John Nurminen Foundation

Sustainable future usage or disposal possibilities of sewage sludge -based biomasses in Finland

Report

Table of contents

Sustainable future usage or disposal possibilities of sewage sludge -based biomasses in Finland

1 Introduction

1.1 Background

Sewage sludge is semisolid residual material that is separated during wastewater treatment. It consists typically of solid material of influent wastewater separated in physical wastewater treatment units, precipitates that result from chemical wastewater treatment, waste sludge from biological wastewater treatment units as well as dissolved compounds and colloidal material in wastewater.

The treatment and utilisation of sewage sludge has been a subject of much debate in recent years, both in Finland and in other countries. Various decisions have been made across Europe on the treatment and utilisation of sludge, and in particular on its utilisation *e.g.* in soil improvement and nutrient use (Hudcová *et al.* 2019, Bauer *et al.* 2020). There are many different aspects involved, such as the disposal of sludge-based biomasses treated in different ways, the utilisation of the energy and nutrient content of the sludge, health and environmental impacts, logistical issues, cost impacts, and brand image issues of companies. For instance in Finland, sewage sludge and its treatment processes have been studied during recent years with focus on techno-economics (Suomen Vesilaitosyhdistys ry 2019), resource recovery (Aatsinki 2021, Lehtoranta *et al.* 2021), fertiliser value and impacts on food chain (Ylivainio *et al.* 2020), risks caused by pollutants (Laine-Ylijoki *et al.* 2015, Vieno *et al.* 2018) and environmental impacts (Suomen Vesilaitosyhdistys ry 2021b, Havukainen *et al.* 2022).

In Finland, 46 % of sewage sludge is used in agriculture after treatment such as anaerobic digestion and/or composting (Suomen Vesilaitosyhdistys ry 2021). However, agriculture use of sewage-based biomasses may be subject to change during the forthcoming decades. For instance, in the neighboring country Sweden, ban of spreading sludge on farmland has been seriously debated in the government (Government Offices of Sweden 2020, Ekane *et al.* 2021). In addition, market-related barriers exist as some of the large Finnish food industry companies have prohibited use of grains fertilised with sewage digestate in their products (see *e.g.* Konola 2019). The European Commission is also currently evaluating urban wastewater treatment directive (91/271/EEC) and agricultural use of sewage sludge directive (86/278/EEC). The changes compared to the requirements set in the current directives are not known yet, which creates uncertainty among the stakeholders in Finland and elsewhere in the EU.

This background motivates the analysis of alternative technological routes for sludge-based nutrient management in near future and the improvement of current practices. The study was done as part of Sustainable Biogas project (https://sustainablebiogas.eu), and its Work Package "*Usage and disposal possibilities for sewage-based biomasses*". Sustainable Biogas project is funded by the Interreg Central Baltic Programme.

This report was prepared by process specialist Henri Haimi, leading adviser Jutta Laine-Ylijoki and environmental specialist Henna Punkkinen from FCG Finnish Consulting Group Ltd.

1.2 Structure of the work

In this report, we first describe the operational framework of sewage sludge management in Finland (Chapter 2. Then the studied sewage sludge management scenarios are described in Chapter 3. Four scenarios for sludge treatment and disposal in Finland were defined in collaboration with the steering group of the study. These include a business-as-usual (BAU) scenario representing the current situation and three scenarios describing potential future sludge treatment options implemented with different treatment technologies for the period 2021-2040. The future scenarios cover technological options such as biogas production, combustion and thermo-chemical treatment of sludge and nutrient recovery.

The sludge scenarios were subject to an impact analysis comparing their costs and analysis of certain environmental and circular economy aspects (Chapter 4). Impact analysis was done using calculation methods (*e.g.* mass balances of the scenarios, carbon footprint) and expert evaluation. Finally, conclusions and insights based on the work done are provided in Chapter 5.

As a part of the project, a stakeholder workshop was organized on February 14, 2022. The aim was to collect feedback on the scenarios and the impact analysis, as well as ideation of feasible solutions for sludge utilisation in interaction with the stakeholders. In addition, measures and policy instruments for the treatment and recovery of sewage sludge were discussed. Altogether 34 experts representing authorities and stakeholders involved in the sewage sludge value chain participated in the workshop. The workshop is documented in Appendix 2.

The main outcomes of the workshop were the following:

- Reducing the risks associated with harmful substances and by doing so, enabling nutrient recycling were prioritized as sludge management objectives
- Only minor modifications for the configurations of sludge management scenarios were suggested, whereas comments on them most often concerned pollutant degradation in processes, nutrient management, and economic aspects
- The majority of comments related on new policy instruments concerned nutrient recovery and recycling, which implies that even though there are drivers for these, the market situation is not yet favorable for secondary fertilisers.
- The challenges related to harmful pollutants were approached from two viewpoints. The first one called for measures for reducing risks of using sludge-based biomasses, *e.g.* more comprehensive monitoring of sludge properties, understanding of exposure routes and setting more strict requirements for sewerage of industrial effluents. The other suggested approach was transition to sludge treatment technologies that remove pollutants and providing investment support for such technology.
- The climate impacts of sludge management were discussed from viewpoints of benefits received from carbon stored in biochar and of potential measures for improving accuracy of carbon footprint assessments.

2 Operational framework of sewage sludge management in Finland

2.1 Sludge generation and nutrient content

Approximately 21 million tons of biomass is generated in Finland annually (Marttinen *et al.* 2017), sewage sludge being one of the biomass types. Biomasses contain organic matter and nutrients among other compounds and substances. The shares of amounts of biomasses from different sources in Finland in 2014–2016 are presented in Figure 1. The biomass shares are expected to describe the current situation well even though some minor changes in generation of some biomass types might have taken place. The share of municipal and industrial wastewater sludge is around 3 % of the total biomass. Livestock manure represents the largest share of the total biomass, approximately 82 %.

Biomass of sewage sludge in report of Marttinen *et al.* (2017) was estimated to be 667 000 t/a whereas in recent report of Suomen Vesilaitosyhdistys ry. (2021) it was estimated to be 813 000 t/a. Therefore, biomass share of sewage sludge may be slightly higher than calculated by Marttinen *et al.* (2017), but presumably not more than 5 %.

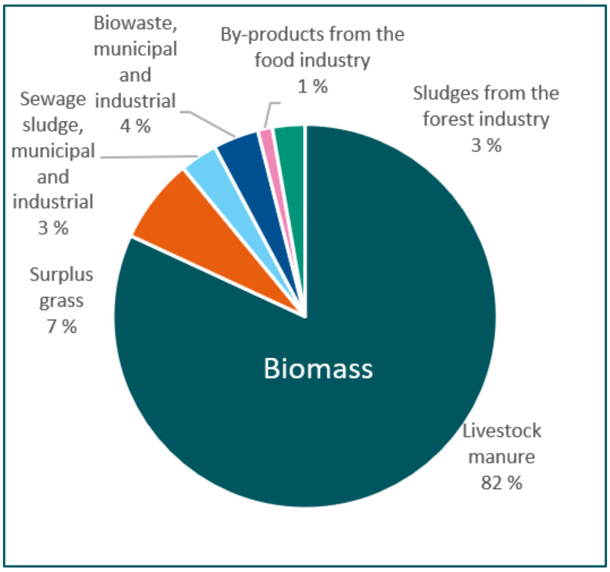

Figure 1. *Shares of the amounts (t/a) of biomasses from different sources generated in Finland in 2014–2016 (modified from Marttinen et al. 2017).*

The total amount of phosphorus in the biomasses generated annually in Finland is approximately 26 000 tons (Marttinen *et al.* 2017). The shares of different sources in Finland in 2014–2016 are presented in Figure 2a. Sewage sludge contained approximately 11 % of the phosphorus content of all the biomasses.

The total amount of nitrogen in the biomasses generated annually in Finland is around 95 000 tons (Marttinen *et al.* 2017). The shares of different sources in Finland in 2014–2016 are presented in Figure 2b. Sewage sludge contained approximately 4 % of the nitrogen content of all the biomasses.

If differences in estimations of yearly sewage sludge amounts discussed above are taken into consideration, the shares of sewage sludge nutrients of all biomass nutrients may be slightly (1–2 %) higher.

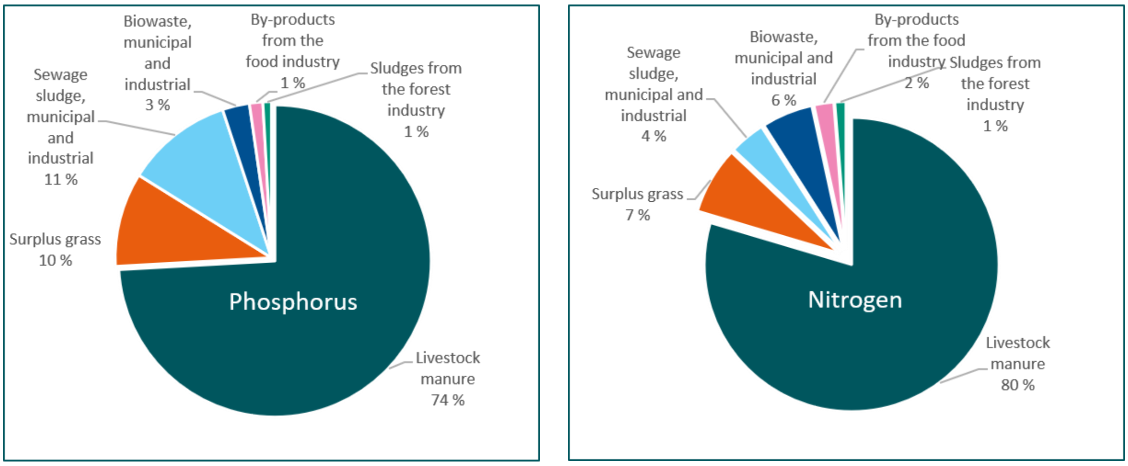

Figure 2. *Shares of the amounts (t/a) of phosphorus (a) and nitrogen (b) in biomasses from different sources generated in Finland in 2014–2016 (modified from Marttinen et al. 2017).*

2.2 Legislative and policy framework

Managing waste-based resources, including sewage sludge, in a sustainable way, plays an important part in reaching the various goals set out in Europe for material resource efficiency, circular economy and raw material policies.

Various targets set out in the EU legislation are already being implemented, but waste management still faces a number of challenges; such as finding balance between promoting recycling and protecting people and environment against harmful chemical substances in recycled materials; insufficient information and quality aspects related to recycling; energy recovery of waste; and waste prevention. Here, the shift towards a more circular economy that benefits environment, human health and economy, is regarded as a great opportunity.

In this section the legislative environment within waste to products framework is described. Both legislation for products and those for targeting waste management and recycling as well as hazardous substances in products and recycling are brought out.

2.2.1 Waste and environmental legislation

Sewage sludges and digestates are wastes by default and their treatment falls under environmental and waste legislation in Finland. Generally, the waste treatment is regulated by the new Waste Act (714/2021).

The classification of waste as non-hazardous or hazardous is regulated by the Waste framework directive (WFD) 2018/851. Classification criteria related to the properties that may render waste hazardous are regulated in the Annex III to the WFD, while classification criteria related to the waste source and waste type is regulated in the European List of Waste (LoW). The Commission Regulation No 1357/2014 defines the hazardous properties for hazardous waste classification as well as substance-specific limit values. It also refers to other properties that may render a waste material hazardous but it does not always prescribe the test methods to be used to assess these properties. (Stenmarck *et al.* 2017)

In Finland, the classification of waste is implemented in Government Decree on Waste (978/2021) (Annex III). Possible European Waste Catalogue (EWC) codes for sewage sludges, depending on their origin and properties, may include *e.g.* (Waste marked with an asterisk (*) is hazardous waste):

- 19 06 04 digestate from anaerobic treatment of municipal waste
- 19 08 05 sludges from treatment of urban wastewater (*e.g.* non-stabilised sludge, digested sludge, lime-stabilised sludge, thermally treated sludge, sludge treated by other pathogen reduction processes, composted sludge from treatment of municipal wastewater)
- 19 08 11* sludges containing hazardous substances from biological treatment of industrial wastewater
- 19 08 13* sludges containing hazardous substances from other treatment of industrial wastewater
- 20 03 04 septic tank sludge

The producer of sewage sludge shall ensure that the quality of the sludge is determined in accordance with the Annex 4 on the Government Decree on Waste. In addition, accounting and reporting obligations are laid down in the Decree.

Prevention of environmental pollution from waste is regulated by the **Environmental Protection Act** (527/2014) and prevention of health hazards from waste by the **Health Protection Act** (763/1994) In the Section 9 of the Environmental Protection Act it is stated that: *"Government decrees to prevent environmental pollution - Further provisions on specifying the obligations laid down in sections 7 and 8 concerning the prevention of environmental pollution may be issued by government decree on the limitation of the release or depositing of sludge in the environment or the prohibition of the release or depositing of sludge in the environment that poses a risk of environmental pollution."*

In addition, the Environmental Protection Act regulates on the need for environmental permit. Basically, the permit is needed for the treatment of sewage sludges and digestates. Exceptions to the permit requirement include (Section 32): "*the recovery and use of wastewater sludge, septage, cesspool sludge or dry closet waste, treated so as to render the waste harmless, or harmless ash or slag, in accordance with the Fertiliser Product Act (539/2006)",* and materials that have undergone the by-product or End-of-Waste (EoW) procedure.

Waste ceases to be waste when it meets the EoW criteria defined by the EC in the Waste Framework Directive. The classification is carried out on a case-by-case basis. If criteria are fulfilled, the material will no longer be classified as waste, but will instead be-come a product subject to free trade and use, but also to product requirements, such as REACH obligations. WFD regulates the circumstances under which certain specified types of waste cease to be waste. This "end-of-waste" status is reached when the waste has undergone a recovery operation, including recycling, and complies with specific criteria to be developed in accordance with certain cumulative conditions. According to section 5 b of the Finnish Waste Act (646/2011), waste that has been recycled or otherwise recovered is no longer waste if:

- it is to be used for special purposes;
- it has a market or demand;
- it meets the technical requirements appropriate to its intended use and complies with the regulations and standards applicable to similar products; and

- its use as a whole does not pose a risk to or harm to health or the environment.

Waste can also be classified as a by-product, for example as part of an environmental permit procedure. By-products can be products that are generated alongside the main product as an integral part of the production process and for which there is a continuous potential for utilisation. The criteria for classification of by-products are also laid down in the Finnish Waste Act.

In the Article 19 of the *"Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003"* it is stated that *"This Regulation lays down criteria in accordance with which material that constitutes waste, as defined in Directive 2008/ 98/EC, can cease to be waste, if it is contained in a compliant EU fertilising product. In such cases, the recovery operation under this Regulation shall be performed before the material ceases to be waste, and the material shall be considered to comply with the conditions laid down in Article 6 of that Directive and therefore to have ceased to be waste from the moment that the EU declaration of conformity was drawn up."*

2.2.2 Persistent Organic Pollutants, the POPs Regulation

POP (Persistent Organic Pollutant) compounds are long-distance transported compounds that are highly persistent, toxic and accumulate in organisms. Most of these compounds have been used as industrial chemicals, flame retardants or pesticides, and some are pollutants or are formed unintentionally, for example during combustion. POPs are among the most harmful environmental toxins, as they persist in the environment for long periods and can cause harm to humans and the environment at low concentrations. Their long-term or combined effects are not yet known. (Ymparisto.fi 2019) Municipal wastewater typically contains a large number of POP compounds that originate from various sources and many of these compounds are absorbed in the sewage sludge (Haimi & Mannio 2008, Kasurinen *et al.* 2014).

The Stockholm Convention entered into force in 2004 and is an international agreement with the aim of reducing and eliminating production, use and release of POPs. The convention comprises production (both intentional and unintentional), use, waste management and environmental supervision of POPs. The Stockholm Convention currently includes 28 substances. In addition, it was agreed to add two new substances to the agreement in 2019. All countries signing the convention shall present implementation plans to limit or phase out emissions of POPs. (Stenmarck *et al.* 2017, Ymparisto.fi 2019)

In Finland the obligations of the Stockholm convention, the POP-protocol of the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) and the Basel Convention provisions for POP-waste are fulfilled by the implementation of Regulation (EU) 2019/1021 on Persistent Organic Pollutants. The regulation is the EU tool of limiting substances listed in the Stockholm Convention and the POPs Protocol. The regulation currently bans or restricts the production and use of the following substances: adrin, chlordane, chlordecone, endosulfan, dieldrin, endrin, hexabromobiphenyl, mirex, toxaphene, DDT, heptachlor, polychlorinated biphenyls (PCB), hexachlorocyclohexanes (HCH) including lindane, polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/PCDF), polycyclic aromatic hydrocarbons (PAH), hexabromocyclododecane, hexachlorobenzene, hexachlorobutadiene (HCBD), hexa-, hepta-, tetra- and pentaBDE (PBDEs), pentachlorobenzene, perfluorooctane sulfonic acid and its derivatives (PFOS), polychlorinated naphthalenes (PCN), pentachlorophenol and its salts and esters, short-chain chlorinated paraffins (SCCPs), and decabromodiphenyl ether (decaBDE). (Ymparisto.fi 2019, Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019 on persistent organic pollutants)

According to Article 7 in the regulation, waste consisting of, containing or contaminated by any substance listed in Annex IV shall be disposed of or recovered in such a way so that the POP content is destroyed or irreversibly transformed in a way that remaining waste and releases do not exhibit the POP characteristics. (Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019 on persistent organic pollutants)

2.2.3 Legislation on fertilisers

The legislation on fertilisers is under change as the legislative proposal for a new fertiliser act (HE 32/2022 vp) is currently discussed by the Finnish Parliament. Until now, the manufacture and use of fertiliser products have been regulated by the **Fertiliser Product Act** (539/2006) and the **Decree of the Ministry of Agriculture and Forestry** (24/11) and its amendments on fertiliser products. The law requires fertiliser products to be of uniform quality, safe and suitable for their purpose of use. The fertiliser product must also not cause any danger to human or animal health or safety, plant health or the environment. The Act and Decrees also contain various handling requirements and limit values for harmful metals, for example, as well as requirements for product hygiene. This means that the product must be used for beneficial purposes, otherwise it is considered as waste disposal.

According to the Act, the following products are categorized as fertiliser products: inorganic and organic fertilisers, liming materials, soil conditioners, substrates, microbial products and by-products used as fertiliser products as such. When assessing the suitability of waste-based fertiliser product, the benefits of its use for plant growth and its potential adverse effects must be considered. Certain waste-based sludges are suitable as fertiliser products as such, others need to be treated first. Currently, the most common treatment methods are screening, hygienisation and stabilisation.

Fertiliser products containing sewage sludge are subject to the same requirements as all other fertiliser products. According to the regulations, sludge-based products are soil conditioners. They are also increasingly becoming a source of plant nutrients, as they may contain significant amounts of primary and secondary nutrients.

Council Directive on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (86/278/EEC) is implemented in Finland through **Decrees 12/12 and 7/13 of the Ministry of Agriculture and Forestry**. Only treated sewage sludge can be used as fertiliser. The sludge can be treated, for example by composting, digestion or lime stabilisation. The approved treatment methods can be found in groups 3A2 and 3A5 of the type designation list. The placing on the market of organic fertiliser products is subject to obtaining a plant authorisation. Authorisation must be obtained before the sludge is handed over or sold as a fertiliser product. (Ruokavirasto 2021)

The Regulation on the limitation of certain emissions from agriculture and horticulture, the so-called Nitrates Regulation, was renewed in 2014 (1250/2014). The conditions of the Nitrates Regulation apply to all farmers who use sewage sludge-based fertiliser products. The Nitrates Regulation regulates the storage of organic fertiliser products, the structural requirements for storage, the obligation to report storage, and the use as fertiliser.

Decree of the Ministry of Agriculture and Forestry on fertiliser activities and their control (11/12) lays down the obligations for wastewater treatment plants producing fertilisers from sewage sludge and other sewage sludge treatment plants.

2.2.4 Other relevant legislation

In Finland, the incineration of sewage sludge is regulated by the **Waste Incineration Decree** (151/2013), which regulates the incineration of waste and its emissions in Finland. The revision of the Decree (1.12.2015) specifies requirements for the quality of the gas that is produced with the gasification process. In the revision (1 section, paragraph 2), it is mentioned that the requirements of WID (Waste Incineration Directive) do not apply to the product gas provided that a) the product gas is not anymore considered to be waste and b) it does not contain particulates, mercury, heavy metals, and compounds of sulphur, fluoride and chlorine, more than natural gas. In the memorandum for this revision, the text refers also pyrolysis, however, it is not mentioned that the product from pyrolysis process is liquid and not gas. It must be noted that the total rated thermal input does not have any influence on the emission limit values, meaning that emission limit values are the same for a small waste incineration installation as for a large one.

With regard processed sewage sludge as a product, *e.g.* for fertilizer use, several regulations apply, for instance REACH and CLP.The EU regulation **REACH (907/2006)** stands for Registration, Evaluation, Authorisation and Restriction of Chemicals. The aim of the regulation is to ensure that all substances are manufactured and used safely (REACH concerns use of substances in products manufactured in EU or imported to EU). The fundamentals of REACH are that manufacturers and importers of chemical substances of at least one tonne per year must register the chemical substances to ECHA, the European Chemical's Agency. Unregistered chemical substances cannot be marketed on the EU market. REACH applies in principle to all chemical substances and puts pressure on companies to identify and manage the risks linked to the substances they produce and market in the EU. The companies producing or importing the substances have to assess the hazards and potential risks presented by the substance. Substances may be identified as a substance of very high concern (SVHC) if they are CMR (carcinogenic, toxic for reproduction or mutagenic), PBT (persistent, bioaccumulative and toxic) or vPvB (very persistent and very bioaccumulative) according to REACH (Annex XIII). Restricted substances can be found in Annex XVII but does not have any connection to the definition of SVHC. The majority of substances in REACH are not covered by restrictions. (Stenmarck *et al.* 2017)

The Regulation on classification, labelling and packaging of substances and mixtures (1272/2008) *i.e.*, **the CLP regulation** aligns existing EU legislation to the United Nations' Globally Harmonised System (GHS). The CLP Regulation contributes to the GHS aim that the same hazards will be described and labelled in the same way all around the world. By using internationally agreed classification criteria and labelling elements, it is expected to facilitate trade and to contribute towards global efforts to protect humans and the environment from hazardous effects of chemicals. The act will complement the REACH Regulation.

Directive 2001/95/EC on general product safety *i.e.,* **Product Safety Directive** provides a generic definition of a safe product. A product is deemed safe once it conforms to the safety provisions provided in European legislation or national legislation of Member States adopted in accordance with EU law. The Directive aims at ensuring that products within the EU are safe regarding health risks from chemicals as well as ensuring the function of the product. Producers must, according to the directive, inform consumers of the risks associated with the products they supply. The directive does not distinguish between products manufactured from virgin materials, and products of recycled materials. In addition, the directive does not include any specific requirements regarding hazardous substances. (Stenmarck *et al.* 2017)

3 Selected scenarios for sludge management

The current practice and future technological routes were examined through compiling and describing a business-as-usual (BAU) scenario and three possible scenarios for sludge management in Finland in 2021–2040. The purpose of the BAU scenario is to describe the current situation in Finland. The possible future scenarios cover technological options, including biogas production, thermal and thermo-chemical sludge treatment and nutrient recovery.

In Finland, municipal and industrial sewage sludges represent around 4 % of the total volumes of biomasses generated annually (Marttinen *et al.* 2017). Municipal wastewater treatment plants (WWTPs) in Finland treat around 500 million m^3 of wastewater annually (Laitinen *et al.* 2014). In 2020, the total amount of municipal sewage sludge treated in these plants was 812 700 tonnes, of which around 76 % (around 620 000 t) was digested. (Suomen Vesilaitosyhdistys ry 2021)

3.1 Business-as-usual (BAU) scenario

There are currently around 350 municipal wastewater treatment plants in Finland (Suomen Vesilaitosyhdistys ry 2021). Around 25 % of the WWTPs (90 plants) are large or middle-sized (*i.e.,* >10 000 Population Equivalent (PE)), and around 4 % (15 plants) have an **integrated digestion process** for sewage sludge treatment (Huttunen *et al.* 2018). These 15 plants represented in Figure 3 treat around 45 % (around 225 million m^3/a) of the total wastewater volume of the Finnish municipal WWTPs, and digest around 57 % (around 350 000 t/a) of the total volume of digested sewage sludge. Wastewater volumes and PE values in figure originate from various reports available from recent years and, thus, do not present values of a certain year, but are provided to give a sufficient overview of the current status of digestion processes integrated to wastewater treatment processes.

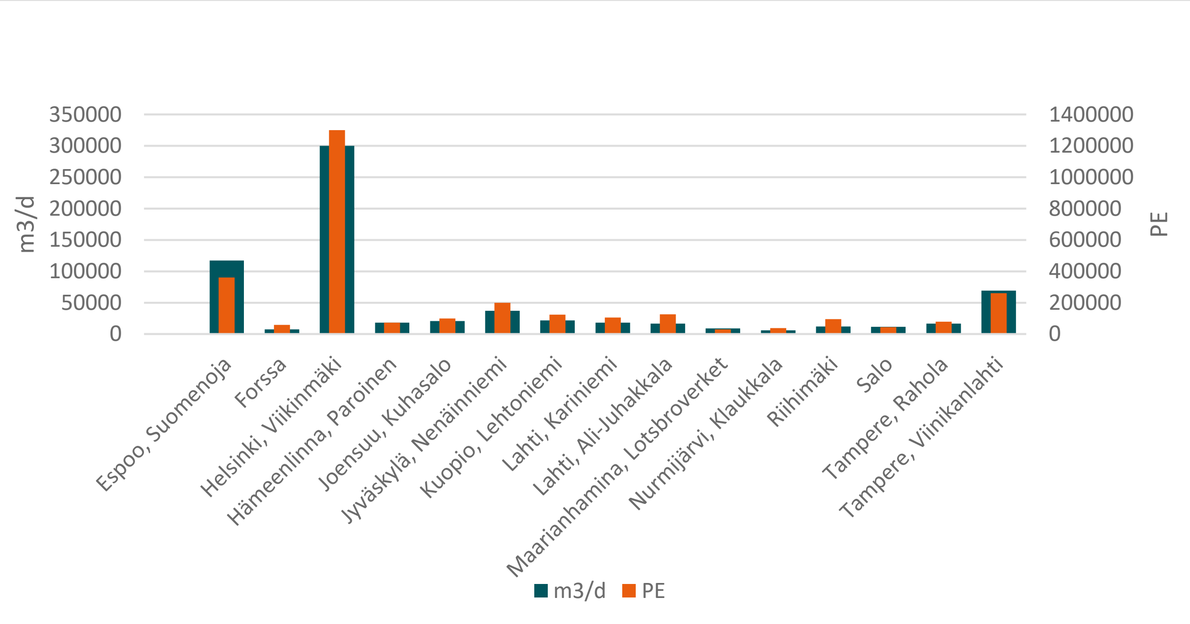

Figure 3. *The Finnish wastewater treatment plants with integrated digestion process for sewage sludge treatment, their daily treatment volumes (m^3/d) and population equivalent (PE).*

Anaerobic digestion (AD) process at WWTPs is a dominant sewage sludge pre-treatment method in Finland based on the reasoning described above. AD processes in Finland are predominantly operated in mesophilic conditions (Kangas *et al.* 2011). The produced dewatered digestate is usually composted as shown in Figure 4 (Suomen Vesilaitosyhdistys ry 2021). In the coming years, the share of integrated anaerobic digestion for pretreatment of sewage sludge will continue to increase after deployment of two large-scale regional WWTPs with an integrated AD process, the Blominmäki (Espoo) and Sulkavuori (Tampere) WWTPs.

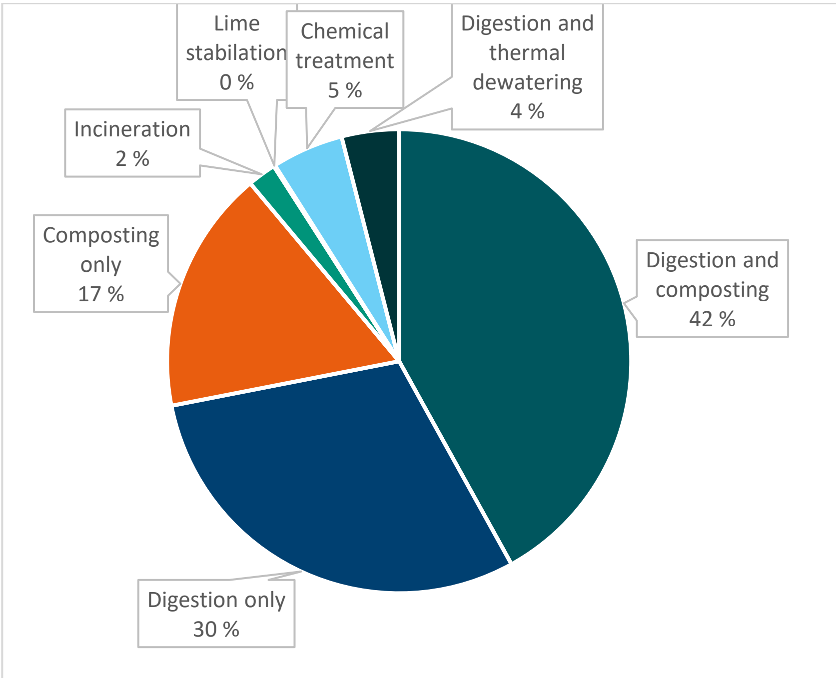

Figure 4. *Shares of sewage sludge treatment methods of the total sewage sludge amount in 2020 in Finland (modified from Vesilaitosyhdistys ry 2021).*

Anaerobic digestion integrated to WWTP was selected as the business-as-usual (BAU) scenario for this study. The BAU scenario contains the following unit processes (Figure 5):

- In the wastewater treatment plant, mixture of primary sludge and waste activated sludge is first gravity-thickened and then pumped to mesophilic anaerobic digestion, which also acts as a sludge hygienisation process. The biogas generated in the anaerobic digestion can be utilised in the plant (the most common alternative) to generate heat and electricity, or just heat. The digestate is pumped to dewatering process, such as a centrifuge, in which polymer is used to enhance dewatering. Reject waters generated during thickening or dewatering are pumped back to the main wastewater treatment process.
- The dewatered digestate is transported to a composting plant. Compost bulking agent, such as wood chips, bark or peat, is used to enhance the composting process. In addition to the composted sludge, air emissions and leachate are generated in the composting. The composted sludge is refined or sieved.
- The end product can be utilised *e.g.* in landscaping or agriculture, whereas the mineral screening exceeds are commonly landfilled and the organic screening exceeds, such as

plastics or fibers are treated thermally (combusted). The use of compost generates air emissions and seepage waters. In addition, emissions are generated in the other processes as well; seepage waters in landfilling and air emissions during thermal treatments. Ashes are also generated in combustion process.

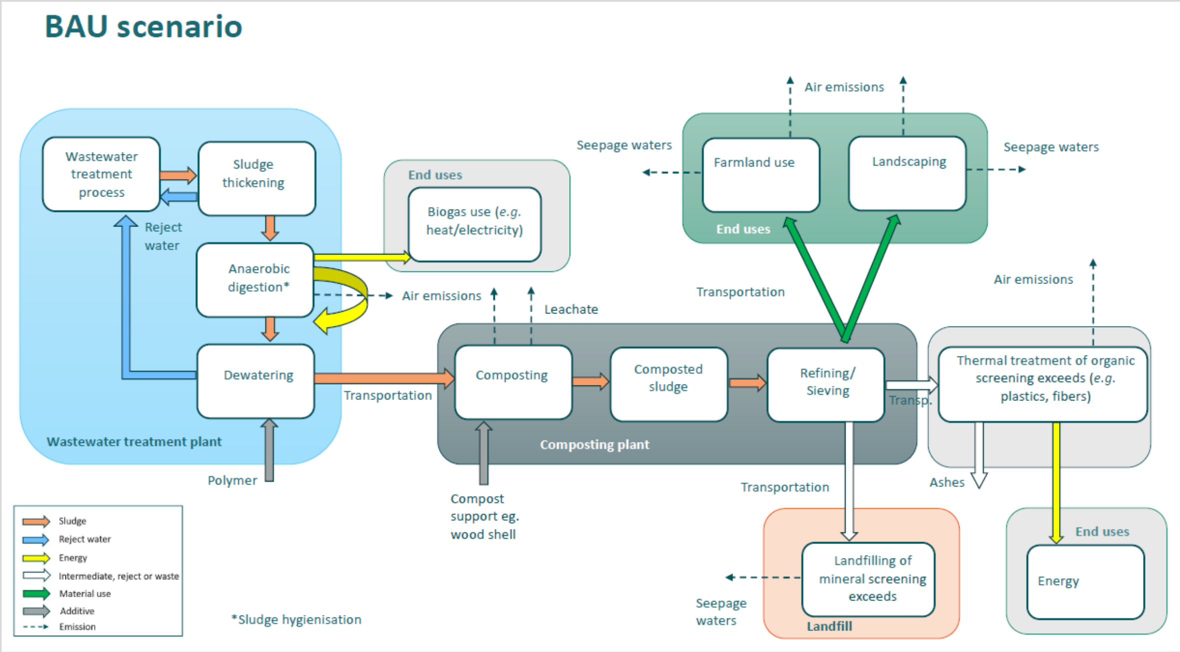

Figure 5. *The business-as-usual (BAU) scenario for sewage sludge treatment.*

A real-life reference for the BAU scenario is the Viikinmäki WWTP in Helsinki and the Metsäpirtti composting site in Sipoo, where dewatered sewage digestate in treated.

3.2 Combustion

Currently, around 1 % of sewage sludge is treated thermally in some combustion plants in Finland (Suomen Vesilaitosyhdistys ry 2021), most commonly as co-combustion in forest industry boilers. In Europe, however, more than 20 % of sewage sludge is combusted (Bianchini *et al.* 2016). The share of combustion (incineration) of sludge in EU member states is shown in Figure 6 in orange colour of the pie charts. There are a number of combustion techniques available with real-life references (see *e.g.* Wiechmann *et al.* 2013, Suomen Vesilaitosyhdistys ry 2019).

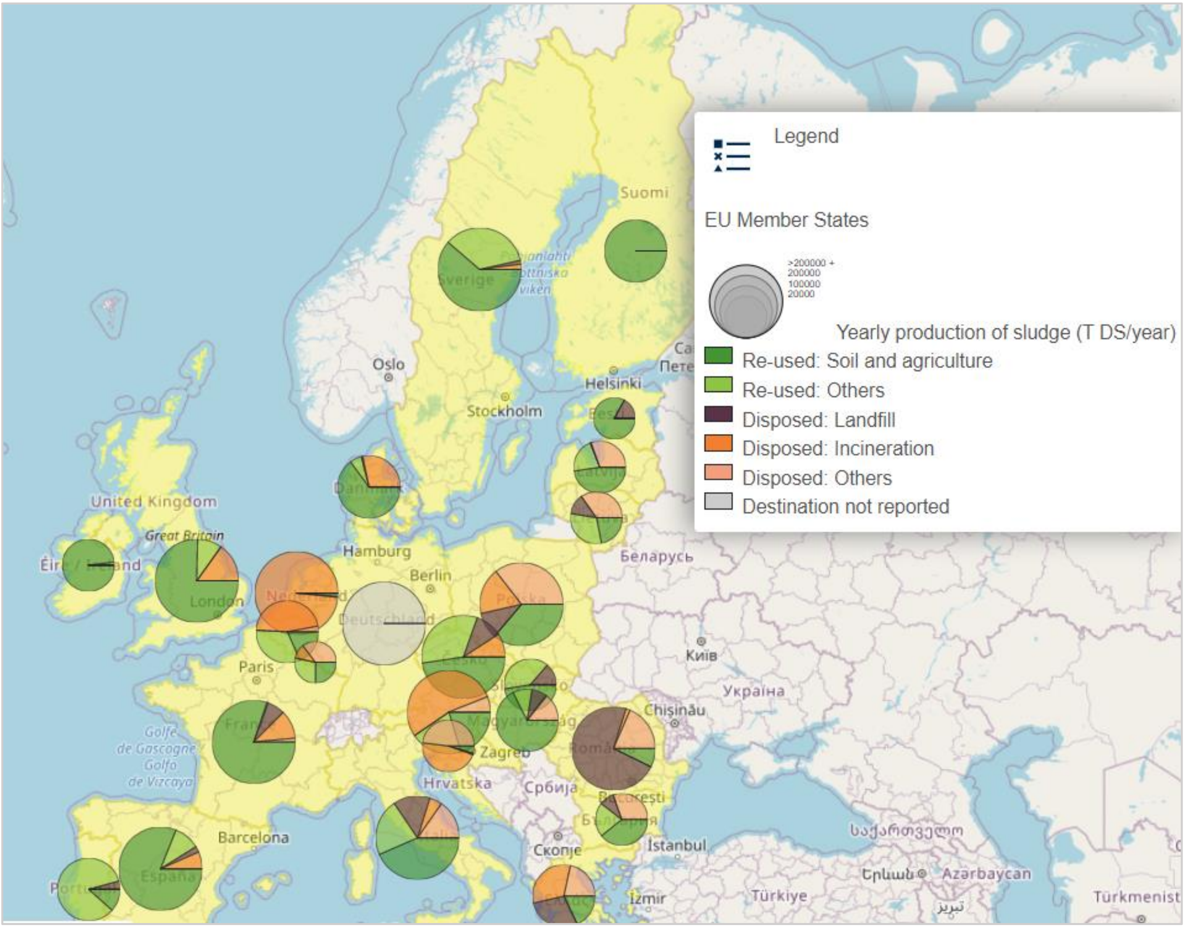

Figure 6. *Shares of sewage sludge re-use and disposal methods and amounts of yearly production of sludge in EU member states (https://uwwtd.eu/content/sewage-sludge-map).*

The combustion of sewage sludge is included in Scenario 1. The scenario contains the following sub-processes (Figure 7):

- In the wastewater treatment plant, the mixed sewage sludge is gravity-thickened and pumped to dewatering process in which polymer is dosed to enhance dewatering. Reject waters generated during thickening or dewatering are pumped back to the main wastewater process.
- The thickened and dewatered sludge is transported to the combustion plant. Thermal or mechanical drying of sludge or digestate is performed prior combustion. Combustion produces energy that can be utilised either as heat and electricity, or just heat. In addition, air emissions are generated. Emission limits are regulated by the Decree on waste incineration (151/2013).
- Combustion of sludge generates different types of solid wastes, such as bottom and fly ashes and different flue gas treatment wastes *e.g.* Air Pollution Control (APC) residues. The potential treatment options of these wastes depend on fuel (*e.g.* sludge) quality, combustion technique and flue gas treatment method. Bottom ash can be used as a material for earth construction or as a raw material for cement production. Fly ashes, including APC-residues are deposited to hazardous waste landfill.

- In some cases, fly ash can be further processed for instance for phosphorus recovery purposes (von Bahr & Kärrman 2019, Bhasin *et al.* 2020).

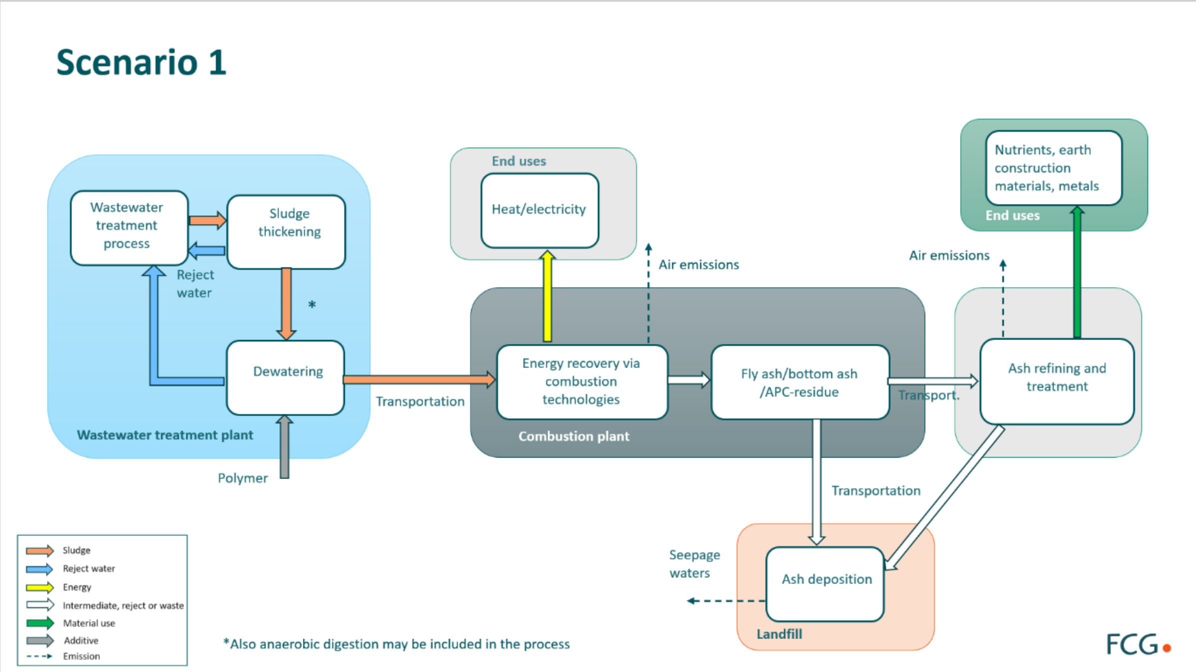

Figure 7. *Scenario 1 containing combustion of sewage sludge/digestate.*

A real-life reference for centralized combustion of sewage sludge is canton of Zürich in Switzerland where sewage sludge from dozens WWTPs is treated mono-incinerators (*e.g.,* the Werdhölzli sewage sludge incinerator) and municipal solid waste incinerators (Morf*,* 2012).

3.3 Centralized anaerobic digestion of sewage sludge

Sewage sludge can also be digested in separate facilities. Typically, separate biogas plants are not designed only for sewage sludge, rather for large variety of other organic feedstocks (*e.g.,* biowaste, food industry waste). The total amount of sewage sludge treated in Anaerobic Digestion facilities (ADs) is slightly smaller than the amount of sewage sludge treated in AD units integrated with WWTPs, as shown in Chapter 3.1. The centralized AD plants digest around 43 % (around 270 000 t/a) of the total volume of annually digested sewage sludge in Finland. Centralized anaerobic digestion of sewage sludge is included in Scenario 2. The scenario contains the following sub-processes (Figure 8):

- In the wastewater treatment plant, the mixed sludge is gravity-thickened and pumped to dewatering process where polymer is dosed. Reject waters generated during thickening or dewatering are pumped back to the main wastewater process.
- After the processes in the WWTP, the sludge is transported to a combined biogas and thermal drying plant. The biogas generated in the anaerobic digestion can be utilised in the plant or used either as heat and electricity, just heat, or liquefied biogas (LBG) can be produced. The AD hygienises the sludge to some extent. The digestate is led to dewatering process in which polymer additives are used. The reject waters from the AD are categorized as wastewaters

and must be treated onsite or discharged to a WWTP for treatment (Kymäläinen & Pakarinen 2015).

- In this scenario the reject waters from digestate dewatering are treated using an evaporation-stripping process for nitrogen recovery purpose. The dewatered digestate is then thermally dried, granulated with the help of adhesives, and sieved. Exhaust gases, dust and reject waters from acid scrubbing are formed as a result of thermal drying.
- Material obtained after sieving can be utilised in farmland use or as raw material for soil production. The mineral screening exceeds are landfilled and the organic screening exceeds, such as plastics and fibres are treated thermally (combusted).

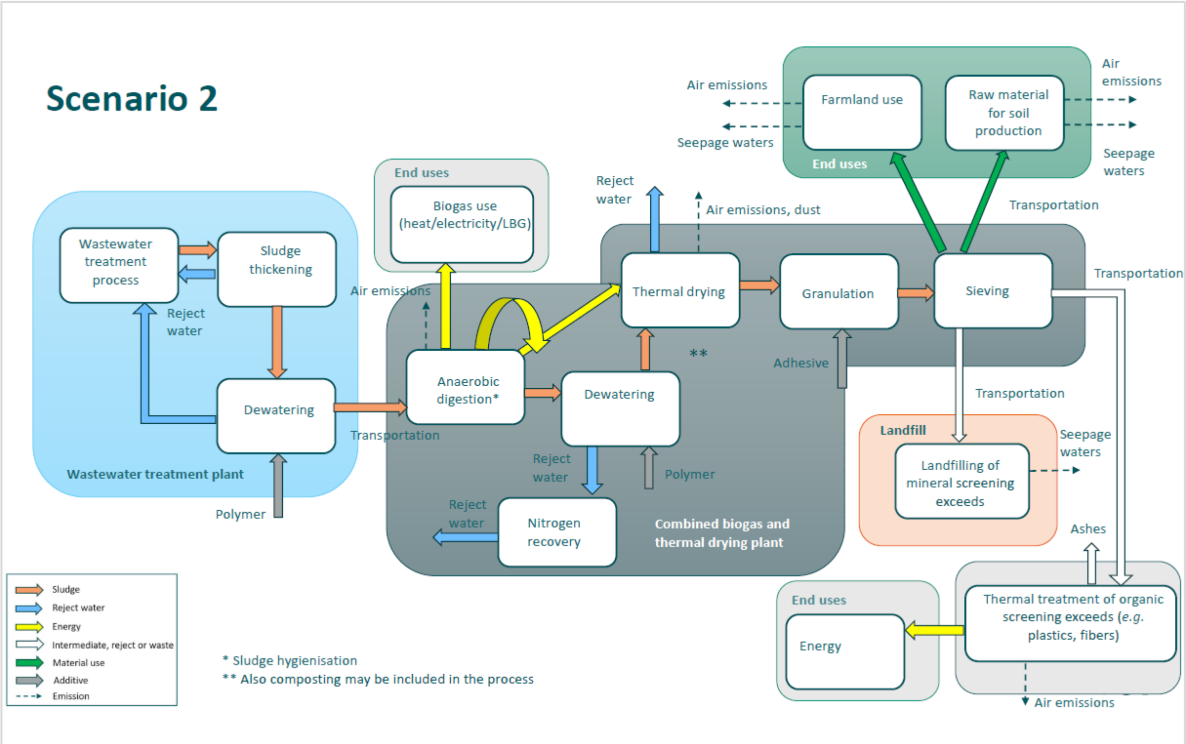

Figure 8. Centralized anaerobic digestion is included in scenario 2.

This scenario is intended to highlight the possibility of producing more highly processed products than those resulting from AD and composting alone. However, composting could also be considered here as an alternative method. This scenario can be thought of as a technology development scenario, where different process technologies are examined and developed.

Real-life references for the scenario 2 include two parts. A reference for centralized biogas plant including a nitrogen recovery process is the Topinoja biogas plant of Gasum Oy in Turku, where dewatered sewage sludge of the Kakolanmäki WWTP and other organic feedstocks are treated. A reference for thermal drying of dewatered and mostly sewage sludge based digestate followed by production of soil conditioner granules is the waste management centre of Lakeuden Etappi Oy in Ilmajoki.

3.4 Thermo-chemical sludge treatment methods

Thermo-chemical treatment, such as thermolysis (pyrolysis) or gasification, forms an interesting future technological route. Thermo-chemical technologies for treating sewage sludge or digestate are currently investigated in Finland (HSY 2021a) and other European countries. Thermo-chemical sludge treatment methods are included in Scenario 3 (thermolysis presented here as an example). The scenario contains the following sub-processes (Figure 9):

- In the wastewater treatment plant, the mixed sludge is gravity-thickened and pumped to anaerobic digestion, which also acts as a sludge hygienisation process. The biogas generated in the anaerobic digestion can be utilised in the plant (the most common alternative) for producing heat and electricity, or just heat. The digestate is led to dewatering process in which polymer is dosed. Reject waters generated during thickening or dewatering are led back to the main wastewater process.
- The digestate is transported to the thermo-chemical treatment plant. Thermal or mechanical drying of digestate is performed prior thermolysis. Treatment process produces energy that can be utilised either as heat and electricity, or just heat. In addition, air emissions are generated. Thermal drying prior to thermochemical treatment produces exhaust gases that need to be treated. Depending on the technology used, the treatment produces a nitrogen-containing solution and/or wastewater.
- Thermo-chemical treatment depending on the technology can produce via hydrocarbon route different fractions to be further refined in (petro)chemical industry. Gases and vapors can be circulated, or flue gas treatment methods utilised. The solid product of thermolysis is char, which can be used *e.g.* as a soil improver.

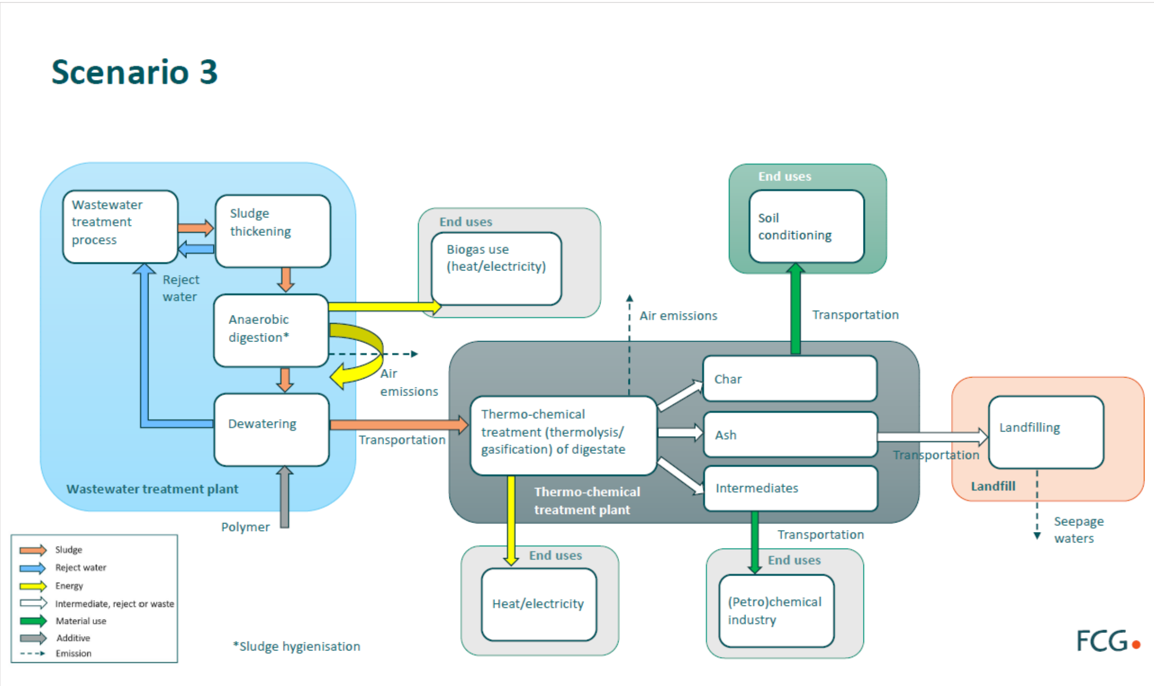

Figure 9. *Scenario 3 presents thermo-chemical treatment (thermolysis) as an alternative method for sewage sludge treatment.*

A real-life reference for the Scenario 3 is a thermal drying process and a pyrolysis process that treat digested sewage sludge produced in the Linz-Unkel WWTP and neighbouring WWTPs in Germany and produce biochar (Oasmaa, 2020; ESSP, 2021). Pyrolysis processes for treating sewage sludge-based biomasses are being piloted in, *e.*g., Finland (HSY, 2021b) and Denmark (Ahrenfeldt, 2018), and hydrothermal carbonisation (HTC) process for sludge treatment has been in Sweden (Baresel *et al.* 2021) and in Finland (Hämäläinen *et al.* 2021).

3.5 Extended scenarios

Additional analysis was done for scenarios modified with the following nutrient recovery process unit when applicable: (1) post-precipitation and recovery of phosphorus in wastewater treatment line, (2) phosphorus recovery from ash, and (3) struvite ($MgNH_4PO_4 \times 6H_2O$) recovery from digested sludge.

Suitability of the considered nutrient recovery units for each scenario was first evaluated. Summary of the outcome of the suitability assessment is provided in Table 1.

Table 1. *Applicability of selected nutrient recovery techniques for scenarios.*

Scenario	BAU		1		2		3	
	Applicability	Notes	Applicability	Notes	Applicability	Notes	Applicability	Notes
Post-precipitation and phosphorus recovery	(x)	Decrease of P in compost and of its end-use options	x		(x)	Decrease of P in granules and of their end-use options	x	Increase of the share of bioavailable P in biochar
Phosphorus recovery from ash	-		x		-		-	
Struvite recovery	x		-	Sludge is not digested	-	Nitrogen in sludge is already recovered with different process	x	

The following extensions of the original scenarios are studied

- Scenario 1:
    - post-precipitation of phosphorus (1b)
    - recovery of phosphorus from product ash (1c)
- Scenario 3:
    - post-precipitation of phosphorus (3b)
    - struvite recovery from digested sludge (3c)

For BAU scenario no extensions are investigated because a modified scenario would not describe a business-as-usual situation anymore, nor allow benchmarking the future scenarios against the current situation. As indicated in Table 1, none of the included recovery techniques would suit well scenario 2 and, therefore, no extensions for that scenario are studied. This is mainly because scenario 2 already includes a larger variety of process units for processing sludge and for recovering the resources it contains.

Post-precipitation was assumed to consist of the phosphorus recovery units of the RAVITA process (Rossi *et al.* 2018, FCG 2020). Phosphorus recovery from ash was assumed to be realized using the ASH DEC process (Hermann 2009, Havukainen *et al.* 2012) integrated to a sludge incineration plant. The Stuttgart process (Meyer *et al.* 2019), which is applicable without the use of an enhanced biological phosphorus removal process, is assumed to be applied for struvite recovery.

Both of the nutrient recovery processes considered in the scenarios to be integrated in the WWTP process (1b/3b and 3c) can be installed to existing plants if there is space for new units in the plant area. However, they necessitate changes in the existing pipelines and, therefore require additional temporary arrangements to allow for continuous operation of the treatment processes. Especially adding struvite recovery process to sludge treatment line would prevent the normal operation of the sludge treatment line and temporary arrangements enabling sludge treatment would be required. Phosphorus recovery from ash (1c) can be added to an existing combustion unit or be realized as a separate plant. When added to an existing plant, integration of the units requires temporary discontinuation of operation. All the considered nutrient recovery units can obviously be included as process lines in greenfield design projects with less effort and challenges than in renovation projects of existing plants.

4 Impact analysis of scenarios

This chapter comprises the results of comparative impact analyses of the selected scenarios. The impact analysis consists of a cost analysis and an analysis of certain environmental and circular economy aspects. The impact analysis was made using calculation methods for mass balances, costs, and carbon footprints. The analysis of other aspects is based on a literature survey and an expert evaluation.

4.1 Cost analysis

4.1.1 Methods

Estimates for investment costs, operating costs and financial revenues associated with the end-products in each scenario were calculated. The estimates include the processes, resources, operations and end-products collected in Appendix 1.

Mass balance calculations of each scenario were utilised in cost estimation as a source for material flows, resource demands *etc*. Calculation examples concern a middle-sized WWTP (size of 70 000–80 000 personal equivalent) where an activated sludge process is operated for nitrogen removal purpose and simultaneous precipitation ·with iron-based chemicals is applied. The boundaries of mass balance calculations correspond the boundaries of the cost estimation: input was mixed sludge from wastewater treatment line and outputs end-products, waste fractions, energy *etc*. Properties of mixed sludge were determined based on expert evaluation. Even though the wastewater treatment line was not included in the mass balances, the approximated impact of implementing resource recovery units in its process line in scenarios 1a and 3a on the quality and quantity of mixed sludge was taken into account.

Information from various projects of the consultant (taking into account the annual inflation rates) as well as literature information were utilised in estimating the costs and revenues associated with the scenarios. The aim of the cost estimation was to provide sufficient information for sorting the different scenarios based on their economic impacts (which is adequate for the impact analysis) rather than calculating the costs in the level of detail of plant design projects.

4.1.2 Results

Investment costs of scenarios 1–3 were compared with the estimated investment costs of the BAU scenario (Figure 9). The investment costs of scenario 1 were estimated to be the lowest among the investigated scenarios. Scenarios 2 and 3 were associated with higher estimated investment costs than the BAU scenario. The large number of different process units in these scenarios compared for instance to scenario 1 leads to higher investments costs.

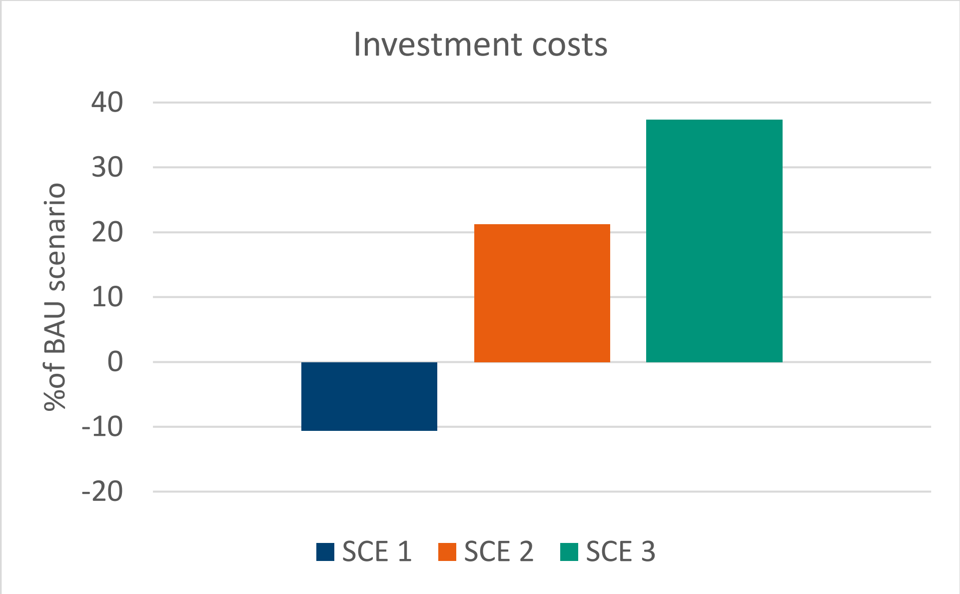

***Figure 9**. Comparison of investment costs of scenarios 1-3 with the investment costs of BAU scenario. Costs of the BAU scenario are approximately 10,7 M€.*

Yearly operating costs and financial benefits from end-products were estimated for each scenario. The comparison between the estimated operating costs and revenues of scenarios 1-3 and the BAU scenario is depicted in Figure 10.

Scenario 1 is found to be associated with the highest sum of operating costs (+) and revenues (-). The revenues from end-products of scenario 2 are higher than those of the BAU scenario. For that reason, the summarized operating costs and revenues are slightly lower even though the energy demand of the multiple process units of scenario 2 is higher than the energy demand in the BAU scenario.

Scenario 3 is estimated to have higher financial revenues than operating costs. That is due to the value of biochar produced in pyrolysis process. The value of the biochar is estimated based on the information by HSY (Kainulainen 2022). In practise, the future market values of the end-products in the scenarios are subject to uncertainty as they depend on the business models and on the market situation.

Most significant estimated financial revenues, 70–95 % in the studied scenarios, originate from utilising the energy content of sludge for producing heat, electricity and/or fuel.

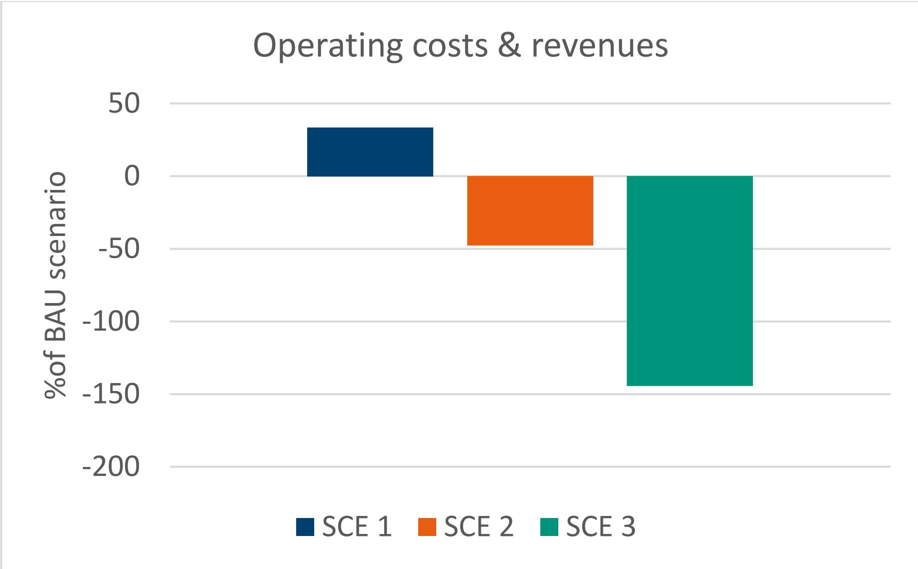

Figure 10. *Comparison of operating costs and revenues of scenarios 1-3 with the operating costs and revenues of BAU scenario. Costs of the BAU scenario are approximately 120 000 €/a.*

A comprehensive comparison of the economic impacts of the scenarios was made by combining investments costs, operating costs and revenues to yearly net costs (Figure 11). A 20-year payment term and 3 % interest rate were assumed in the investment cost calculations. Scenario 1 results in the lowest total net costs, which are slightly lower than those of the BAU scenario. Total yearly costs of scenario 2 are considerably higher and those of scenario 3 slightly higher than the costs of the BAU scenario. The weight of the investment costs was shown to be more significant than the weight of operating costs and revenues from the end products in this comprehensive comparison.

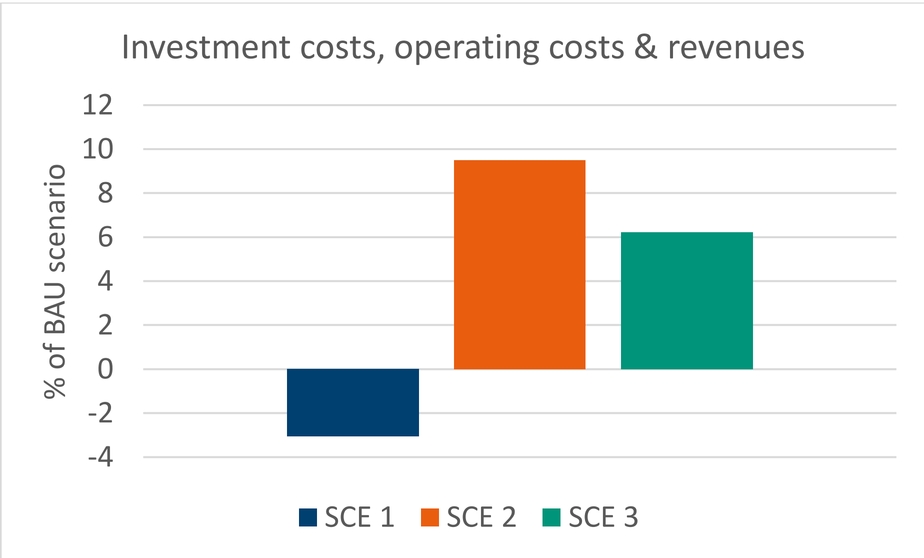

Figure 11. *Comparison of investment costs, operating costs and revenues of scenarios 1-3 with the investment costs, operating costs and revenues of BAU scenario. Costs of the BAU scenario are approximately 840 000 €/a.*

The impacts of modifying the scenarios 1–3 with additional nutrient recovery processes (Section 3.5) on costs were estimated, too. Figure 11 presents the combined investments costs, operating costs and revenues as yearly net costs. Scenario 1 is extended with a phosphorus post-precipitation process in scenario 1b and with phosphorus recovery from ash in scenario 1c. Scenario 3 is extended with a phosphorus post-precipitation process in scenario 3b and with struvite recovery from sludge in scenario 3c.

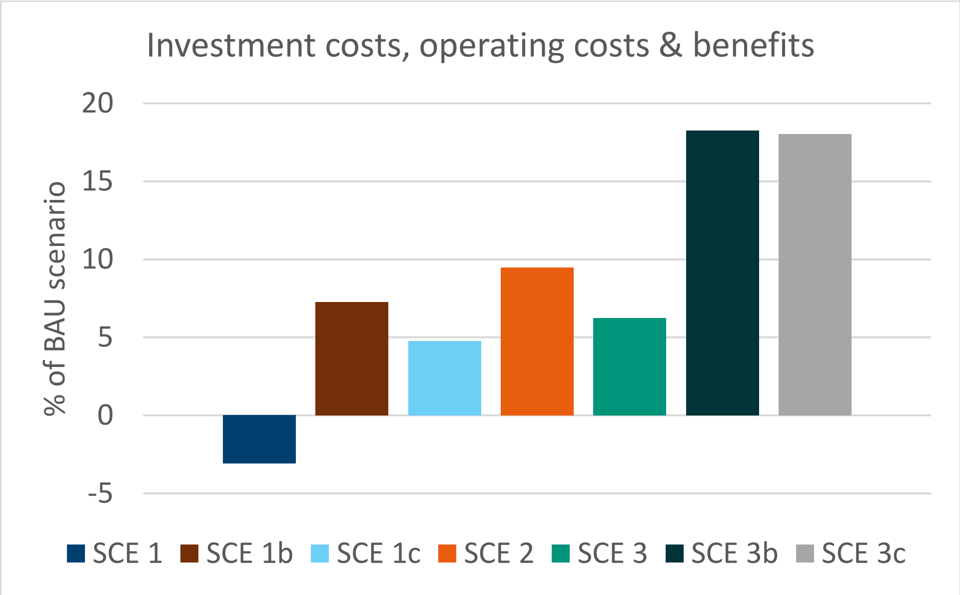

***Figure 12**. Comparison of investment costs, operating costs and revenues of scenarios 1-3 and modified scenarios 1b–1c and 3b–3c with the BAU scenario.*

Additional process units and their operation in scenarios 1b and 1c increase the comprehensive costs to a similar level as in scenario 2. The estimated comprehensive costs of scenario 3 extended with nutrient recovery process units (scenarios 3b and 3c) are higher than in the other scenarios.

As a summary, the estimated comprehensive costs of scenario 1 are on a similar level as those of the BAU scenario, whereas the costs of the other future scenarios are higher than the costs of the BAU scenario. The comprehensive costs include yearly operating and investment costs from which financial revenues were subtracted. Extending scenario 1 with phosphorus recovery units raised its comprehensive costs to a similar level as in scenario 2. The costs of scenario 3 were in the middle-range of the main scenarios, but when additional resource recovery units were added, its estimated costs were the highest among the investigated scenarios.

4.2 Environmental and circular economy aspects

The consideration of environmental and circular economy aspects focused on the main environmental impacts of the sewage sludge treatment options. From the EU Sustainable Taxonomy and its 'Do no significant harm' (DNSH) -evaluation, the following criteria were selected for the analysis of sludge treatment scenarios:

- Pollution prevention
- Climate change mitigation

- Transition to a circular economy

The starting point of the analysis for environmental and circular economy aspects was set at the WWTP gate. However, the carbon footprint calculation includes also the WWTP processes.

The analysed unit operations were:

- Biological treatment, both aerobic and anaerobic
- Mechanical treatment *e.g.* sieving
- Combustion
- Thermo-chemical treatment
- End use applications *e.g.* soil improvers, fuels or chemicals

4.2.1 Selected environmental impacts

The following tables comprise the main environmental aspects, such as emissions to air, water and soil of key operations along the sludge treatment chain. The analysis is done as an expert evaluation and based on literature.

Table 2 presents main effects of operating selected unit processes in treatment chain on air, on surface and ground waters and on soil though water. Also other aspects were considered. The summarized effects are general in nature and those should be evaluated case-specifically for each sludge treatment chain. That is often done in an environmental permit application. If waste treatment BAT (Pinasseau *et al.* 2018) is taken into account in designing a sludge treatment facility, most of the summarized impacts are considered in the design phase.

In Table 3 environmental aspects related to end-use of sludge-based material as soil improvers and green platforms are highlighted. The summarized aspects cover effects on air, water and soil as well as legislative aspects.

Table 2. *The framework of environmental impact along the sludge treatment chain.*

Treatment process	Air	Water (surface and ground waters) & effects on soil through water	Other

Anaerobic digestion	• Process enclosed and CH_4 desired product
	• Air emissions (odours and fugitive emissions) arise[1]
	  • H_2S, N-compounds and mercaptans
	  • Minor amount of CH_4 emissions as a result of storage of feed materials and digestate, or gas cleaning.[2]
	• Commonly monitored parameters: NH_3, NMVOC and odour[1]
		• Reject waters, stormwaters and runoff waters are produced during process-related storage, pre- and post-treatment and side activities[1]
		• Reject water is categorized as wastewater and must be treated onsite or discharged to WWTP for treatment.[2]
		  • Process located at the WWTP allows direct discharge of reject water back into the WWTP
		  • Process located outside the WWTP requires separate treatment of reject waters with high concentrations of organic matter and N [3]
		• Stormwaters discharge allowed either into the environment or into sewers, normally the quality is monitored twice a year.
		• Runoffs usually treated onsite or discharged to sewers.
			• odours, noise and vibration from treatment, transport and storage[4]
			• Metals, drug residues, microplastics *etc.* are not removed
			• Destroys pathogens, degrades pesticides, reduces odours and hygiene risks[3]
			• Mesophilic digestion reduces concentrations of some organic pollutants to some extent[5]

Indoor composting of sludge/digestate
Outdoor composting of sludge/digestate
	• Odorous/gaseous emissions and dust [1,3]
	  • NH_3, S-compounds
	  • CO_2 and H_2O,[3]
	  • VOCs, N_2O, CH_4)[1]
	• Bioaerosols *e.g.* different bacteria
	• In open/outdoor composting diffuse air emissions[1]
		• **Outdoor composting**
		  • Leachate generation from sludge and from natural water precipitation through piles
		  • Wastewater contains runoff waters from storage treatment areas and washing water used to clean plant, equipment and surfaces[1]
		  • High DOC content of leachates increases the oxygen demand and causes changes in leaching behavior of compounds leading to changes in prevailing environmental conditions
		• **Indoor composting:**
		  • Wastewaters conducted and treated in WWTP (*i.e.,* load stays at the plant).
		  • Monitored emissions *e.g.*: TSS, pH, COD, total N and BOD[1]
		• Note: According to Environmental Protection Act (527/2014): "*wastewater means such water that may cause environmental pollution and that is discharged after use…*". The definition also covers stormwater and leachate where it is likely to cause pollution.[6]
			• odours, noise and vibration from treatment, transport and storage[4]
			• Metals, drug residues, microplastics *etc.* are not removed
			• Hygienises sludge and some of the organic contaminants decompose.[5]

Thermal drying	• Exhaust gases and dust
	  • high moisture content and concentrations of pollutants *e.g.* organic matter, solids
	  • N-compounds *e.g.* NH_3
	• Gas treatment *e.g.* acid scrubbing needed to avoid odour and particulate emissions[4]
	• Dusting of dried sludge, even if the sludge is granulated.
	• Organic sludge dust harmful if inhaled[3]
		• Wastewater from acid scrubbing contains N-compounds such as $(NH_4)_2SO_4$ or NH_3 and can be recycled or discharged into sewers.[4]
		• Effluent treatment by a biofilter *e.g.* in cases when a particularly low odour impact is required, produces a wastewater containing significant amounts of solids, organic matter and N.[4]
			• Hygienises sludge[3]
			• Organic contaminants, metals ant microplastics *etc.* are not removed[4,5]
			• Fire and explosion risk of thermally dried sludge[3]

Mechanical treatment (sieving, mixing)	• Dust and process specific emissions (odours and bioaerosols)	• Leachates, stormwaters and runoff waters are produced during process-related storage, pre- and post-treatment and side activities	• Noise and vibration
Combustion	• Air emissions: CO_2, SO_X, NO_X • Emission limits are strictly regulated by the Decree on waste incineration (151/2013) • Thermal/mechanical) drying often included and subsequent exhaust air treated to reduce emissions[4]	• Only wet flue-gas cleaning systems produce wastewater, which is evaporated or treated and reused and/or discharged[7] • Pre-drying produces condensed wastewater with high COD, concentrations of N (NH_3) and pollutants[7]. The condensate can be discharged to sewer, but may increase N-load at WWTP[4]	• Removes effectively organic pollutants, pharmaceuticals and plastics. • Inorganic compounds and heavy metals retain in fly or bottom ash, which are treated under waste legislation[4] • Fly ashes and APC residues are not included in the list of fertiliser product categories in Fertiliser Decree and therefore cannot be used as fertiliser. [3,5]
Thermo-chemical treatment (gasification, pyrolysis)	• Air emissions: CO_2, SO_X, NO_X • Emission limits are strictly regulated by the Decree on waste incineration (151/2013) • Thermal/mechanical) drying often included and subsequent exhaust air treated to reduce emissions[4]	• The pyrolysis is a closed process[4] • Wet flue-gas cleaning systems produce wastewater, which is evaporated or treated and reused and/or discharged [4,7]	Gasification • Removes effectively organic pollutants, pharmaceuticals and plastics. • Inorganic compounds and heavy metals retain in fly or bottom ash, which are treated under waste legislation[4] • Fly ashes and APC residues are not included in the list of fertiliser product categories in Fertiliser Decree and therefore cannot be used as fertiliser. [3,5] Pyrolysis • Large proportion of organic pollutants, excl. PAH degraded and majority of the microplastics removed • Inorganic compounds and heavy metals retain in fly or bottom char, which are treated under waste legislation[4] • Char is of good hygienic quality

Landfilling	• Landfill gas shall be collected and, if possible, put to use	• Landfill leachate and other contaminated water needs be collected and treated effectively at the landfill site or conducted elsewhere for treatment. • Clean surface water within the landfill site and external runoff shall be kept separate from the waste and landfill leachate and other contaminated water • Landfilled waste shall be prevented from coming into contact with groundwater.	• Landfill criteria for waste to be landfilled

Table 3. *Environmental risks related to sludge end use as soil improvers / green platforms.*

End-product	Air	Water & effects on soil through water	Legislative aspects

Soil improvers / green platforms	• Odour and dust[4]
	• Bioaerosols and bacteria *e.g.* Legionella bacteria transmitted by air may be present in various sludge-based products [10]
		• Leaching, precipitation and runoff of harmful substances, pollutants and excess nutrients to groundwater and surface waters [9]
		• Accumulation of harmful substances and pollutants in soil
		• Organic pollutants
		  • potential risk to soil and groundwater organisms[10], but risks caused are not fully known yet [5, 8]
		  • PFOS, the flame retardant TBBPA, and some antibiotics being persistent and slowly migrating pose the greatest risk
		  • Risks more evident in landscaping than in agriculture due to larger application volumes[10]
		• Inorganic substances
		  • Cd is the primary target for monitoring with regard plants, animals and human health [10]
		  • Cu toxic for water organisms
		• Ecotoxic properties (algae) related to reactivity and heavy metal content[11]
		• Pathogens show risk to plants and animals
		• Prevalence of viruses and spore-forming bacteria such as norovirus and C. difficile in sewage sludge products and
			• In agriculture, there are legal requirements for use regarding the fertiliser product quality (*e.g.*, limits for the heavy metal content, hygienisation, stability, pathogens, impurities, such as rubbish and stones).
			  • Use of sewage sludge -based digestates as such is more restricted than use of sewage sludge -based organic soil improvers
			  • For digestates, there are limitations as regards to 1) application to crops and a safety period, 2) soil pH and heavy metal content, 3) heavy metal input, 4) storage of fertiliser product and timing of fertilisation, and 5) N, P and Cd input. For organic soil improvers, only 4) and 5) apply[9]
			• Fertiliser Decree (one of the regulations mentioned above) sets limit values for total content of certain substances and hygiene requirements
			  • Sewage sludge-based fertiliser products are classified as soil improvers
			  • Sewage sludge-based organic soil improvers can be used as raw material for growing media.
			  • Max. concentrations of heavy metals are set out in the legislation
			  • Fertiliser product must not contain *Salmonella* bacteria and there are maximum limits for *E. coli*
			  • Legislation regulates *e.g.*, plant pathogens, debris and other contaminants.
			  • No legislative limits for organic pollutants [10]
			• In landscaping, legal requirements exist as regards the fertiliser product quality but use of fertiliser products and application levels of P and N are not regulated by legislation[9]

End-product	Air	Water & effects on soil through water	Legislative aspects
		the effectiveness of hygienisation methods on them should be assessed [10] • More information on microplastics and antibiotic resistance is needed[10]	• For landscaping or golf courses, it is only stated that “the provisions of sections 10 and 11 of the Nitrates Decree (1250/2014) concerning the application times, mulching and use of nitrogen fertilisers near water bodies and the provisions of other applicable environmental and water protection legislation must be complied with, as applicable” [9] • ”Nitrates Decree” regulates the use of organic fertiliser products near water bodies to prevent runoff into surface and groundwaters [8]

References of Table 2 and Table 3:
1. Pinasseau *et al.* 2018; 2. Kymäläinen & Pakarinen 2015; 3. Pöyry Environment Oy 2007; 4. Vesilaitosyhdistys ry 2019, Berninger 2018; 6. Tieteen termipankki 2022; 7. Neuwahl *et al.* 2019; 8. Vesilaitosyhdistys ry 2020; 9. John Nurminen Foundation 2021; 10. Vieno *et al.* 2018; 11. Laine-Ylijoki *et al.* 2015

4.2.2 Climate and carbon footprint

Climate effects of the scenarios were investigated by means of a carbon footprint (CF) assessment. The CF covers operating of the sludge treatment process and production of end-products in each of the scenarios. The aim of the carbon footprint assessment was to provide sufficient information for sorting the different scenarios based on their climate effects rather than calculating the CFs in detail level of academic research.

A general CF calculation procedure divided into different steps is described in Awaitey (2020) and it was applied where appropriate for the purpose of the impact analysis. The CF calculation included direct GHG emissions, indirect GHG emissions and emission offsets (Table 4). Emission factors used in calculations were collected from various sources such as manufacturers of resources, national databases and literature.

Table 4. *Direct emissions, indirect emissions and emission offsets included in carbon footprint assessment.*

Direct	Indirect	Emission offsets
• CH_4 from process units • N_2O from process units and agriculture • GHGs from waste treatment	• energy used (electricity, heat) • chemicals • other resources (bulking agent, sand, activated carbon) • transportation (sludge, resources, end-products)	• energy produced (electricity, heat, fuels) • nutrients (available for plants) • biochar (carbon storage)

Because the aim is to produce an overview of the climate impacts of the scenarios, also the impact of carbon stored in biochar in scenario 3 is included in the calculations. Use of biochar as a soil amendment slows the rate at which photosynthetically fixed carbon is returned to the atmosphere because biochar decomposes slowly (Woolf *et al.* 2010). The fraction of initial carbon of sewage sludge -based biochar remaining after 100 years has been estimated to be 78 % (Corbo 2020).

The net CFs of operation of scenarios 1–3 were compared with the CF of the BAU scenario (Figure 13). The CF of scenario 3 was estimated to be the lowest among the investigated scenarios. The emission offsets were the largest in scenario 3. The net CF of scenario 1 was also significantly smaller than the CF of the BAU scenario. The CF of scenario 2 was at a similar level as the CF of the BAU scenario. The reason for this was higher emissions in scenario 2 due to inclusion of energy-intensive process units even though the emission offsets were larger in scenario 2 than in the BAU scenario. The GHG emissions from transportation were highest in scenario 2. Nevertheless, those did not have significant impact on the CF of scenario 2, because the share of transportation emissions was calculated to be less than 2 % of the total emissions.

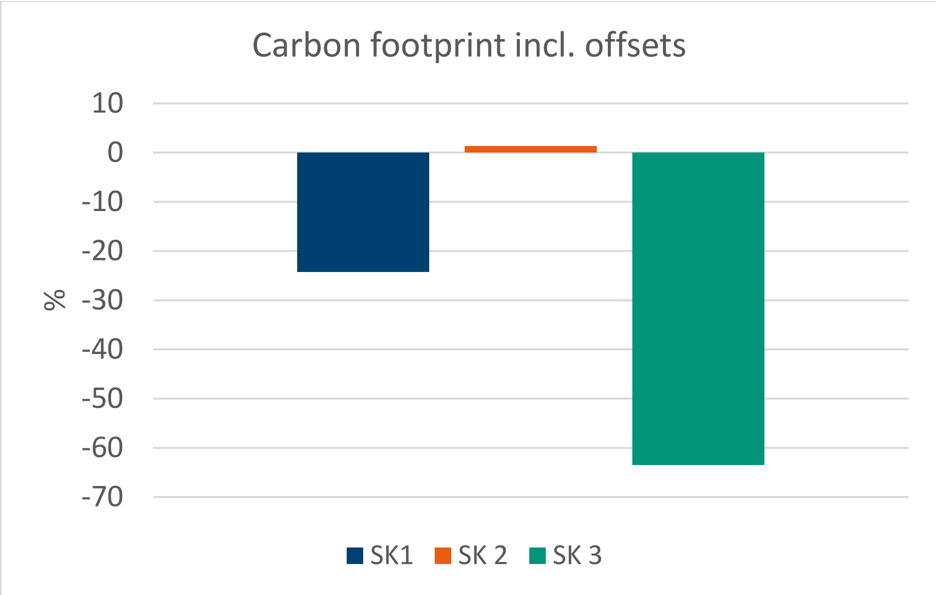

Figure 13. *Comparison of net carbon footprints of scenarios 1-3 with the net carbon footprint of BAU scenario. Net carbon footprint of the BAU scenario is approximately 1,6 kg CO_2e/kg TS sludge.*

The impacts of modifying the scenarios 1–3 as described in Section 3.5 on the net CF were estimated, too. Figure 14 presents differences of the net CFs of scenarios to the CF of the BAU scenario.

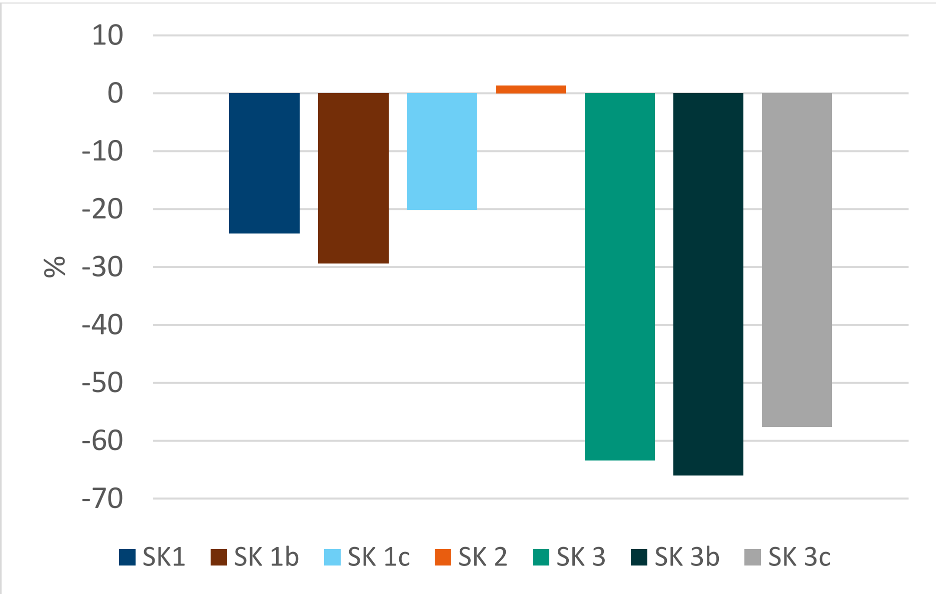

Figure 14. *Comparison of net carbon footprints of scenarios 1-3 and modified scenarios 1b–1c and 3b–3c with the net carbon footprint of BAU scenario.*

Adding resource recovery units in process lines increases energy and chemical consumption, but also brings more emission benefits as some valuable materials are recovered. A post-precipitation system also reduces amount of inorganic sludge pumped to the sludge treatment line. Based on the calculations, the additional emissions and emission benefits caused by nutrient recovery units (scenarios 1b, 1c, 3b and 3c) do not cause significant increase or decrease in the net CFs of the main scenarios 1 and 3.

As a summary, estimated CF of scenarios 1 and 3 were lower than CF of the BAU scenario. Particularly, the scenario 3 was associated with positive climate impacts according to the analysis. CF of scenario 2 was on the same level as that of the BAU scenario. Extensions of scenarios with resource recovery unit did not have substantial impact on calculated CF, because emissions due to needed resources and emissions offsets from end-products balanced each other in calculations.

4.2.3 Circular economy aspects

The circular economy (CE) is a production and consumption model that involves sharing, leasing, reusing, repairing, refurbishing and recycling materials and products for as long as possible. In other words, the CE aims to extend the life cycle of products. Extending the life cycle leads to reduced waste amounts. After reaching its end-of-life, the materials of a product are kept within the economy wherever possible. The further value can be created by using the materials productively again and again. The CE means a shift away from the traditional linear economy which follows a take-make-consume-throw away pattern. (European Parliament 2021)

Circular economy aspects are related in this context to mass balance changes throughout the treatment chain.

The decrease in the amounts of total solids in sludge during the treatment processes of different scenarios varies considerably. The main reason for this relies on the differences of removing volatile solids. Secondary reason is associated with the differences in adding various materials to sewage sludge -based biomasses (*e.g.* bulking agent for composting, sand for incineration or wood chips for pyrolysis). The differences between summarized total solids of the outgoing streams from the processes of each main scenario to total solids in the output of the BAU scenario are depicted in Figure 15. The outgoing total solids in the BAU scenario include also solids that originates from the bulking agent used in composting.

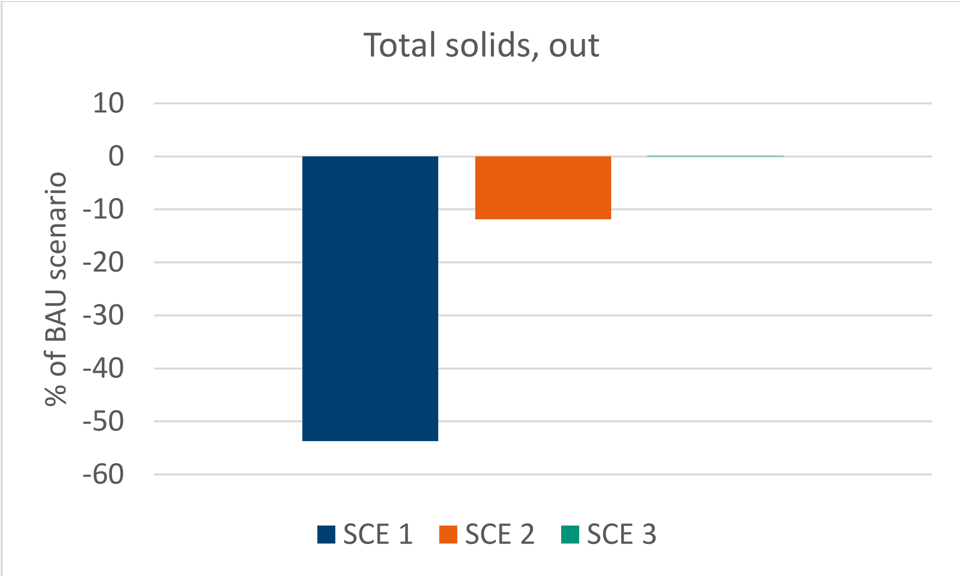

Figure 15*. Comparison of total solids in outgoing streams of scenarios 1-3 with the outgoing total solids of BAU scenario. The share of the total solids of outgoing material streams of the total solids of input sludge in the BAU scenario is approximately 67 %.*

The process line of scenario 1 is calculated to decrease significantly more total solids from the initial amount of the sludge. The amounts of solids in outputs of scenario 3 is estimated to be on the corresponding level as that of the BAU scenario. The pyrolysis process reduces the volatile solids, but at the same time the added wood chips increase the solid content. However, if only sludge-based solids are considered, total solids of outgoing material streams in scenario 3 would be approximately one third less than the solids in the BAU scenario.

The differences between summarized total nitrogen of the outgoing material streams from the processes of each main scenario to total nitrogen in the output of the BAU scenario are presented in Figure 16. The outgoing total nitrogen in the BAU scenario include also some nitrogen that originates from the bulking agent used in composting. The smallest amount of total nitrogen is contained in the outputs of scenario 1 and the largest amount in the outputs of scenario 2. This is an expected situation as scenario 2 aims at recovering nitrogen whereas scenario 1 aims at reducing the amount of compounds sludge contains.

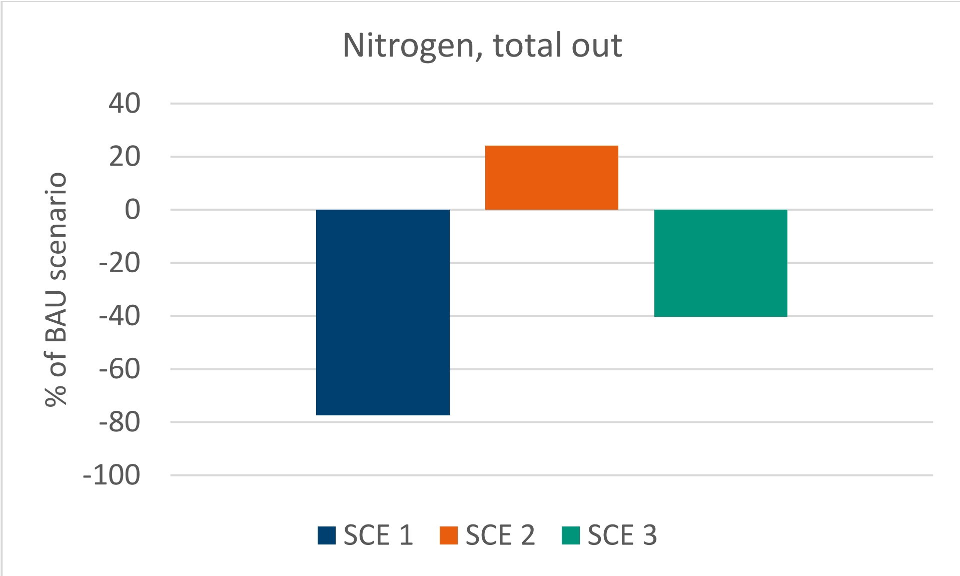

Figure 16*. Comparison of total nitrogen in outgoing streams of scenarios 1-3 with the outgoing total nitrogen of BAU scenario. The share of the total nitrogen of outgoing material streams of the total nitrogen of input sludge in the BAU scenario is approximately 70 %.*

All nitrogen in the outputs is not readily available for plants. If the goal is to recover nitrogen that can replace nitrogen of commercial fertilisers, the amounts of bioavailable nitrogen should be compared instead of amounts of total nitrogen. Figure 17 presents a comparison of the estimated amounts of nitrogen usable for plants in the main scenarios and extended scenarios. The shares of available nitrogen in different end-products are evaluated based on literature and those values contain uncertainty. Even so, estimated differences between the scenarios can be considered applicable for impact analysis where recognition of the differences between the scenarios is targeted for.

The extension of scenarios 1 and 3 by adding resource recovery processes does not affect the order of the scenarios regarding the amount of nitrogen available for plants is outputs of scenarios. Scenario 2 is the most efficient one for recovering usable nitrogen due to the dedicated ammonia recovery process units.

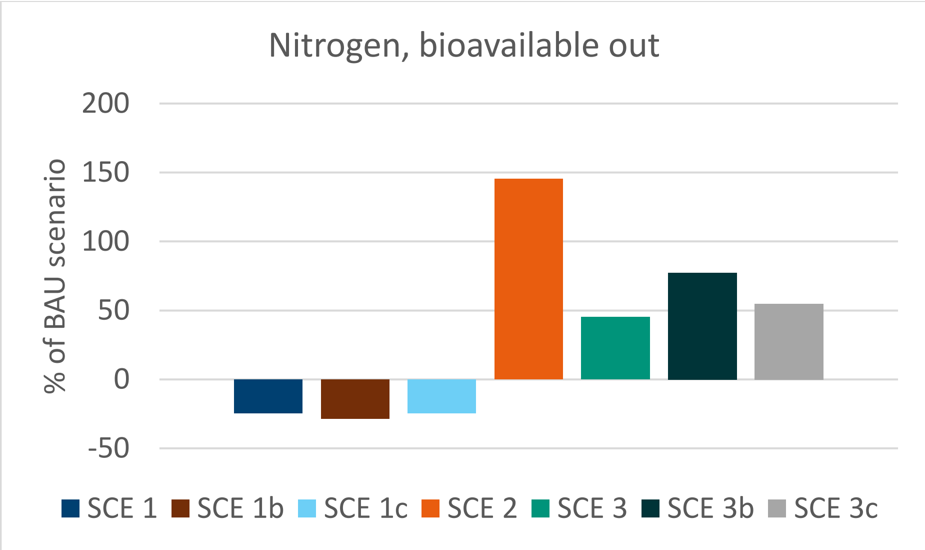

Figure 17. *Comparison of nitrogen available for plants in outputs of scenarios 1-3 and modified scenarios 1b–1c and 3b–3c with the available nitrogen in outputs of BAU scenario. The share of the plant-available nitrogen of outgoing material streams of the total nitrogen of input sludge in the BAU scenario is approximately 20 %.*

The differences between summarized total phosphorus of the outgoing streams from the processes of each main scenario to total phosphorus in the output of the BAU scenario are shown in Figure 18. The outgoing total phosphorus in the BAU scenario include also some phosphorus that originates from the bulking agent used in composting. The smallest amount of total phosphorus is contained in the outputs of scenario 1. The total phosphorus contents of the output streams of scenarios 2 and 3 are on a similar level as in the BAU scenario.

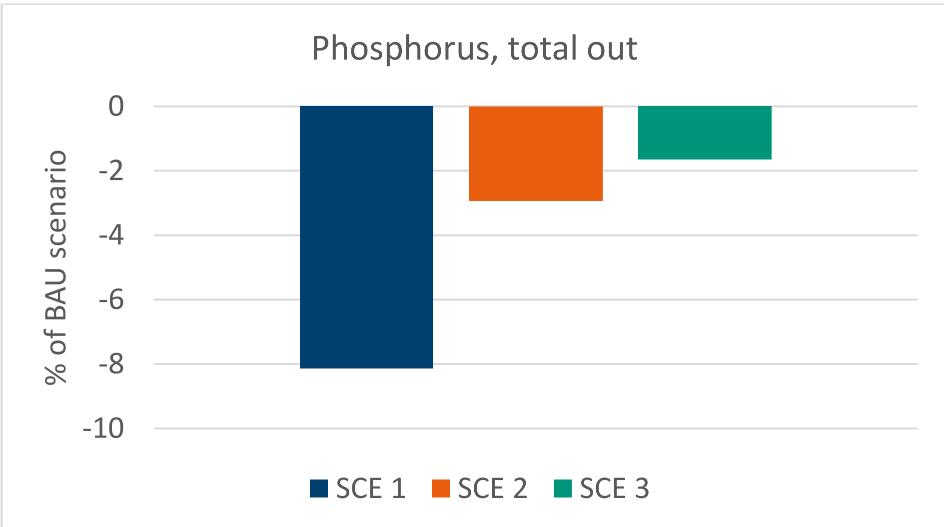

Figure 18*. Comparison of total phosphorus in outgoing streams of scenarios 1-3 with the outgoing total phosphorus of BAU scenario. The share of the total phosphorus of outgoing material streams of the total phosphorus of input sludge in the BAU scenario is approximately 95 %.*

Only some of total phosphorus in the outputs is readily available for plants. Figure 19 illustrates a comparison of the estimated amounts of phosphorus usable for plants in the main scenarios and extended scenarios.

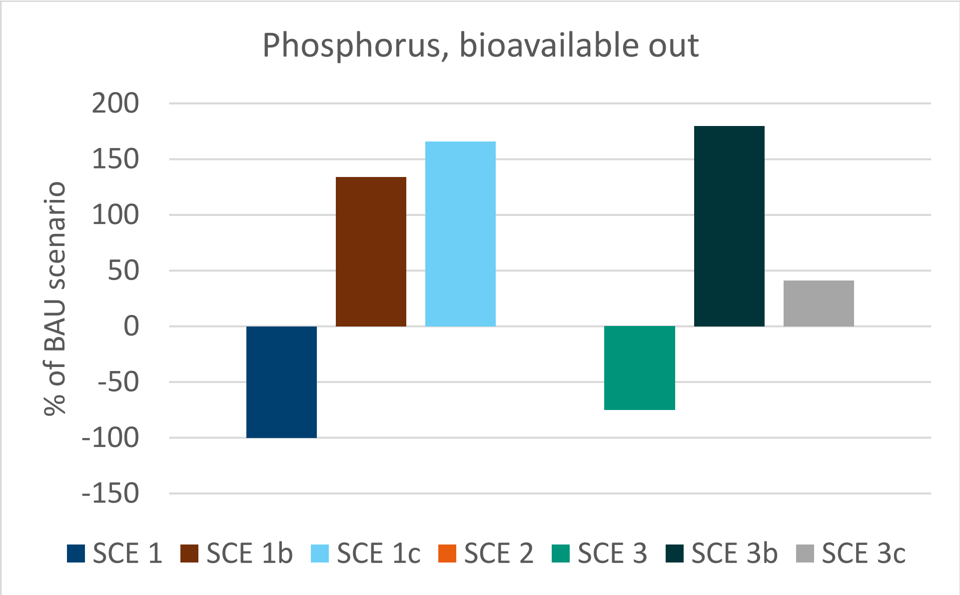

Figure 19. *Comparison of phosphorus available for plants in outputs of scenarios 1-3 and modified scenarios 1b–1c and 3b–3c with the available phosphorus in outputs of BAU scenario. The share of the plant-available phosphorus of outgoing material streams of the total phosphorus of input sludge in the BAU scenario is approximately 37 %.*

Obvious benefits from adding phosphorus recovery process units to scenarios 1 and 3 can be observed with regards the amount of bioavailable phosphorus in the outputs. As for scenario 3, the primary reason for this is that only a small part of phosphorus in biochar is easily available for plants if sludge contains mainly phosphorus precipitated with iron (Rasa *et al.* 2015). A large share of phosphorus in sewage sludge -based biomasses is not either easily plant-available when sludge contains mainly iron-phosphates (Berninger 2018).

The differences between organic matter (volatile suspended solids) of the outgoing streams from the processes of each main scenario to organic matter in the output of the BAU scenario are shown inFigure 20. The outgoing organic matter in the BAU scenario include also some organic matter that originates from the bulking agent used in composting. In the scenario 1, the whole organic content if the feedstock is assumed to be combusted. The amount of sludge-based organic contents in the output streams of scenarios 2 and 3 are evaluated to be considerably larger than in the BAU scenario. The reason for this is that in a composting process a large share of carbon is given off as carbon dioxide gas.

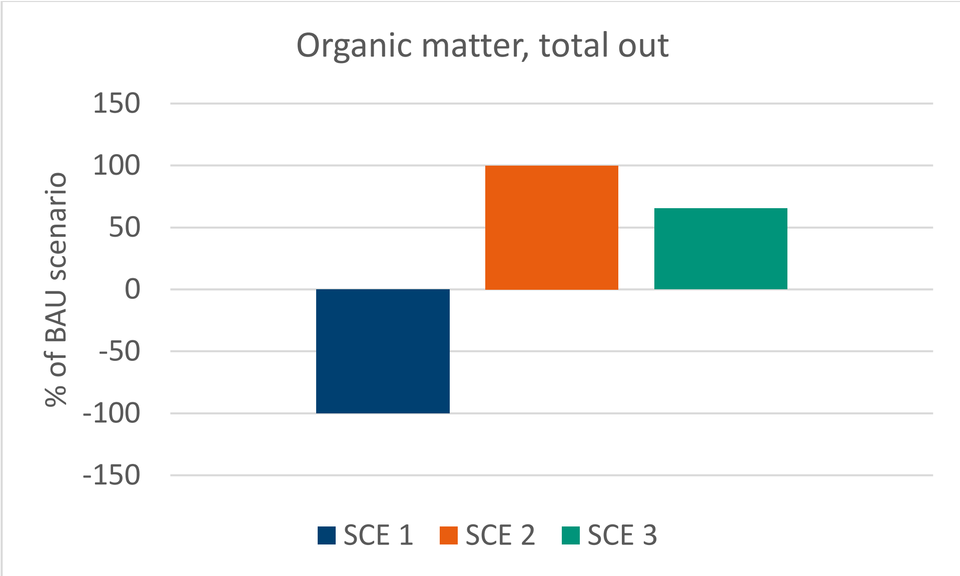

Figure 20*. Comparison of organic matter in outgoing streams of scenarios 1-3 with the outgoing total organic matter of BAU scenario. The share of the organic matter of outgoing material streams of the organic matter of input sludge in the BAU scenario is approximately 40 %.*

To summarize, scenario 1 reduced the amount of sludge considerably more than the other scenarios. Scenario 2 was most efficient in recovery of nitrogen that is easily plant-available. Also in scenario 3 more nitrogen was recovered than in the BAU scenario. As for phosphorus recovery in plant-available forms in end-products, in scenarios 1 and 3 the rate was lower than in the BAU scenario and in scenario 2. Adding phosphorus recovery processes to those scenarios increased their phosphorus recovery rate considerably and in most cases to a higher level than that of the BAU scenario. The phosphorus recovery rate of scenario 2 was approximately on a similar level as that of the BAU scenario. The outgoing materials in scenarios 2 and 3 contained more organic matter than the BAU scenario. Organic matter in scenario 1 was combusted

4.3 Summary

The key findings of the impact analysis are compiled in Table 5. The findings were based on scenario calculations and expert opinions on similar treatment chains as in studies scenarios.

Table 5. *Impact matrix of the analysed sludge management options.*

	AD integrated to WWTP + composting (*e.g.* Scenario BAU)	Combustion of sewage sludge (*e.g.* Scenario 1)	Centralised AD outside WWTP (*e.g.* Scenario 2)	AD integrated to WWTP + Thermo-chemical treatment (*e.g.* Scenario 3)
Net costs	• BAU sets reference level	• Net cost similar to BAU	• Net costs higher than BAU	• Net costs higher than BAU
Environmental aspects	**Air emissions:** • Diffuse odorous/gaseous emissions and dust including bioaerosols in outdoor composting **Water:** 1) Outdoor composting: • Leachate generation • Wastewaters (runoff and washing waters) • Stormwaters discharged to environment or sewers • Runoffs treated onsite or discharged to sewers 2) Indoor composting: • Wastewaters conducted and treated in WWTP	**Air emissions:** • Air pollution control (APC) system required **Water:** • Pre-treatment of wastewaters onsite and their treatment finalized in WWTP	**Air emissions:** • Exhaust cleaning system required **Water:** • Pre-treatment of wastewaters onsite and their treatment finalized in WWTP	**Air emissions:** • Air pollution control (APC) system required **Water:** • Pre-treatment of wastewaters onsite and their treatment finalized in WWTP
Carbon footprint	• BAU sets reference level	• Carbon footprint moderate (lower than BAU)	• Carbon footprint similar to BAU	• Carbon footprint low (considerably lower than BAU)
Circular economy aspects	• In many cases high-value recycling (upscaling) difficult to achieve, therefore sham recycling possible • Sustainable and techno-economically feasible recycling of huge amounts of sludge-based material with heterogenous quality challenging • Low-value market product (downscaling)	• Removal of harmful substances from circulation • provides minimal amount of material to be utilized or disposed • Ferrous and non-ferrous metals recoverable • Phosphorus recoverable with dedicated process unit (included in scenario 1b) • Utilization of bottom ash in earth construction	• Sustainable and techno-economically feasible recycling of significant amounts of sludge-based material with heterogenous quality challenging • Highest N and P recovery-rate	• Removal of harmful substances from circulation • Valuable market products (hydrocarbons, char) • Use of iron in WWTP limits bioavailable phosphorus in char

Other aspects	**During treatment no notable chemical changes take place in sludge**
	• Reduction of material volume questionable
	• No removal of metals, microplastics *etc.*
	• Some of the pharmaceuticals decomposed, but not all, and decomposition of many have not been studied yet
	Risks at soil-improver use:
	• Spreading of harmful substances, pollutants and excess nutrients to ground and surface waters
	• Accumulation of harmful substances and pollutants in soil
	• Organic pollutants -> risk to soil and groundwater organisms
	• Pathogens -> risk to plants and animals
	• Inorganic substances, *e.g.* Cd and Cu
	• Ecotoxicity properties related to reactivity and heavy metal content
	• Research needed:
	  • Prevalence of viruses and spore-forming bacteria in products, the effectiveness of hygienisation
	  • Microplastics and antibiotic resistance
	Maturity of technology:
	• Business as usual
		During treatment chemical changes take place in sludge
		• Minimisation of material volume
		• Production of stable and hygienic dry materials
		• Removal of organic pollutants, pharmaceuticals and plastics
		• Retainment of inorganic compounds and heavy metals in fly or bottom ash, which are treated under waste legislation
		Maturity of technology:
		• Business as usual
			During treatment no chemical changes take place in sludge
			• Moderate reduction of material volume
			• No removal of metals, microplastics etc.
			• Some of the pharmaceuticals decomposed, but not all
			Risks at soil-improver use:
			• Spreading of harmful substances, pollutants and excess nutrients to ground and surface waters
			• Accumulation of harmful substances and pollutants in soil
			• Organic pollutants -> risk to soil and groundwater organisms
			• Pathogens -> risk to plants and animals
			• Inorganic substances, *e.g.* Cd and Cu
			• Ecotoxicity properties related to reactivity and heavy metal content
			• Research needed:
			  • Prevalence of viruses and spore-forming bacteria in products, the effectiveness of hygienisation
			  • Microplastics and antibiotic resistance
			Maturity of technology:
			• No industrial references for the full scenario yet, but for all process units references available
				During treatment chemical changes take place in sludge
				• Adding support material to thermal drying increases material volume to a similar level as in BAU
				1) Gasification
				• Removal of organic pollutants, pharmaceuticals and plastics
				• Retainment of inorganic compounds and heavy metals in fly or bottom ash, which are treated under waste legislation
				• Fly ashes and APC residues are not included in the list in Fertilizer Fertiliser Decree
				2) Pyrolysis
				• Large proportion of organic pollutants, excl. PAH degraded and majority of the microplastics removed
				• Retainment of inorganic compounds and heavy metals in fly ash and char
				Char is of good hygienic quality
				Maturity of technology:
				• A few industrial references exist
				•

5 Conclusions and insights

The main conclusions from the work and insights on the sludge management options are provided in this chapter.

- Possible future sludge management scenarios were defined and investigated. Also, a business-as-usual scenario was determined and used as a baseline for the future scenarios in an impact analysis. Economics, environmental impacts and circular economy aspects were among studied impacts. The analysis showed that none of the scenarios outweighed others in all impact categories. For instance, if one scenario reduces most efficiently the amount of sludge, it is not likely to have the highest nutrient recovery rate. Or if the retention rate of organic matter in another scenario is high, then the scenario is likely to be associated with higher environment and health -related risks caused by pollutants retained in the sludge-based biomass.
- Preferred sludge management options depend crucially on how the different treatment objectives are weighted. There are several levels where objectives are defined. For instance, when the directives that concern wastewater treatment and sewage sludge use are being updated, the general goals and action plans set in the EU are considered. Therefore, these objectives will also impact the future sludge management in the EU member states. On the other hand, national objectives for sludge management can be and have been set, and those may affect for instance the agricultural use of sludge-based biomasses. On a local level where investment decisions are made, *i.e.,* in water utilities and companies providing outsourced sludge management, different objectives are weighted based, for instance, on strategies of municipalities/joint municipal authorities and business plans of companies as well as on economic and regulatory aspects.
- Based on a workshop organized during the project, reducing the risks associated with harmful substances and enabling nutrient recycling are considered the most important sludge management objectives by stakeholders of sludge management chain in Finland.
- The impact analysis indicated that utilising efficiently the energy content of sludge is the most impactful resource recovery action in sludge management. For instance, energy production integrated to sludge digestion or combustion had more significant effect on economics and carbon footprint than nutrient recovery and recycling. Therefore, the existing biogas plants are recommended to explore means to increase energy production and energy-efficiency of the plant operation (see, *e.g.* Motiva 2018).
- The estimated price of recycled fertiliser products is still high in comparison with primary fertilisers. However, it is possible that demand for especially recycled phosphorus will increase during next decades, if for instance such an objective is prioritized nationally and promoted with policy instruments or if obligation for phosphorus recovery from wastewater is set in the updated urban wastewater directive. For that reason, it is recommended that phosphorus recovery is considered in design and renovation of large WWTPs even if recovery processes would not be realized yet.
- One future option is that the agricultural use of sewage sludge -based biomasses will become restricted or more demanding due to changing regulatory situation. This already is the case in some countries and regions. If such regulatory changes are anticipated, thermal sludge treatment techniques should be preferred.

- Plenty of compounds have been analyzed in sludge monitoring campaigns (*e.g.* Vieno *et al.* 2018; Buta *et al.* 2021), but as there are tens of thousands of organic chemicals in use, only a minor part of those can be analysed from sludge samples (Harrison *et al.* 2006) for practical and economic reasons. Thus, the options are either to select a subset of organic pollutants to be screened from sludge based on scientific knowledge and accept certain risk due to hazardous compounds left out from analysis or to promote technologies that remove organic pollutants efficiently or address measures that reduce the amounts of challenging compounds in WWTP influent.
- A dedicated treatment process for sludge dewatering reject water treatment is recommended for medium-sized and large biogas plants. Especially nitrogen treatment and potentially its recovery are beneficial due to reducing capacity demand of WWTP and reducing the wastewater fees of centralized biogas plants.
- The investigated scenarios with a larger number of process units were associated with higher investment and operating costs than scenarios with simpler process lines. A large number of process units also makes plant-wide operation and optimization more demanding. Decision-makers need to consider whether benefits received from additional process unit (*e.g.* for resource recovery) outweigh the mentioned drawbacks.
- One impact of climate change is increasing frequency of extreme events, such as heavy rains. That will increase challenges with runoff waters in agriculture and, the consequent risks of sludge-based nutrient and pollutant runoff, if heterogenous sludge-based biomasses are applied. Runoff water from fields where sludge-based biomasses have been applied have been found to contain pollutants, nutrients and pathogens during rainfall events (Khan *et al.* 2018). More research on this topic is suggested.
- Carbon sequestration using biochar was estimated to result in a considerable benefit when climate impacts of scenarios were studied. More research on this topic is suggested as well as on the properties of sewage sludge -based biochar.

References

Aatsinki, T. 2021. Termiset käsittelymenetelmät energian ja ravinteiden talteenottoon puhdistamolietteestä. Diplomityö, Lappeenrannan-Lahden teknillinen yliopisto LUT, 131 p. (In Finnish)

Ahrenfeldt, J. 2018. Pyrolysis and thermal gasification of sludge - energy production in waste water treatment. IEA workhop "Addressing the Energy-Water Nexus through R&D Planning and Policies", 28 - 29 May 2018

Awaitey, A. 2021. Carbon footprint of Finnish wastewater treatment plants. Master's thesis, Aalto University. 84 + 8 p.

Baresel C., Yang, J.-J., Lazic, A. and Axegård, P. 2021. Framtidens slamhantering vid Roslagsvattens reningsverk i Margretelund - Beskrivning av nuläget för slambehandling. IVL Svenska Miljöinstitutet AB, 40 p.

Berninger, K. 2018. Puhdistamolieteselvitys - Yhteenveto toteutettujen hankkeiden tuloksista. Tyrskykonsultointi Oy. 33 p. (In Finnish)

Bauer, T., Andreas, L., Lagerkvist, A. & Burgman, L.E., 2020. Effects of the different implementation of legislation relating to sewage sludge disposal in the EU. Detritus, Vol. 10, p. 92-99.

Bhasin, A., Almemark, M., Arnberg, R., Ekengren, Ö., Johansson, K. & Tjus, K. 2020. Framtida slamhantering – Förbränning kombinerat med fosforåtervinning ur askan. Report U 2401, IVL Svenska Miljöinstitutet. (In Swedish)

Bianchini, A., Bonfiglioli, L., Pellegrini, M. & Saccani, C. 2016. Sewage sludge management in Europe: a critical analysis of data quality. Int. J. Environ. Waste Manag. 18, 226–238.

Buta, M., Hubeny, J., Zielinski, W., Harnisz, M. and Korzeniewska E. 2021. Sewage sludge in agriculture—the effects of selected chemical pollutants and emerging genetic resistance determinants on the quality of soil and crops—a review. Ecotoxicol Environ Saf, 214:112070.

Corbo, A. 2020. Biochar as a carbon dioxide removal solution: An assessment of carbon stability and carbon dioxide removal potential in Sweden. DTU Technical University of Denmark & KTH Royal Institute of Technology. 49 p.

Ekane, N., Barquet, K. & Rosemarin, A. 2021. Resources and Risks: Perceptions on the Application of Sewage Sludge on Agricultural Land in Sweden, a Case Study. Frontiers in Sustainable Food Systems.

European Parliament 2021. Circular economy: definition, importance and benefits. Page accessed: 18.3.2022. Available at: https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits

ESPP European Sustainable Phosphorus Platform, DPP German Phosphorus Platform and NNP Netherlands Nutrient Platform 2021. ESPP – DPP – NNP phosphorus recovery technology catalogue. https://phosphorusplatform.eu/images/download/ESPP-NNP-DPP_P-recovery_tech_catalogue_v26_4_22.pdf

FCG Finnish Consulting Group Oy 2020. RAVITA-prosessin investointi- ja operointikustannusten arviointi. Report. (In Finnish)

Government Offices of Sweden 2020: Hållbar slamhantering - Betänkande av Utredningen om en giftfri och cirkulär återföring av fosfor från avloppsslam. Stockholm: Miljödepartementet, 758 p. (In Swedish)

Haimi, H. & Mannio, J. 2008. Haitallisten aineiden näytteenotto ja esiintyminen jätevedenpuhdistamoilla. Kirjallisuusselvitys. Suomen ympäristökeskuksen raportteja 5/2008, 56 p. (In Finnish)

Harrison, E.Z., Oakes, S.R., Hysell, M. & Hay, A. 2006. Organic Chemicals in Sewage Sludges. Science of the Total Environment 367, pp. 481–497.

Havukainen, J., Horttanainen, M. & Linnanen, L., 2012. Feasibility of ASH DEC process in treating sewage sludge and manure ash in Finland. Research Report 26. Lappeenranta University of Technology.

Havukainen, J., Saud, A., Fruergaard Astrup, T., Peltola, P. & Horttanainen, M. 2022. Environmental performance of dewatered sewage sludge digestate utilization based on life cycle assessment. Waste Management 137 (2022) 210–221

Helsingin seudun ympäristöpalvelut HSY 2021a. Hiiltämällä jätevesilietteen ravinteet kiertoon – Lietehiilihanke. Loppuraportti, 50 p. (In Finnish)

Helsingin seudun ympäristöpalvelut HSY 2021b. Vastuullisuus 2020. 50 p. https://julkaisu.hsy.fi/vastuullisuus-2020.pdf (In Finnish)

Hermann, L. 2009. P-recovery from sewage sludge ash – technology transfer from prototype to manufacturing facilities. In: Ashley, K., Mavinic, D. and Koch, F. (Eds.). International Conference on Nutrient Recovery from Wastewater Streams, Vancouver, Canada. IWA Publishing, London.

Hudcová, H., Vymazal, J. & Rozkošný, M. 2019. Present restrictions of sewage sludge application in agriculture within the European Union. Soil Water Res. 14, 104–120.

Huttunen, M.J., Kuittinen, V. & Lampinen A. 2018. Finnish National biogas statistics – Data year 2017. Publications of University of Eastern Finland, N:o 33. 50 p. (In Finnish)

Hämäläinen, A., Kokko, M., Kinnunen, V., Hilli, T. and Rintala, J. 2021. Hydrothermal carbonisation of mechanically dewatered digested sewage sludge—Energy and nutrient recovery in centralised biogas plant. Water Research, 2021, 117284.

John Nurminen Foundation 2021. Review of Current Situation, Existing Regulations and Nutrient Leakage Risks of Practices in Finland. Sustainable Biogas WP5 Analysing usage and disposal possibilities for sewage-based biomasses. 26 p.

Kainulainen, A. 2022. E-mail conversation 4.4.2022.

Kangas, A., Lund, C., Liuksia, S., Arnold, M., Merta, E., Kajolinna, T., Carpén, L., Koskinen, P. & Ryhänen, T. 2011. Energiatehokas lietteenkäsittely. Suomen ympäristö 17/2011.

Kasurinen, V., Munne, P., Mehtonen, J., Türkmen, A., Seppälä, T., Mannio, J., Verta, M. & Äystö, L. 2014. Orgaaniset haitta-aineet puhdistamolietteissä. Suomen ympäristökeskuksen raportteja 6/2014. Suomen ympäristökeskus, Helsinki. 69 p. (In Finnish)

Khan, M.N., Mobin, M., Abbas, Z.K. and Alamri, S.A. 2018. Fertilizers and their contaminants in soils, surface and groundwater. In Dellasala, D.A. and Goldstein, M.I. (Eds.), Encyclopedia of the Anthropocene, Elsevier, Oxford, pp. 225-240.

Konola, I. 2019. Optimization and Quality Assessment of Fertilizers Based on Resource Recovery Technologies. Master's thesis, Aalto University. 58+43 p.

Kymäläinen, M. & Pakarinen, O. (Eds.) 2015. Biokaasuteknologia – Raaka-aineet, prosessointi ja lopputuotteiden hyödyntäminen. Suomen Biokaasuyhdistys ry. HAMKin e-julkaisuja 36/2015. (In Finnish)

Laine-Ylijoki, J., Merta, E., Kaartinen, T. & Wahlstöm, M. 2015. Esiselvitys puhdistamolietteiden ominaisuuksien merkityksestä jäteluokituksessa. VTT-CR-04519-15, Teknologian tutkimuskeskus VTT Oy, 15 p. (In Finnish)

Laitinen, J., Nieminen, J., Saarinen, R. & Toivikko S. 2014. Paras käyttökelpoinen tekniikka (BAT) - Yhdyskuntien jätevedenpuhdistamot. Suomen ympäristökeskus 3/2014. (In Finnish)

Lehtoranta, S., Malila, R., Fjäder, P., Laukka, V., Mustajoki, J. & Äystö, L. 2021. Jätevesien ravinteet kiertoon turvallisesti ja tehokkaasti. Suomen ympäristökeskuksen raportteja 18 | 2021, Suomen ympäristökeskus. 84 p. (In Finnish)

Leppäkoski, L., Marttila, M.P, Uusitalo, V., Levänen, J., Halonen, V. & Mikkilä, M.H. 2021. Assessing the Carbon Footprint of Biochar from Willow Grown on Marginal Lands in Finland. Sustainability. 13, 10097.

Meyer, C., Preyl, V., Steinmetz, H., Maier, W., Mohn, R.-E. & Schönberger, H. 2019. The Stuttgart Process (Germany). In *Phosphorus Recovery and Recycling*; Ohtake, H., Tsuneda, S., Eds.; Springer, pp 283– 295.

Marttinen, S., Venelampi, O., Iho, A., Koikkalainen, K., Lehtonen, E., Luostarinen, S., Rasa, K., Sarvi, M., Tampio, E., Turtola, E., Ylivainio, K., Grönroos, J., Kauppila, J., Koskiaho, J., Valve, H., Laine-Ylijoki, J., Lantto, R., Oasmaa, A. & zu Castell-Rüdenhausen, M. 2017. Kohti ravinteiden kierrätyksen läpimurtoa. Nykytila ja suositukset ohjauskeinojen kehittämiseksi. Luonnonvara- ja biotalouden tutkimus 45/2017. Luonnonvarakeskus, Helsinki. 46 p. (In Finnish)

Morf, L.S. 2012. Phosphorus from sewage sludge – The strategy of the Canton of Zurich and Switzerland, 45. Essener Tagung Wasser und Abfallwirtschaft, 14.-16. März 2012. Essen, Germany.

Motiva 2018. Energiatehokas lietteen käsittely ja biokaasun tuotanto. Energiatehokas vesihuoltolaitos, 8 p. (In Finnish)

Neuwahl, F., Cusano, G., Gómez Benavides, J., Holbrook, S. & Roudier, S. 2019. Best Available Techniques (BAT) Reference Document for Waste Incineration: Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). Publications Office of the European Union, 764 p.

Oasmaa A. 2020. Thermal and catalytic processes for treatment of biomass and waste. Presentation 05.02.2020.

Pinasseau, A., Zerger, B., Roth, J., Canova, M. & Roudier, S. 2018 Best Available Techniques (Bat) Reference Document for Waste Treatment; European Commission Industrial Emissions Directive 2010/75/EU. Publications Office of the European Union, 851 p.

Pöyry Environment Oy 2007. Lietteenkäsittelyn nykytila Suomessa ja käsittelymenetelmien kilpailukyky -selvitys. 52 p. (In Finnish)

Rasa, K., Ylivainio, K., Rasi, S., Eskola, A., Uusitalo, R. & Tiilikkala, K. 2015. Jätevesilietteen pyrolyysi - laboratorio- ja pilot-mittakaavan kokeita. Luonnonvara- ja biotalouden tutkimus 21/2015, Luonnonvarakeskus, 25 p. (In Finnish)

Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019 on persistent organic pollutants.

Rossi, L., Reuna, S., Fred, T.& Heinonen, M. 2018. RAVITA Technology – new innovation for combined phosphorus and nitrogen recovery. Water Science & Technology, 78 (12): 2511–2517.

Ruokavirasto 2021. Jätevesilietteiden käyttö lannoitevalmisteena. Page accessed: 18.3.2022. Available at: https://www.ruokavirasto.fi/yritykset/rehu--ja-lannoiteala/lannoitevalmisteet/laatuvaatimukset/kierratysravinteet/jatevesilietteet/ (In Finnish)

Stenmarck, Å., Belleza. E., Fråne. A., Busch, N., Larsen. Å. and Wahlström. M. 2017. Hazardous substances in plastics – ways to increase recycling, TemaNord 2017:505 ISSN 0908-6692.

Suomen Vesilaitosyhdistys ry 2019. Puhdistamolietteen termiset käsittelymenetelmät ja niiden soveltuvuus Suomeen. Vesilaitosyhdistyksen monistesarja nro 56, Helsinki 2019. 125 p. (In Finnish)

Suomen Vesilaitosyhdistys ry 2021. Yhdyskuntalietteen käsittelyn ja hyödyntämisen nykytilannekatsaus vuosilta 2019–2020. Vesilaitosyhdistyksen monistesarja nro 71, Helsinki 2021. 28 p. (In Finnish)

Suomen Vesilaitosyhdistys ry 2021b. Puhdistamolietteen termisten käsittelymenetelmien hiilijalanjälki. Vesilaitosyhdistyksen monistesarja nro 61, Helsinki 2021. 42 p. (In Finnish)

Tieteen termipankki 2022: Oikeustiede: jätevesi. Page accessed: 18.3.2022. Available at: https://tieteentermipankki.fi/wiki/Oikeustiede:jätevesi (In Finnish)

Vieno, N., Sarvi, M., Salo, T., Rämö, S., Ylivainio, K., Pitkänen, T. & Kusnetsov, J. 2018. Puhdistamolietteiden sisältämien haitta-aineiden aiheuttamat riskit lannoitekäytössä. Luonnonvara- ja biotalouden tutkimus 58/2018, Luonnonvarakeskus. 129 p. (In Finnish)

von Bahr, B. & Kärrman, E. 2019. Tekniska processer för fosforåtervinning ur avloppsslam. RISE Rapport 2019:59, RISE - Research Institutes of Sweden. (In Swedish)

Wiechmann, B., Dienemann, C., Kabbe, C., Brandt, S., Vogel, I. & Roskosch, A. 2013 Sewage Sludge Management in Germany; Umweltbundesamt GVP: Bonn, Germany.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. & Joseph S. 2010. Sustainable biochar to mitigate global climate change. Nature Communications.

Ylivainio, K., Äystö, L., Fjäder, P., Suominen, K., Lehti, A., Perkola, N., Ranta, J., Meriläinen, P., Välttilä, V. & Turtola, E. 2020. Jätevesilietteen pitkäkestoinen fosforilannoitusvaikutus ja yhteys ympäristö- ja ruokaturvallisuuteen. Jätevesilietteen potentiaali kasvintuotannossa ja vaikutukset ympäristöön ja elintarviketurvallisuuteen (PProduct) -hankkeen loppuraportti. Luonnonvara- ja biotalouden tutkimus 55/2020, Luonnonvarakeskus, 120 p. (In Finnish)

Ymparisto.fi 2019. Pysyvät orgaaniset yhdisteet (POP). Page accessed: 18.3.2022. Available at: https://www.ymparisto.fi/POP (In Finnish)

APPENDIX 1. Process units, resources, operations and end-products included in cost estimation of the scenarios.

	Scenario BAU (AD integrated to WWTP + composting)	Scenario 1 (Combustion of sewage sludge/digestate)	Scenario 2 (Centralized AD)	Scenario 3 (AD integrated to WWTP + Thermo-chemical treatment)
WWTP*	• Thickening • Anaerobic digestion • CHP • Dewatering • Treatment of reject waters in the main process	• Thickening • Dewatering • Treatment of reject waters in the main process	• Thickening • Dewatering • Treatment of reject waters in the main process	• Thickening • Anaerobic digestion • CHP • Dewatering • Treatment of reject waters in the main process
Centralized treatment	• Tunnel composting	• Thermal Drying • Combustion plant • Condensate treatment • Air pollution control system	• Anaerobic digestion • CHP • Biogas upgrade & LBG production • Dewatering • Reject water treatment / N-recovery • Thermal Drying • Granulation	• Thermal Drying • Support material • Pyrolysis • Gas combustion and treatment • Condensate treatment • Air Pollution control system
Waste treatment	• Landfill waste	• Landfill ash • APC residue	• Landfill waste	• Landfill ash • APC residue
Transportation	• Dewatered sludge • Compost • All solid and liquid resources • Waste fractions	• Dewatered sludge • Product ash • Ammonium sulphate • All solid and liquid recourses • Waste fractions	• Dewatered sludge • Granules • Ammonia water • All solid and liquid recourses • Waste fractions	• Dewatered sludge • Biochar • Ammonium sulphate • All solid and liquid recourses • Waste fractions
Resources	• Electricity • Heat • Bulking agent • Sand • Biotite • Polymer • Lime • Human resources	• Electricity • Heat • Sand • Activated carbon • Polymer • Lime • Sodium hydroxide • Sulphur acid • Human resources	• Electricity • Heat • Polymer • Sodium hydroxide • Human resources	• Electricity • Heat • Woodchips • Activated carbon • Polymer • Lime • Sulphur acid • Human resources
End-products	• Electricity • Heat • Nitrogen • Phosphorus	• Electricity • Heat • Nitrogen	• Electricity • Heat • LBG • Nitrogen • Phosphorus	• Electricity • Heat • Nitrogen • Biochar

*process units were dimensioned based on mixed sludge characteristics: 6 000 TS/d; 200 m^3/d; 70 % VTS/TS

FCG

John Nurminen Foundation

Workshop of "Sustainable future usage or disposal possibilities of sewage sludge -based biomasses in Finland" project

Appendix 2

SUSTAINABLE BIOGAS

Interreg Central Baltic

EUROPEAN UNION
European Regional Development Fund

Table of contents

Workshop of "Sustainable future usage or disposal possibilities of sewage sludge -based biomasses in Finland" project

1 Introduction

The current status and alternative technological routes for sewage sludge-based nutrient management in near future were investigated in the project "Sustainable future usage or disposal possibilities of sewage sludge -based biomasses in Finland". The study was done as part of Sustainable Biogas project (https://sustainablebiogas.eu/), and its Work Package "Usage and disposal possibilities for sewage-based biomasses". Sustainable Biogas project is funded by the Interreg Central Baltic Programme. As a part of the project, a stakeholder workshop was organized on February 14, 2022.

2 Description of the workshop

The stakeholder workshop was organized virtually via MS Teams. The event was by invitation only. Altogether 34 experts representing authorities and stakeholders involved in the sludge value chain participated in the workshop. The list of participants is presented in Appendix 1. The aim of the workshop was to collect feedback on preliminary sludge management scenarios defined by the project team of FCG Finnish Consulting Group Ltd. and steering group of the project (John Nurminen Foundation and Finnish Biocycle and Biogas Association). Additionally, the aim was to ideate feasible solutions for sludge utilisation in interaction with the stakeholders and measures that should be taken for that purpose.

The program of the started with description of aims and background of the project by Anna Saarentaus from John Nurminen Foundation. Then, Ari Kangas from Ministry of the Environment gave a presentation on status of regulatory framework of utilization of sewage sludge and possible changes in that framework in near future. Next, Henri Haimi and Jutta Laine-Ylijoki from FCG presented preliminary sludge management scenarios and preliminary outcome of the analyses carried out. After that, the sludge management scenarios defined in the project and the required measures and policy instrument needed to enable sustainable sludge management were discussed in four small-groups. Padlet application was used in the small-group work. Finally, the outcomes of the group works were presented for all the participants by the chairs of the small-groups. The workshop also included a poll about preferred objectives of sludge management realized with Mentimeter application.

Material produced in group-work and poll as well as notes from the final discussions after the small group work is presented in the next chapters. The main findings from the workshop are summarized in the last chapter.

3 Results of the poll

The workshop participants were asked to prioritize certain objectives of sewage sludge treatment. Five predefined objectives were as options: (1) enabling nutrient recycling; (2) reduction of the risks associated with harmful substances; (3) minimization of greenhouse gas emissions; (4) minimization of costs; and (5) reduction of mass. Each participant was asked to divide total number of 15 points between the objectives. Maximum number of points per objective was 5 representing "very important". Minimum number of points per objective was 0 representing "not at all important". The results of the poll are depicted in Figure 1.

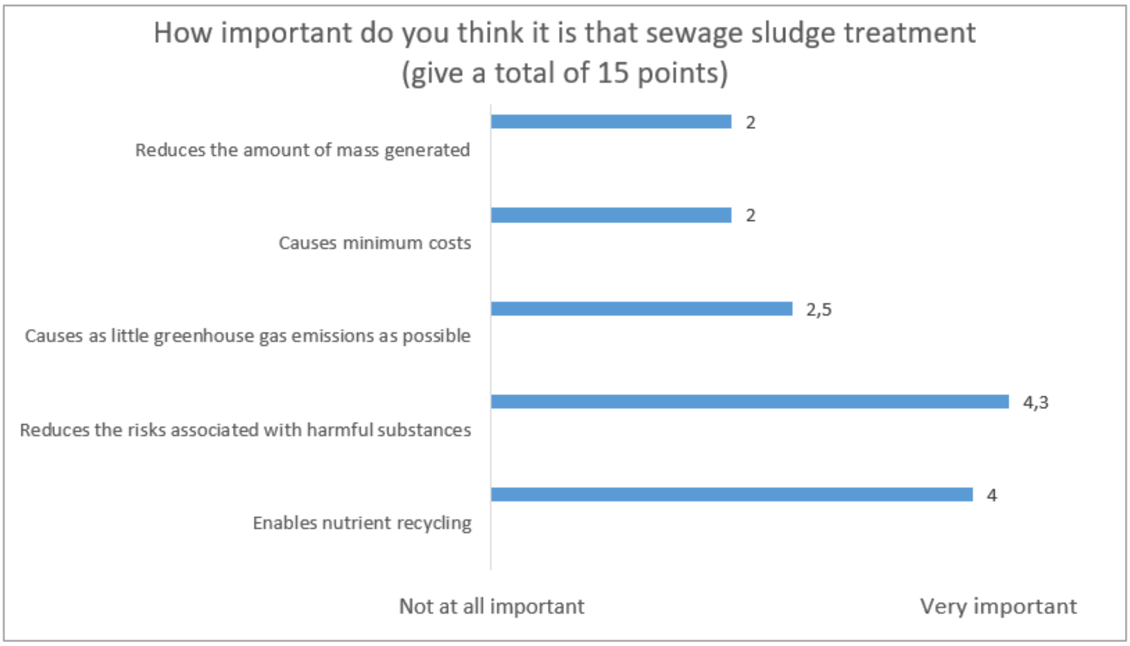

Figure 1. *Stakeholder opinions on the importance of objectives of sewage sludge treatment.*

Based on the results of the poll, the participants evaluated reducing the risks associated with harmful substances (4,3 points on average) and enabling nutrient recycling (4,0 points on average) as the most important objectives of the predefined options. The other three options were given considerably less points on average (2,0–2,5) indicating that they were not considered as important objectives for sludge management in Finland as the other two above-mentioned objectives.

Figure on the results of the poll from Mentimeter application is also available in Appendix 2 in Finnish. That figure includes also distribution of the given points for different objectives. The distributions indicate that majority of participants considered reducing the risks associated with harmful substances) and enabling nutrient recycling as the most important objectives since neither of them were given many points lower than 3 unlike the other options in the poll.

4 Notes from the small-group work

A brief summary of the small-group work including written material from Padlet application and discussions is given in this chapter.

4.1 Preliminary sludge management scenarios

The scenario-specific benefits, drawbacks and other comments on the sludge management scenarios from the small-group Padlet work are presented in below (BAU scenario (Table 1), scenario 1 (Table 2), scenario 2 (Table 3) and scenario 3 (Table 4)). Detailed written notes of the Padlet work (in Finnish) are provided in Appendix 3.

Table 1. *Workshop participants' views on benefits, drawbacks and other comments on the BAU scenarios from the Padlet notes.*

Business-as-usual (BAU) scenario	
Benefits	• The equipment and know-how exist • Biogas recovery and utilisation as energy • Sludge volume decreases • No transfer of water back and forth between plants • Partial hygienisation of sludge
Drawbacks	• Harmful substances end up in agricultural crops, concentrate in fields and/or run-off into water bodies • Persistent organic pollutants do not decompose in the process • Harmful substances remain in the digestate, for which a utilization option or disposal site must be found • Struvite precipitation is problematic with chemical phosphorus removal • Not cost-efficient for small wastewater treatment plants • Lack of storage capacity for digestate on farms
Comments/ Other aspects	• Taxation of self-use of biogas tightened, plants of a certain size will be "fallen between two stools" • Digestion does not yet take a position on whether the sludge will be treated after digestion?

Table 2. *Workshop participants' views on benefits, drawbacks and other comments on Scenario 1 from the Padlet notes.*

Scenario 1: Combustion of sewage sludge/digestate	
Benefits	• Removes organic pollutants • EU approved, proven sustainable solution • Cost-effective • Can be incinerated with other waste, creating synergies, does not require additional investment • Mass reduction • Phosphorus can be processed into a CE-marked fertiliser product • Metals can be recovered
Drawbacks	• All the carbon is released into the atmosphere • The last option in the waste hierarchy • Excess ash from which phosphorus has been removed is hazardous waste and must be disposed of • Lot of chemicals needed for nutrient recovery • Generally low efficiency • Heavy metals are enriched in the final product • Most organic matter is lost • P poorly recoverable • Separation of phosphorus from ash or recovery of ash is costly and otherwise challenging • Harmful substances are not lost, but decompose into other compounds or end up in flue gases • Nutrient recovery is not possible without additional investment • Requires a large plant, expensive method • Increases landfilling? • Long distance transport of sludge masses • Nitrogen is lost • Incineration tax may increase costs

Comments/ Other aspects	• Can be operable in a medium size range • Consideration should be given to the type of funding available for facilities that do not meet recycling requirements

Table 3. *Workshop participants' views on benefits, drawbacks and other comments on Scenario 2 from the Padlet notes.*

Scenario 2: Centralized anaerobic digestion of sewage sludge	
Benefits	• Thermally dried sludge is easier to store and cheaper to transport than mechanically dried sludge. • Economy of scale • Granulation (or similar) is a major benefit to the usability of the final product • Improves the economic viability of sludge treatment, as biomethane has a higher price compared to other energy products • Suitable for economic areas of different sizes (large, medium) and cooperation between municipalities in the area. • Easier to handle and spread than digestate
Drawbacks	• Odour problems and CO_2 emissions • Customer requirements for the final product • Persistent organic pollutants do not decompose in the process, also microplastics partly remaining • Environmental impacts and economics of transporting large mass volumes? • Requires large plant size and high plant investment • Increases transport (+costs and disadvantages of transport and handling). Unlikely to be suitable for remote areas due to long transport distances • The nutrient content of the reject water is significant compared to mechanical drying. They need to be treated
Comments/ Other aspects	• Granulation would not be undertaken in all situations

Table 4. *Workshop participants' views on benefits, drawbacks and other comments on Scenario 3 from the Padlet notes.*

Scenario 3: Thermo-chemical sludge treatment methods	
Benefits	• Part of the carbon is converted into very stable form • Sludge coal has potential end uses • Binds carbon in the soil for longer time periods • Several organic pollutants and microplastics are likely to be removed in the process • Biochar is potential material already in use for green building, storm water treatment, *etc.*
Drawbacks	• Degradation products of pollutants may be more harmful than the original compound • Levels of persistent pollutants increase in the final product if not degrade during treatment or are not removed in the exhaust gases • An economically expensive solution at the moment. Suitable solution only for big cities due to the high investment costs • Increases landfilling? • Phosphorus is immobilized in pyrolysis
Comments/	• Is there enough market for all biochar? There is interest in biochar from willow to construction waste and everything in between.

Other aspects	• Not all degradation products are known, and there are no analytical methods for analysing them (because they are not known). This also applies to incineration. • Pyrolysis oil does not necessarily end up as an industrial feedstock (e.g. it is not allowed to condense). Processing can be challenging as it is a mixture / compound of several substances

In addition the written notes in Padlet application, the perspectives that the experts were particularly keen to highlight were discussed. The following aspects were raised:

- In terms of legislation, sewage sludge is also subject to the POP Regulation and its limit values for harmful substances. The limit values are so high that they are not expected to be exceeded
- It should be possible to produce products as uniformly as possible
- The best benefits are obtained, when products that cannot be classified as waste, can be made
- The most important aspect is (persistent) pollutants: promoting nutrient recycling is important, but it must be done safely
- At the regional level in the Baltic Sea, it has emerged that different countries have very different traditions in the treatment of sewage sludge. The Baltic Sea Action Plan aims to promote safe recycling of nutrients, but it is challenging to create common regulations across countries.
- From an agricultural and market perspective, it is problematic to talk about waste. It is difficult to market them, even though many uses are already allowed
- There is indeed a need for recycled phosphorus, but from a consumer point of view this is a challenge
- It is also good to remember that these (biochar) can be good soil conditioners and improve carbon sequestration
- The composition of sewage sludge is unknown. It is difficult to prove that it is harmless when you don't even know what it might contain
- Could the perspective be reversed: not to try to remove harmful substances from sewage sludge, but instead to extract the nutrients?
- Instead of technology, attention should be paid to the requirements of different customer segments for the final product. The forest industry wants to promote a circular economy and is under different pressure to use recycled nutrients than a farmer (agriculture). The market is moving faster than in agriculture. End products from the plant for industry, soil product and agriculture.

4.2 Measures and policy instruments

Th measures and policy instruments needed to enhance reaching the predefined sludge management objectives was second topic of the small-group work.

The experts' notes written in Padlet are collected below (enabling nutrient recycling (Table 5), reduction of the risks associated with harmful substances (Table 6), minimization of greenhouse gas emissions (Table 7); minimization of costs (Table 8) and reduction of mass (Table 9). Detailed written notes of the Padlet work (in Finnish) are provided in Appendix 4.

Table 5. *Workshop participants' views on measures and policy instruments promoting nutrient recycling taken from the Padlet notes.*

Promoting nutrient recycling
• Securing markets for products • The right treatment techniques for the end market of a nutrient product • Products must be accepted by customers • Nutrient recovery • Investment support and market support for innovation by SMEs • Policy and regulatory coherence, holistic approach: agricultural masses vs. sewage sludge in nutrient recycling • Mixing obligation for recycled nutrients and possibly a specific sub-target for the use of sewage sludge-based nutrients • End-of-Waste legislation needed • Promote solutions that both recycle nutrients and control risks associated with harmful substances • Launch work to set a national target to accelerate nutrient recycling of sewage sludge • Clear communication by experts to the public on the need for nutrient recycling. The public is not aware of the issue. Different campaigns? • Communication: a model (similar to the waste hierarchy) for the utilisation of sewage sludge • Address the sources of polluting emissions in wastewater as far as possible • Promoting nutrient recovery through legislation or economic support measures

Table 6. *Workshop participants' views on measures and policy instruments reducing the risks associated with harmful substances taken from the Padlet notes.*

Reducing the risks associated with harmful substances
• Awareness-raising for consumers and businesses • Innovative processing technologies • Determining an acceptable level of risk • Understanding and numericalization the risks associated with contaminants • More research • Management and pre-treatment of potential primary emission sources • More extensive quality and analytical requirements • Development of ecotoxicological tests • Limit values also for organic pollutants • Regular bio-testing, in particular for genotoxic effects • Monitoring and assessment of long-term effects

Table 7. *Workshop participants' views on measures and policy instruments promoting minimization of carbon footprint taken from the Padlet notes.*

Minimizing the carbon footprint
• Choosing the locally optimal solution - regulation must allow for this • Calculating the life cycle model • Processing methods that retain some of the carbon • Using technology that is a self-sufficient regarding heat energy • Products in which carbon is in a permanent form • In the calculation of the carbon footprint, the product that is replaced by the circular economy product must also be taken into account in calculating the footprint

• Making emissions visible, including alternative costs • The shortest possible transfer distances between products. No unnecessary transports. • Monitoring of carbon footprint through measurement and case-by-case calculation (emission factors very imprecise) • Reliable return of organic matter to the soil • Uniform measurement methods: transport of feeds and end products should be taken into consideration in addition to the plant. The amount of energy generated and its role in replacing fossil energy should be considered

Table 8. *Workshop participants' views on measures and policy instruments promoting minimization of cost taken from the Padlet notes.*

Minimization of costs
• Feasible solutions may differ from those favored by university researchers • Choosing the locally optimal solution - regulation must allow for this • Methods that do not generate much reject • Whose cost? An individual actor in his own business, or in terms of the whole? • Minimise transfer distances and transfer volumes • Possibility of different solutions in different situations (in different orders of magnitude) • A sufficiently comprehensive assessment of the total costs of the different options (including the costs of phosphorus recycling)

Table 9. *Workshop participants' views on measures and policy instruments promoting mass reduction taken from the Padlet notes.*

Mass reduction
• Transporting water is not sustainable • Energy efficient method for water evaporation • Sludge incineration, phosphorus recovery and use of ash for soil construction • Pelletizing • Facilitates end use and allows the product to be transported further away • Renewal of the entire infrastructure • Incineration removes organic matter and water, effectively reducing mass • Does the benefit of mass reduction outweigh the disadvantage of carbon loss? • Reduces transportation • Improving the regulation of landscaping • No separate guidance needed for mass reduction

In addition the written notes in Padlet application, the perspectives that the experts were particularly keen to highlight were discussed. The following opinions were raised:

- Mineral fertilisers are becoming more expensive. Green deal directs towards recycled fertilisers
- The end use needs to be considered in nutrient recycling. The company buying the primary products is concerned about the purity of the products and of the arable lands. Treatment technologies are expensive. The different biomass fractions need to be divided to different destinations. The company does not accept the use of sewage sludge from its contracted producers.

- A society is responsible for the cost of treating wastewater. The same must apply to the treatment of sludge. Politicians are afraid of rising wastewater fees, but residents accept it if it is justified
- Solutions must be scientifically justified and not reputation driven. A report by Natural Resources Institute LUKE recommends the use of sludge in agriculture
- Water separation is a prerequisite for the sustainable treatment of large masses
- The product status of sludge-based fertilisers is important. Uncertain information slows down investments. Even within agriculture there are different segments, not all are cereal farmers
- The market is hampered by the limited parameter list of limit values, which does not give credibility to the safety of materials. If the quality criteria were more stringent and broader, it would give real credibility to the products.
- The most important thing would be to capture phosphorus in a form that could be easily distributed
- Global markets can cause drastic changes in fertiliser prices, which will certainly increase interest in them
- A holistic approach is needed, where we talk about all biomasses together, not just one at a time. The objectives of the different sectors need to be aligned so that the regulations in the different policy areas are pointing in the same direction.
- Our current wastewater treatment system is really out of date. Could we consider a fundamental overhaul of the whole system to allow better recycling of nutrients? For example, if industrial wastewater were treated separately, it would be easier to produce recyclable fractions.
- Coherence is needed in the sector. At present, the different actors are looking strictly from their own point of view. Legislation also needs to be updated so that the sectors are not so separate.
- Consideration should be given to the weighting of different measures
- What is the role of biotesting? There is no legal requirement and it is not currently in use. Difficult to get the right result as it is difficult to know what to test.

5 Main findings

The views of the workshop participants on sludge management showed to be quite diverse.

The participants evaluated reducing the risks associated with harmful substances and enabling nutrient recycling as the most important sludge management objectives. Importance of these two objectives was on a similar level.

Majority of participants did not suggest changes to the preliminary sludge management scenarios. However, plenty of opinions were given regarding the scenarios. Based on the frequency of the things mentioned, the predominant scenario-specific views are as follows:

> BAU scenario: Anaerobic digestion of sludge is found to be beneficial treatment technique for several reasons. Harmful substances in sewage sludge -based compost causes concern among participants. Scenario is not a cost-efficient alternative for small wastewater treatment plants.

Scenario 1: Incineration of sludge is proven technology that removes organic pollutants and reduces mass. However, loss of organic matter was also seen as a drawback. Loss of nitrogen and need to landfill ash were also considered as drawbacks. Lack of phosphorus recovery from ash in the scenario was paid attention to, but on the other hand it was noted that the scenario enables resource recovery (also of other material than phosphorus).

Scenario 2: Centralized treatment was found suitable for economic areas of different sizes. On the other hand, increased environmental impacts and costs from transporting sludge to a centralized plant was considered a drawback. Granules are easier to store and spread than digestate and, also cheaper to transport to end-user. However, persistent organic pollutants are not removed in the process and they may end up in agricultural crops, which was considered a risk.

Scenario 3: Carbon stored in a stable form in biochar produced in scenario was considered a benefit. However, immobilization of phosphorus (due to precipitation with iron in wastewater treatment process) in biochar was found a drawback. There is still uncertainty about fate of pollutants and harmfulness of their degradation products in the process. Many potential applications for the produced biochar were found a positive aspect.

Specific policy instruments needed to promote sludge management objectives were rarely mentioned during the workshop, whereas the participants mostly discussed about objectives on a more general level. However, policy instruments suggested in the workshop are summarized as follows:

- Economic support for nutrient recovery investments and for creating markets for secondary fertilizers
- Mixing obligation for recycled nutrients in fertilizer products
- Policy and regulatory coherence needed regarding nutrient recovery from different biomasses
- Information campaigns about need of nutrient recycling to the public to make sewage sludge -based fertilizers widely accepted
- Information campaigns about harmful substances to the public and industries to decrease their amounts in municipal wastewater
- End-of-Waste legislation
- More strict regulations for pre-treating industrial wastewater led to sewer network

Other measures that suggested to promote sludge management objectives during the workshop were discussed during workshop. The most relevant ones are listed below:

- Promote solutions that both recycle nutrients and control risks associated with harmful substances
- More monitoring, analytics, research and tests for recognizing harmful pollutants in sludge and toxic properties of sludge
- Setting limit values also for organic pollutants in sludge-based fertilizers
- Setting national targets for nutrient recovery and recycling from sewage sludge

- Use of measurements to monitor direct greenhouse gas emissions from treatment processes instead of using emission factors for improving the accuracy of carbon footprint calculations

Majority of observations on scenarios and discussion about policy instruments and measures required concerned nutrient recovery and risks created by harmful substances in sewage sludge. These were also voted as the most important objectives for sludge management by the workshop participants.

When considering other aspects of resource recovery than nutrient recovery, energy recovery from sludge was not much discussed during the workshop. This may be due several reasons: firstly, energy was not among the predefined objectives, secondly, process units for energy recovery are included in all presented scenarios and, thirdly, techniques for energy recovery from sludge have been used for decades in Finland and the objective is not novel like nutrient recovery.

APPENDIX 1: List of workshop participants:

Name		Organisation
Alhonoja	Katja	Gasum Oy
Berlin	Titta	Maa- ja metsätalousministeriö
Fjäder	Päivi	Suomen ympäristökeskus
Gareis	Christoph	HSY Jätehuolto
Graan	Marina	HSY - Jätevedenpuhdistus
Haimi	Henri	FCG Finnish Consulting Group Oy
Hirvi	Tero	Fazer Finland Oy, Fazer Mylly
Jaakonmäki	Seppo	Varsinais-Suomen ELY-keskus
Kaipia	Vesa	Etelä-Karjalan Jätehuolto Oy
Kangas	Ari	Ympäristöministeriö
Karjala	Rauni	Gasum Oy
Kiviniemi	Polina	FCG Finnish Consulting Group Oy
Laasonen	Arttu	Endev Oy
Laine-Ylijoki	Jutta	FCG Finnish Consulting Group Oy
Lehto	Kirsi-Maarit	Tampereen yliopisto
Lindell	Paula	Vesilaitosyhdistys
Malmilehto	Sakari	ELY-Keskus
Mikola	Anna	Aalto-yliopisto
Näsilä	Varpu	AFRY Finland
Porvari	Marjukka	JNF Foundation
Punkkinen	Henna	FCG Finnish Consulting Group Oy
Retkin	Risto	Ruokavirasto
Riikonen	Anu	Viherympäristöliitto ry
Ruokanen	Lotta	HELCOM - Baltic Marine Environment Protection Commission
Saarentaus	Anna	JNF Foundation
Senilä	Katri	SYKE/UEF
Solla	Maarit	V-S ELY-keskus/Maatalousyksikkö
Suomalainen	Mika	Etelä-Karjalan Jätehuolto Oy
Tähtikarhu	Eeva	JNF Foundation
Virolainen-Hynnä	Anna	Suomen Biokierto ja Biokaasu ry
Virtanen	Eetu	Soilfood Oy
Wikström	Ulrika	Vilja-alan yhteistyöryhmä VYR ry
Väänänen	Mikko	HSY Vesihuolto
Äystö	Lauri	Suomen Ympäristökeskus (SYKE)

Anna yhteensä 15 pistettä. Kuinka tärkeänä pidät, että jätevesilietteen käsittely

21

Ryhmä 1: Puhdistamolietteen käsittelyyn liittyvät hyödyt ja haitat

Lisää +-napista uusi "lappu" seinälle. Kirjoita jokainen hyöty ja haitta eri lapuille. Voit myös peukuttaa muiden lisäämiä lappuja tai täydentää niitä lisäämällä kommentin.

EEVATAHTIKARHU 11.02.2022 11.04

Lietteen mädätys jätevedenpuhdistamolla

Laitekanta ja osaaminen olemassa.

Mädätyksessä syntyvää biokaasua voidaan hyödyntää energiana

Biokaasun omakäytön verotus tiukentunut

Haitta-aineita päätyy maatalouskäytössä satoon, konsentroituu peltoon ja/tai valuu vesistöön

Mädättäminen ei ota vielä kantaa käsitelläänkö liete mädätyksen jälkeen? — NIMETÖN

Lietteen poltto

Paljon orgaanista ainetta menetetään

Kaikki hiili päästetään ilmakehykseen

Jätehierarkian mukaisesti viimeinen vaihtoehto

Poistaa orgaaniset haitta-aineet kierrosta

Fosfori vaikeasti hyödynnettävässä muodossa

EU:n hyväksymä, tutkitusti kestävä ratkaisu

Kustannustehokas

Yli jäävä tuhka, josta on poistettu fosfori on vaarallinen jäte ja joudutaan loppusijoitamaan

Vaatii kalliita investointeja

Ravinnetalteenottoon tarvitaan paljon kemikaalia

Lietteen mädätys muualla kuin puhdistamon yhteydessä + terminen kuivaus ja rakeistus

Rekkarallin aiheuttama liikenne, hajuongelmat ja co2 -päästöt

Orgaaniset haitta-aineet ja mikromuovi osittain jäljellä

Asiakassegmentin vaatimukset lopputuotteelle

Lietteen termokemiallinen käsittely

Osa hiilestä muutetaan hyvin pysyväksi hiileksi

Toistaiseksi taloudellisesti kallis ratkaisu

Omat selvitykset koelaitoksessa osoittavat, että jäävä osa on mitätön pieni. — NIMETÖN

Organiset haitta-aineet ja mikromuovi eliminoidaan.

Vaatii kalliita investointeja

Osa orgaanisista haitta-aineista jää jäljelle

******

Ryhmä 2: Puhdistamolietteen käsittelyyn liittyvät hyödyt ja haitat

Lisää +-napista uusi "lappu" seinälle. Kirjoita jokainen hyöty ja haitta eri lapuille. Voit myös peukuttaa muiden lisäämiä lappuja tai täydentää niitä lisäämällä kommentin.

EEVATAHTIKARHU 11.02.2022 13.02

Lietteen mädätys jätevedenpuhdistamolla

Pysyvät orgaaniset haitta-aineet eivät hajoa prosessissa

Lietteen tilavuus pienenee

Mädätysjäännöksen varastointikapasiteettipula maatiloilla

Lietteen poltto

Yleisesti heikko hyötysuhde

Valtaosa orgaanisista haitta-aineista saadaan todennäköisesti poistettua

Raskasmetallit rikastuvat lopputuotteeseen

Valtaosa orgaanisesta aineksesta menetetään

Massamäärä pienenee poltossa

P huonosti hyödynnettävissä

Fosfori voidaan jalostaa CE-merkityksi lannoitevalmisteeksi

Lietteen mädätys muualla kuin puhdistamon yhteydessä + terminen kuivaus ja rakeistus

Pysyvät orgaaniset haitta-aineet eivät hajoa prosessissa

Helpommin käsiteltävä ja levitettävä kuin mädäte

Suurten massamäärien kuljetuksen ympäristövaikutukset ja taloudellisuus?

Lietteen termokemiallinen käsittely

Uset orgaaniset haitta-aineet todennäköisesti poistuvat prosessissa

Hiilen pitkäaikainen varastointi

Lietehiili/biohiili potentiaalinen jo käytössä oleva materiaali viherrakentamisessa, hulevesien käsittely ym.

Yleisiä

Lainsäädännön osalta puhdistamolietteitä koskee myös POP-asetus ja sen jäteraja-arvot. Ne ovat toki niin korkeat, ettei raja-arvojen ylityksiä oleteta tapahtuvan

Tuotteita olisi pystyttävä tuottamaan mahdollisimman tasalaatuisina

******

Ryhmä 3: Puhdistamolietteen käsittelyyn liittyvät hyödyt ja haitat

Lisää +-napista uusi "lappu" seinälle. Kirjoita jokainen hyöty ja haitta eri lapuille. Voit myös peukuttaa muiden lisäämiä lappuja tai täydentää niitä lisäämällä kommentin.

EEVATAHTIKARHU 11.02.2022 13.04

Lietteen mädätys jätevedenpuhdistamolla

Hyöty 1

Ei siirretä vettä edes takaisin eri laitosten välillä — NIMETÖN

Kaasun talteenotto. — NIMETÖN

Osittainen hygienisointi. — NIMETÖN

Haitta 1

Ei kustannustehokasta pienillä jätevedenpuhdistamoilla — NIMETÖN

Kaasu voidaan hyödyntää jätevedenpuhdistamon energialähtenä

Haitta-aineet jäävät mädätejäännökseen, jolle on löydyttävä hyötykäyttö- tai loppusijoituskohde.

Vaati toimenpiteitä jäteveden syntypisteessä (vrt. Ruotsi) — NIMETÖN

Kemiallisen fosforin poiston kanssa struviittisaostus ongelmallista

Lietteen poltto

Orgaaniset haitta-aineet poistuvat

Lietteeseen sitoutunut orgaaninen aines menetetään poltossa

Fosforin erottaminen tuhkasta tai tuhkan hyödyntäminen kallista ja muuten haastavaa

Energian käyttö. — NIMETÖN

Mikäli liete poltetaan erikseen, tuhkassa on suhteellisen paljon fosforia erotettavaksi. — NIMETÖN

Ei välttämättä sellaisenaan sovellu jatkossa lannoitevalmisteeksi — NIMETÖN

Haitta-aineet eivät häviä, vaan hajoavat muiksi yhdisteiksi tai päätyvät savukaasuihin

Ei saada talteen ravinteita ilman lisäinvestointeja.

Vaatinee ison laitoksen

Kallis menetelmä. — NIMETÖN

Lisää kaatopaikkasijoittamisen määriä?

Lietemassojen kuljettaminen pitkiä matkoja

Olemassa olevilla laitoksilla voidaan polttaa muun jätteen joukossa, joten ei vaadi lisäinvestointeja.

Typpi menetetään

Voidaan polttaa muiden jätteiden kanssa, mikä luo synergiaa.

Jätteenpolttovero voi lisätä kustannuksia — NIMETÖN

Sopii erikokosilla talousalueille (isot, keskisuuret) ja yhteistyö alueen kuntien kesken.

Lietteen mädätys muualla kuin puhdistamon yhteydessä + terminen kuivaus ja rakeistus

Terminen kuivaus poistaa jonkin verran org. haitta-aineita

Kuljetuksesta ja käsittelystä aiheutuvat kustannukset ja haitat

Vaatii suuren laitoksen ja laitosinvestoinnit ovat suuret — NIMETÖN

Ei todennäköisesti sovellu syrjäisille alueille pitkien kuljetusmatkojen takia — NIMETÖN

Lisää kuljetuksia. — NIMETÖN

Termisesti kuivattua lietettä on helpompi varastoida ja edullisempi kuljettaa kuin mekaanisesti kuivattua.

Suuruuden ekonomia

Rakeistus (tai vastaava) on lopputuotteen käytettävyyden kannalta iso hyöty

Parantaa lietteen käsittelyn taloudellista kannattavuutta, sillä biometaanin hinta on korkeampi suhteessa muihin energiatuotteisiin.

Rejektiveden ravinnepitoisuudet ovat huomattavat mekaaniseen kuivaamiseen verrattuna. Niille järjestettävä käsittely.

Lietteen termokemiallinen käsittely

Poistaa jonkin verran orgaanisia haitta-aineita

Ehkä enemmän kuin jonkin verran.. toki prosessiolosuhteista riippuvaista — NIMETÖN

Haitta-aineiden hajoamistuotteet voivat olla alkuperäistä yhdistettä haitallisempia

Pysyvien haitta-aineiden määrät kasvat lopputuotteessa jos eivät hajoa käsittelyn aikana tai poistu poistokaasujen mukana — NIMETÖN

Lietehiilellä potentiaalisia hyödyntämistapoja

Sitoo hiiltä maaperään pidemmäksi ajaksi — NIMETÖN

Riittääkö kaikelle biohiilelle markkinoita? Biohiilestä ollaan kiinnostuneita pajusta rakennuspuujätteeseen ja kaikkeen siltä väliltä. — NIMETÖN

Kallis investointi

Lisää kaatopaikkasijoittamisen määriä?

Ratkaisu ainoastaan isoille kaupungeille investoinnin korkean hinnan vuoksi.

******

Ryhmä 1: Toimet ja ohjauskeinot puhdistamolietteen käsittelyyn ja hyödyntämiseen

Lisää jokainen toimi tai ohjauskeino omalle lapulleen. Voit kannattaa (tai vastustaa) seinällä olevia lappuja peukuttamalla ja täydentää niitä lisäämällä kommentin.

EEVATAHTIKARHU 11.02.2022 11.38

Ravinnekierrätyksen edistäminen

Markkinoiden varmistaminen tuotteille

Oikeat puhdistustekniikat ravinnetuotteen loppumarkkinan kannalta

Loppuasiakkaiden kuuntelu

Tuotteiden tulee olla asiakkaiden sekä heidän asiakkaidensa hyväksymiä. — NIMETÖN

Haitta-aineisiin liittyvien riskien vähentäminen

Valistustyö kuluttajille ja yrityksille.

Innovatiivista käsittelytekniikkaa

Hyväksyttävän riskitason määrittäminen - kiertotaloudessa on aina olemassa tietty riski, koska kiertotaloustuotteet eivät ole neitseellisiä tuotteita

Haitta-aineisiin liittyvien riskien tunteminen ja numeraalistaminen

Hiilijalanjäljen minimointi

Paikallisesti optimiratkaisun valitseminen - sääntelyn tulee antaa tälle tilaa

Elinkaarimallin laskeminen

Käsittelymenetelmiä, joka säilyttävät osan hiilestä

Lämpöenergiasta omavaraista tekniikka

Tuotteet, jossa hiili on pysyvässä muodossa

Hiilijalanjälkilaskennassa tulee huomioida jalanjälkeä laskevasti myös tuote, jonka kiertotaloustuote korvaa.

Päästöt näkyviksi, ml. vaihtoehtoiskustannus. Turha liikenne on turhaa, vaikka tehtäisiin sähköllä tai biokaasulla.

Kustannusten minimointi

Toteutuskelpoiset ratkaisut voivat poiketa yliopistotutkijoiden suosikeista

Paikallisesti optimiratkaisun valitseminen - sääntelyn tulee antaa tilaa tälle

Menetelmiä, josta ei synny paljon rejektiä

Kenen kustannus :D Yksittäisen toimijan omassa liiketoiminnassaan, vai ajatellen koko kokonaisuutta?

Massan vähentäminen

Veden kuskaaminen ei kestävää

Energiatehokas menetelmä veden haihduttamiseen

******

Ryhmä 2: Toimet ja ohjauskeinot puhdistamolietteen käsittelyyn ja hyödyntämiseen

Lisää jokainen toimi tai ohjauskeino omalle lapulleen. Voit kannattaa (tai vastustaa) seinällä olevia lappuja peukuttamalla ja täydentää niitä lisäämällä kommentin.

EEVATAHTIKARHU 11.02.2022 13.11

Ravinnekierrätyksen edistäminen

Ravinteiden talteenotto jo aiemmin jätevedenpuhdistusprosessista

Investointituet ja PK-yritysten innovaatioiden markkinoille tukeminen

Politiikan ja säädösten koherenssi, kokonaisvaltaisuus: maatalouden massat vs. jätevesilietteet ravinteiden kierrätyksessä

Haitta-aineisiin liittyvien riskien vähentäminen

Tutkimuksen lisääminen

Mahdolliset primääripäästölähteiden hallinta ja esikäsittely

Nykyistä laajemmat laatu- ja määritysvaatimukset

Ekotoksikologisten testien kehittäminen

Hiilijalanjäljen minimointi

Mahdollisimman lyhyet siirtoetäisyydet tuotteiden välillä

Kustannusten minimointi

Siirtoetäisyydet mahdollisimman pienet ja siirtomäärät mahdollisimman alhaiset

Massan vähentäminen

Lietteen poltto, fosforin talteenotto ja tuhkan maanrakennuskäyttö.

Pelletöinti

Helpottaa loppukäyttöä ja mahdollistaa tuotteen siirtämisen kauemmaksi

Koko infran uudistaminen

Yleisiä

Markkina

Ryhmä 3: Toimet ja ohjauskeinot puhdistamolietteen käsittelyyn ja hyödyntämiseen

Lisää jokainen toimi tai ohjauskeino omalle lapulleen. Voit kannattaa (tai vastustaa) seinällä olevia lappuja peukuttamalla ja täydentää niitä lisäämällä kommentin.

EEVATAHTIKARHU 11.02.2022 13.12

Ravinnekierrätyksen edistäminen

Toimi 1

Kommentoimalla voit täydentää muiden lisäämiä lappuja — NIMETÖN

Sekoitevelvoite

Kierrätysravinteiden sekoitevelvoite ja mahdollisesti puhdistamolietepohjaisten ravinteiden käytölle oma alatavoite — NIMETÖN

Ohjataan lainsäädännöllä.

EoW tarvitaan! — NIMETÖN

Ravinteiden talteenotto

Tämä tulee osin jo Taksonomian kautta. — NIMETÖN

Lainsäädännössä velvoite ravinteiden talteenottoon.

Sellaisten ratkaisujen edistäminen, joissa saadaan sekä ravinteet kierrätettyä että haitta-aineisiin liittyvät riskit hallittua.

Käynnistetään työ kansallisen tavoitteen asettamiseksi puhdistamolietteiden ravinteiden kierrätyksen joudutamiseksi.

Asiantuntijoiden selkeä viestintä julkisuudessa ravinnekierrätyksen välttämättömyydestä. Ihmiset ovat kovin innostuneita esimerkiksi muovin kierrätyksestä tällä hetkellä, mutta kuinka moni maallikoista on huolissaan ravinnekierrätyksestä? Erilaiset kampanjat?

Viestintään: Laaditaan jätehierarkian kaltainen malli puhdistamolietteiden hyödyntämiselle.

Tartutaan jätevesien haitta-aineiden päästölähteisiin siltä osin kuin mahdollista.

Haitta-aineisiin liittyvien riskien vähentäminen

Raja-arvot asetettava myös orgaanisille haitta-aineille

vaatii paljon tutkimusta, jota ei vielä ole tehty, kuka rahoittaa? — NIMETÖN

EU:n lannoitelaissa vain PAH16 raja-arvo ja haitalliset metallit. — NIMETÖN

Erityisesti PFAS-yhdisteet ongelmallisia (PFOS varsinkin). Ei hajoa, biokertyvä — NIMETÖN

Kattavat haitta-aineanalyysit ovat kalliita. — NIMETÖN

Säännönmukainen biotestaus etenkin genotoksisten vaikutusten löytämiseksi

Biotestausta voidaan käyttää suosituksena jossain käyttökohteissa, mutta lainsäädäntövelvoitteena ei ole vielä valmis. — NIMETÖN

Ravinteiden talteenoton edistäminen lainsäädännöllä tai taloudellisin tukitoimin

Pitkäaikaisvaikutusten seuranta ja arviointi

Hiilijalanjäljen minimointi

Hiilijalanjäljen monitorointi mittaamalla ja tapauskohtaisella laskennalla (päästökertoimet hyvin epätarkkoja)

Orgaanisen aineksen palauttaminen maaperään luotettavasti.

Yhtenäiset mittaustavat.

Tarkasteluun laitoksen ohella myös syötteiden ja lopputuotteiden kuljetus. Huomioitava syntyvän energian määrä ja sen rooli fossiilisen energian korvaamisessa (omakäyttö, sähkön - ja lämmön käyttö toisaalla, biometaanin käyttö liikenne, teollisuus yms.) — NIMETÖN

Kustannusten minimointi

Mahdollisuus erilaisiin ratkaisuihin erilaisissa tilanteissa (eri suuruusluokissa)

Eri vaihtoehtojen kokonaiskustannusten arviointi riittävän kattavasti (huomioiden myös fosforin kierrätyksen kustannukset)

Massan vähentäminen

Polttamalla saadaan poistettua orgaaninen aines ja vesi ilmaan, eli massa vähenee tehokkaasti.

onko saatava massan vähennyshyöty suurempi kuin hiilen menetyksen haitta? — NIMETÖN

Vähentää kuljetuksia.

Viherrakentamisen sääntelyn tehostaminen

******