kalderis, D., Aivalioti, M., & Gidarakos, E. (2010). Options for sustainable sewage sludge management in small wastewater treatment plants on islands: The case of Crete. *Desalination*, *260*(1-3), 211-217.

Kim, W. K., Lorenz, E. S., & Patterson, P. H. (2002). Effect of enzymatic and chemical treatments on feather solubility and digestibility. *Poultry science*, *81*(1), 95-98.

Lanko, I., Flores, L., Garfí, M., Todt, V., Posada, J. A., Jenicek, P., & Ferrer, I. (2020). Life cycle assessment of the mesophilic, thermophilic, and temperature-phased anaerobic digestion of sewage sludge. *Water*, *12*(11), 3140.

Lanko, I., Flores, L., Garfí, M., Todt, V., Posada, J. A., Jenicek, P., & Ferrer, I. (2020). Life cycle assessment of the mesophilic, thermophilic, and temperature-phased anaerobic digestion of sewage sludge. *Water*, *12*(11), 3140.

Li, H., Jin, C., Zhang, Z., O'Hara, I., & Mundree, S. (2017). Environmental and economic life cycle assessment of energy recovery from sewage sludge through different anaerobic digestion pathways. *Energy*, *126*, 649-657.

Li, Y., Manandhar, A., Li, G., & Shah, A. (2018). Life cycle assessment of integrated solid state anaerobic digestion and composting for on-farm organic residues treatment. *Waste Management*, *76*, 294-305.

Lin, L., Xu, F., Ge, X., & Li, Y. (2018). Improving the sustainability of organic waste management practices in the food-energy-water nexus: A comparative review of anaerobic digestion and composting. *Renewable and Sustainable Energy Reviews*, *89*, 151-167.

Liu, S., Zhu, N., & Li, L. Y. (2011). The one-stage autothermal thermophilic aerobic digestion for sewage sludge treatment. *Chemical Engineering Journal*, *174*(2-3), 564-570.

Liu, X., Han, Z., Yang, J., Ye, T., Yang, F., Wu, N., & Bao, Z. (2018, February). Review of enhanced processes for anaerobic digestion treatment of sewage sludge. In *IOP Conference Series: Earth and Environmental Science* (Vol. 113, No. 1, p. 012039). IOP Publishing.

Maher, M. J., Magette, W. L., Smyth, S., Duggan, J., Dodd, V. A., Hennerty, M. J., & McCabe, T. (2000). *Managing spent mushroom compost*. Teagasc.

Makan, A., & Fadili, A. (2020). Sustainability assessment of large-scale composting technologies using PROMETHEE method. *Journal of Cleaner Production*, *261*, 121244.

Muduli, S., Champati, A., Popalghat, H. K., Patel, P., & Sneha, K. R. (2019). Poultry waste management: An approach for sustainable development. *Int. J. Adv. Sci. Res*, *4*(1), 8-14.

Murphy, J. D., & Power, N. M. (2006). A technical, economic and environmental comparison of composting and anaerobic digestion of biodegradable municipal waste. *Journal of Environmental Science and Health Part A*, *41*(5), 865-879.

Murray, A., Horvath, A., & Nelson, K. L. (2008). Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-use scenarios: a case study from China.

Nasir, I. M., Mohd Ghazi, T. I., & Omar, R. (2012). Anaerobic digestion technology in livestock manure treatment for biogas production: a review. *Engineering in Life Sciences*, *12*(3), 258-269.

Othman, N. Z., Sarjuni, M. N. H., Rosli, M. A., Nadri, M. H., Yeng, L. H., Ying, O. P., & Sarmidi, M. R. (2020). Spent mushroom substrate as biofertilizer for agriculture application. *Valorisation of Agro-industrial Residues–Volume I: Biological Approaches*, 37-57.

Paranjpe, A., Saxena, S., & Jain, P. (2023). A review on performance improvement of anaerobic digestion using co-digestion of food waste and sewage sludge. *Journal of Environmental Management*, *338*, 117733.

Sahoo, K., & Mani, S. (2019). Economic and environmental impacts of an integrated-state anaerobic digestion system to produce compressed natural gas from organic wastes and energy crops. *Renewable and sustainable energy reviews*, *115*, 109354.

Schnell, M., Horst, T., & Quicker, P. (2020). Thermal treatment of sewage sludge in Germany: A review. *Journal of environmental management*, *263*, 110367.

Serafini, L. F., Feliciano, M., Rodrigues, M. A., & Goncalves, A. (2023). Systematic review and meta-analysis on the use of LCA to assess the environmental impacts of the composting process. *Sustainability*, *15*(2), 1394.

Sillero, L., Sganzerla, W. G., Carneiro, T. F., Solera, R., & Perez, M. (2023). Techno-economic analysis of single-stage and temperature-phase anaerobic co-digestion of sewage sludge, wine vinasse, and poultry manure. *Journal of environmental management*, *325*, 116419.

Slorach, P. C., Jeswani, H. K., Cuéllar-Franca, R., & Azapagic, A. (2020). Assessing the economic and environmental sustainability of household food waste management in the UK: Current situation and future scenarios. *Science of The Total Environment*, *710*, 135580.

Slorach, P. C., Jeswani, H. K., Cuéllar-Franca, R., & Azapagic, A. (2019). Environmental and economic implications of recovering resources from food waste in a circular economy. *Science of the Total Environment*, *693*, 133516.

Solcova, O., Knapek, J., Wimmerova, L., Vavrova, K., Kralik, T., Rouskova, M., ... & Hanika, J. (2021). Environmental aspects and economic evaluation of new green hydrolysis method for waste feather processing. *Clean Technologies and Environmental Policy*, *23*, 1863-1872.

Song, U., & Lee, E. J. (2010). Environmental and economical assessment of sewage sludge compost application on soil and plants in a landfill. *Resources, conservation and recycling*, *54*(12), 1109-1116.

Spinosa, L., Ayol, A., Baudez, J. C., Canziani, R., Jenicek, P., Leonard, A., ... & Van Dijk, L. (2011). Sustainable and innovative solutions for sewage sludge management. *Water*, *3*(2), 702-717.

Suh, Y. J., & Rousseaux, P. (2002). An LCA of alternative wastewater sludge treatment scenarios. *Resources, conservation and recycling*, *35*(3), 191-200.

Tan, W. E., Liew, P. Y., Tan, L. S., Woon, K. S., Mohammad Rozali, N. E., Ho, W. S., & NorRuwaida, J. (2022). Life cycle assessment and techno-economic analysis for anaerobic digestion as cow manure management system. *Energies*, *15*(24), 9586.

Teoh, S. K., & Li, L. Y. (2020). Feasibility of alternative sewage sludge treatment methods from a lifecycle assessment (LCA) perspective. *Journal of Cleaner Production*, *247*, 119495.

Tomei, M. C., Rita, S., & Mininni, G. (2011). Performance of sequential anaerobic/aerobic digestion applied to municipal sewage sludge. *Journal of environmental management*, *92*(7), 1867-1873.

Wei, Y. S., Fan, Y. B., & Wang, M. J. (2001). A cost analysis of sewage sludge composting for small and mid-scale municipal wastewater treatment plants. *Resources, conservation and recycling*, *33*(3), 203-216.

Xiao, H., Zhang, D., Tang, Z., Li, K., Guo, H., Niu, X., & Yi, L. (2022). Comparative environmental and economic life cycle assessment of dry and wet anaerobic digestion for treating food waste and biogas digestate. *Journal of Cleaner Production*, *338*, 130674.

Yoshida, H., ten Hoeve, M., Christensen, T. H., Bruun, S., Jensen, L. S., & Scheutz, C. (2018). Life cycle assessment of sewage sludge management options including long-term impacts after land application. *Journal of Cleaner Production*, *174*, 538-547.

Zaini, N. S. M., Basri, N. E. A., Zain, S. M., & Saad, N. F. M. (2015). Selecting the best composting technology using analytical hierarchy process (AHP). Jurnal Teknologi, 77(1).

4 Results: Assessment of environmental impacts prevention and control costs

All seven value chains for seven alternative fertilisers were examined for their overall damage costs. For most cases, alternative fertilisers have overall less damage costs than their baseline. Although the results cannot be taken as facts due to lack of standardisation in quantification method for these monetarisation factors, but these calculations can help to highlight impacts from which the most ‘economical’ burdens emerge for each specific case even if the impacts are not significant.

4.1 Urban waste water struvite

The average of the total damage costs for all three regions equals 422 € per tonne of struvite, which is less 75 € less than the baseline non-renewable fertilisers. For struvite, the highest share of costs of about 64 % is originating from impact category ‘Particulate matter’, followed by 20 % share of costs from category ‘Climate Change’. Comparing this with the weighting results of the environmental assessment, climate change and particulate matter have similar influences with third highest impacts among the top categories with 80% of the impacts.

Baseline non-recovered fertiliser (NRF) have 38 %, 34 % and 12 % share of costs in impact category of Particulate matter, Climate change and Eutrophication marine, respectively. In environmental impacts weighting results, Climate change is second and Particulate matter is the third most impactful category.

Table 16: Total costs for Urban waste water struvite LCA – EUR, year: 2022.

Impact category and unit	Damage costs - Circular fertiliser			Damage costs - Baseline
Acidification [Mole of H+ eq.]	North	Central	Mediterranean	
Climate Change [kg CO2 eq.]	17.27	17.42	17.27	11.50
Climate Change [kg CO2 eq.]	78.79	90.56	78.79	169.59
Ecotoxicity, freshwater [CTUe]	0.37	0.40	0.37	0.99
Eutrophication, freshwater [kg P eq.]	14.07	14.44	14.07	14.46
Eutrophication, marine [kg N eq.]	17.56	17.88	17.56	58.89

Impact category and unit	**Damage costs - Circular fertiliser**			**Damage costs - Baseline**
Eutrophication, terrestrial [Mole of N eq.]	-	-	-	-
Human toxicity, cancer [CTUh]	2.67	2.74	2.67	3.60
Human toxicity, non-cancer [CTUh]	1.03	1.19	1.03	2.96
Ionising radiation, human health [kBq U235 eq.]	0.19	0.13	0.19	0.06
Land Use [Pt]	3.60	4.16	3.60	13.75
Ozone depletion [kg CFC-11 eq.]	0.00	0.00	0.00	0.00
Particulate matter [Disease incidences]	267.41	269.17	267.41	190.63
Photochemical ozone formation, human health [kg NMVOC eq.]	4.47	4.67	4.47	7.93
Resource use, fossils [MJ]	8.93	8.71	8.93	19.17
Resource use, mineral and metals [kg Sb eq.]	0.01	0.01	0.01	0.03
Water use [m³ world equiv.]	0.41	0.25	0.41	3.54
Sum	416.79	431.74	416.79	497.09
Average		**421.77**		**497.09**

4.2 Industrial waste water struvite

The average of the total damage costs for all three regions equals 437 € per tonne of struvite, which is less 88 € less than the baseline non-renewable fertilisers. Struvite recovered from industrial waste water (IWW) has 15 € more damage costs than urban waste water.

For industrial waste water struvite and for the NRF the trend in impact categories' share of costs is quite similar. Particulate matter and climate change share about on average 38 % and 35 %, respectively of the overall costs. The other most prominent costs are originating from Eutrophication marine at 11 %. Compared with most environmental impact categories, Particulate matter is at third position with 15 % for IWW struvite and climate change is at third position for NRF with 14 % of the impacts.

Table 17: Total costs for Industrial waste water struvite LCA – EUR, year: 2022.

Impact category and unit	Damage costs - Circular fertiliser			Damage costs - Baseline
Acidification [Mole of H+ eq.]	North	Central	Mediterranean	
Climate Change [kg CO2 eq.]	9.43	9.55	9.43	11.95
Climate Change [kg CO2 eq.]	129.47	195.35	132.16	185.87
Ecotoxicity, freshwater [CTUe]	0.65	0.71	0.66	1.43
Eutrophication, freshwater [kg P eq.]	6.11	8.18	6.25	14.42
Eutrophication, marine [kg N eq.]	53.57	54.43	53.73	54.71
Eutrophication, terrestrial [Mole of N eq.]	-	-	-	-
Human toxicity, cancer [CTUh]	0.61	0.64	0.55	0.58
Human toxicity, non-cancer [CTUh]	2.72	3.76	2.78	3.10
Ionising radiation, human health [kBq U235 eq.]	0.74	0.37	0.67	0.12
Land Use [Pt]	13.86	10.72	8.77	19.52
Ozone depletion [kg CFC-11 eq.]	0.00	0.00	0.00	0.00
Particulate matter [Disease incidences]	163.69	161.55	161.54	200.35
Photochemical ozone formation, human health [kg NMVOC eq.]	3.33	3.60	3.74	4.69
Resource use, fossils [MJ]	24.72	29.97	31.54	23.39
Resource use, mineral and metals [kg Sb eq.]	0.03	0.03	0.03	0.03
Water use [m³ world equiv.]	3.86	3.65	3.71	4.78
Sum	412.77	482.50	415.56	524.94
Average		**436.94**		**524.94**

4.3 Stabilised sludge

For stabilised sludge from sewage sludge, the average of the total damage costs for all three regions equals 34 € per tonne of stabilised sludge which is 79 € less than the NRF. For stabilised sludge the most costs are emerging from Climate change, Eutrophication marine and ¨Particulate matter at 46 %, 30 % and 18 %, respectively. For NRF most share of costs at 36 % is from Particulate matter, followed by Climate change at 34 %.

In contrast with the weighting results of environmental assessment, Eutrophication marine and Climate change are the second and third most impactful categories for stabilised sludge. In the case of NRF, Climate change and Particulate matter are in the top six categories.

Table 18: Total costs for Stabilised sludge LCA – EUR, year: 2022.

Impact category and unit	**Damage costs - Circular fertiliser**			**Damage costs - Baseline**
Acidification [Mole of H+ eq.]	North	Central	Mediterranean	
Climate Change [kg CO2 eq.]	0.47	0.50	0.40	2.47
Climate Change [kg CO2 eq.]	17.88	17.30	11.54	38.88
Ecotoxicity, freshwater [CTUe]	0.07	0.04	0.03	1.43
Eutrophication, freshwater [kg P eq.]	2.18	2.23	2.14	2.31
Eutrophication, marine [kg N eq.]	9.79	9.90	9.90	10.51
Eutrophication, terrestrial [Mole of N eq.]	-	-	-	-
Human toxicity, cancer [CTUh]	0.01	0.01	-0.01	0.14
Human toxicity, non-cancer [CTUh]	0.11	0.13	0.05	0.70
Ionising radiation, human health [kBq U235 eq.]	0.01	0.01	-0.07	0.03
Land Use [Pt]	0.46	0.33	-0.01	4.65
Ozone depletion [kg CFC-11 eq.]	0.00	0.00	0.00	0.00
Particulate matter [Disease incidences]	6.51	6.38	5.15	40.69
Photochemical ozone formation, human health [kg NMVOC eq.]	0.93	0.88	0.75	1.75
Resource use, fossils [MJ]	2.09	1.03	-1.84	9.03
Resource use, mineral and metals [kg Sb eq.]	0.00	0.00	0.00	0.01
Water use [m³ world equiv.]	-1.39	-1.46	-2.06	0.88
Sum	39.15	37.28	25.97	113.47
Average		**34.14**		**113.47**

4.4 Composted biowaste

For composted bio-waste the average of the total damage costs for all three regions equals 233 € per tonne of compost which is 97 € more than the NRF. Highest costs are of category Particulate matter with 39 % of share, followed by Climate change at 29 % and Human toxicity non-cancer at 18 %. These categories are completely different from the categories with the highest environmental impacts, which is primarily just Land use.

For the NRF, Climate change accounts for 39 % of the total costs, followed by Particulate matter at 29 %, Resource use fossils about 14 % and Eutrophication marine at 11 %. Resource depletion fossils reports 50 % of the total environmental impacts in weighting for NRF.

Table 19: Total costs for Composted bio-waste LCA – EUR, year: 2022.

Impact category and unit	**Damage costs - Circular fertiliser**			**Damage costs - Baseline**
Acidification [Mole of H+ eq.]	North	Central	Mediterranean	
Climate Change [kg CO2 eq.]	5.37	5.24	5.16	2.65
Climate Change [kg CO2 eq.]	73.97	64.09	62.98	53.13
Ecotoxicity, freshwater [CTUe]	0.11	0.10	0.11	0.42
Eutrophication, freshwater [kg P eq.]	0.36	0.07	0.34	0.39
Eutrophication, marine [kg N eq.]	20.83	20.51	19.56	15.03
Eutrophication, terrestrial [Mole of N eq.]	-	-	-	-
Human toxicity, cancer [CTUh]	2.23	2.23	2.24	0.17
Human toxicity, non-cancer [CTUh]	41.53	41.39	41.53	2.20
Ionising radiation, human health [kBq U235 eq.]	-0.09	-0.04	-0.07	0.02
Land Use [Pt]	1.10	1.47	1.66	1.70
Ozone depletion [kg CFC-11 eq.]	0.00	0.00	0.00	0.00
Particulate matter [Disease incidences]	84.87	93.93	92.11	39.60
Photochemical ozone formation, human health [kg NMVOC eq.]	4.54	4.42	3.97	1.43
Resource use, fossils [MJ]	0.64	-0.46	-0.14	18.33
Resource use, mineral and metals [kg Sb eq.]	0.00	0.00	0.00	0.00
Water use [m³ world equiv.]	-0.14	-0.26	-0.07	0.79

Impact category and unit	**Damage costs - Circular fertiliser**			**Damage costs - Baseline**
Sum	235.33	232.69	229.37	135.86
Average		**232.46**		**135.86**

4.5 Feather meal

For feather meal, the average of the total damage costs for all three regions equals 968 € per tonne of fertiliser which is 588 € more than the NRF. The most costs are emerging from Particulate matter, Climate change, Eutrophication marine and at 63 %, 16 % and 13 %, respectively. NRF similarly has the highest costs of 48 % Particulate matter, 26 % Climate change and 19 % Eutrophication marine.

Environmental impact results indicate Particulate matter as the second most significant category for feather meal and for NRF. Climate change is at third position with most impacts for feather meal and Eutrophication marine for NRF.

Table 20: Total costs for Feather meal LCA – EUR, year: 2022.

Impact category and unit	**Damage costs - Circular fertiliser**			**Damage costs - Baseline**
Acidification [Mole of H+ eq.]	North	Central	Mediterranean	
Climate Change [kg CO2 eq.]	36.78	37.87	37.66	11.26
Climate Change [kg CO2 eq.]	105.00	218.32	148.52	100.12
Ecotoxicity, freshwater [CTUe]	0.24	0.35	0.31	0.15
Eutrophication, freshwater [kg P eq.]	0.12	1.88	0.57	0.05
Eutrophication, marine [kg N eq.]	123.98	125.89	125.32	71.28
Eutrophication, terrestrial [Mole of N eq.]	-	-	-	-
Human toxicity, cancer [CTUh]	0.18	0.39	0.32	0.10
Human toxicity, non-cancer [CTUh]	0.68	2.17	1.47	0.55
Ionising radiation, human health [kBq U235 eq.]	0.31	0.23	0.48	0.01
Land Use [Pt]	5.69	10.52	8.60	1.54
Ozone depletion [kg CFC-11 eq.]	0.00	0.00	0.00	0.00
Particulate matter [Disease incidences]	595.28	621.96	618.63	183.34

Impact category and unit	**Damage costs - Circular fertiliser**			**Damage costs - Baseline**
Photochemical ozone formation, human health [kg NMVOC eq.]	1.51	3.56	3.49	0.89
Resource use, fossils [MJ]	9.57	25.63	27.20	9.75
Resource use, mineral and metals [kg Sb eq.]	0.00	0.00	0.00	0.00
Water use [m³ world equiv.]	0.81	1.17	1.29	0.50
Sum	880.18	1049.93	973,88	379,56
Average		**967.99**		**379.56**

4.6 Solid fraction of digestate

In the case of solid fraction of digestate (SFD), the total damage costs vary a lot according to the region. For central region the costs are only 0.5 €/tonne of fertiliser, indicating almost zero damage costs. For northern region the costs are highest at 95 €/tonne of fertiliser. The difference in total damage costs is emerging from variation in impacts due to different share of feed stocks (manure, sewage sludge and food waste) in varying regions. Central region has 93 % share of manure, whereas north has 67 % and 30 % share of manure and sewage sludge, respectively. The most share of costs is of category Particulate matter, Human Toxicity non-cancer and Eutrophication marine. In case of northern regions, Particulate matter and Human Toxicity non-cancer share the same weight of costs. For the NRF, the biggest segment of costs is originating from Climate change at 38 %, followed by Particulate matter at 31 % and approximately 18 % of Resource use fossils and Eutrophication marine.

Contrasting these results with the environmental assessment, cost dominating impact categories do not have any similarities with environmental impact categories for solid fraction of digestate. However, for NRF 42 % of the total weighted impacts are arising from Resource use fossils.

Table 21: Total costs for Solid fraction of digestate LCA – EUR, year: 2022.

Impact category and unit	**Damage costs - Circular fertiliser**			**Damage costs - Baseline**
Acidification [Mole of H+ eq.]	North	Central	Mediterranean	
Climate Change [kg CO2 eq.]	2.86	2.51	2.69	0.91
Climate Change [kg CO2 eq.]	-11.32	-52.30	-40.30	16.85
Ecotoxicity, freshwater [CTUe]	-0.79	-1.26	-1.20	0.14

Impact category and unit	Damage costs - Circular fertiliser			Damage costs - Baseline
Eutrophication, freshwater [kg P eq.]	0.36	-0.21	0.17	0.24
Eutrophication, marine [kg N eq.]	13.72	12.30	12.62	5.03
Eutrophication, terrestrial [Mole of N eq.]	-	-	-	-
Human toxicity, cancer [CTUh]	4.47	0.90	1.31	0.06
Human toxicity, non-cancer [CTUh]	50.30	15.03	19.57	0.62
Ionising radiation, human health [kBq U235 eq.]	-0.12	-0.10	-0.15	0.01
Land Use [Pt]	-1.45	-5.07	-4.10	0.68
Ozone depletion [kg CFC-11 eq.]	0.00	0.00	0.00	0.00
Particulate matter [Disease incidences]	51.24	49.24	49.83	13.44
Photochemical ozone formation, human health [kg NMVOC eq.]	2.01	0.15	0.37	0.50
Resource use, fossils [MJ]	-8.51	-16.59	-15.56	5.19
Resource use, mineral and metals [kg Sb eq.]	-0.01	-0.01	-0.01	0.00
Water use [m³ world equiv.]	-7.46	-4.11	-4.22	0.28
Sum	95.30	0.47	21.01	43.95
Average	**Not calculated due to high variance**			**43.95**

4.7 Spent mushroom substrate

For spent mushroom substrate (SMS), the average of the total damage costs for all three regions equals 136 € per tonne of fertiliser which is 43 € more than the NRF. The most costs are reflected by Climate change, Particulate matter, Human toxicity non-cancer, and Eutrophication marine at 42 %, 31 %, 15 % and 6 %, respectively. NRF also have the most costs for Climate change at 41 %, followed by Particulate matter at 28 % but then 13 % by Resource use fossils and lastly 10 % by Eutrophication marine category.

Judging the cost segmentation with the environmental impact assessment, cost dominating impact categories do not have any matches with environmental impact categories for SMS. On the contrary, for NRF 35 % of the total weighted impacts are arising from Resource use fossils.

Table 22: Total costs for Spent mushroom substrate LCA – EUR, year: 2022.

Impact category and unit	**Damage costs - Circular fertiliser**			**Damage costs - Baseline**
Acidification [Mole of H+ eq.]	North	Central	Mediterranean	
Climate Change [kg CO2 eq.]	2.58	2.54	2.60	1.76
Climate Change [kg CO2 eq.]	56.88	57.80	55.05	37.90
Ecotoxicity, freshwater [CTUe]	0.03	0.03	0.03	0.51
Eutrophication, freshwater [kg P eq.]	0.46	0.49	0.46	0.50
Eutrophication, marine [kg N eq.]	8.66	8.70	8.70	9.28
Eutrophication, terrestrial [Mole of N eq.]	-	-	-	-
Human toxicity, cancer [CTUh]	0.65	0.65	0.64	0.14
Human toxicity, non-cancer [CTUh]	20.66	20.67	20.69	1.41
Ionising radiation, human health [kBq U235 eq.]	0.01	0.01	0.01	0.02
Land Use [Pt]	0.28	0.24	0.21	2.00
Ozone depletion [kg CFC-11 eq.]	0.00	0.00	0.00	0.00
Particulate matter [Disease incidences]	40.36	44.47	41.10	26.22
Photochemical ozone formation, human health [kg NMVOC eq.]	0.76	0.81	4.33	1.13
Resource use, fossils [MJ]	0.55	0.66	0.65	11.76
Resource use, mineral and metals [kg Sb eq.]	0.00	0.00	0.00	0.00
Water use [m³ world equiv.]	1.28	1.29	1.27	0.67
Sum	133.14	138.35	135.75	93.28
Average		**135.75**		**93.28**

4.8 Conclusions

For most alternative fertilisers the highest share of damage costs was mostly originating from Particulate matter followed by Climate change category. Other prominent categories were Eutrophication marine, Resource use fossils and Human toxicity non-cancer. For most value chains, the actual characterised impacts from Particulate matter are very insignificant, but its monetisation factor for damage costs is very high, this is also the case for Human toxicity non-cancer. Whereas in the case of Climate change, the monetisation factor is low but impact characterisation results are higher. Monetisation factors are also low for Eutrophication marine and Resource use fossils, comparatively.

5 References

Amadei, A. M., De Laurentiis, V., & Sala, S. (2021). A review of monetary valuation in life cycle assessment: State of the art and future needs. Journal of Cleaner Production, 329, 129668.

Environmental Prices Handbook EU28 version - CE Delft - EN. (2021, December 7). CE Delft - EN. https://cedelft.eu/publications/environmental-prices-handbook-eu28-version/

External costs : energy costs, taxes and the impact of government interventions on investments : final report. (2020). Publications Office of the EU. https://op.europa.eu/en/publication-detail/-/publication/91a3097c-1747-11eb-b57e-01aa75ed71a1/language-en

Eco-costs estimate EPDs - Sustainability Impact Metrics. (2024, January 3). Sustainability Impact Metrics. https://www.ecocostsvalue.com/lca/eco-costs-estimate-epds/

“This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement N° 101060426.”

fertiplay

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.