BONUS RETURN

Reducing Emissions by Turning Nutrients and Carbon into Benefits

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x	PU	Public.
	PP	Restricted to other project partners.
	RE	Restricted to a group specified by the consortium.
	CO	Confidential, only for members of the consortium.

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EXECUTIVE SUMMARY

In this report, sustainability assessments of different potential systems for recovering and reusing nutrients and carbon (organic matter and energy) from different wastes are presented. The assessments were done in three different case-studies: the Vantaanjoki catchment area in Finland, the Fyriså catchment area in Sweden and the Słupia catchment area in Poland. A sustainability analysis approach with multi-criteria analysis (MCA) was used to assess different system alternatives in the three case studies. A review of sustainability criteria was used as the starting point for selection of criteria. Systematic maps of ecotechnologies for the recovery and reuse of nutrients and carbon within the Baltic Sea region were used as the basis for selection of technological system components and overall system alternative design.

Two workshops were held in each case study. The aim of the first workshop was to gain insights into the local contexts, challenges, opportunities and stakeholders' interests. Knowledge gained from the workshop influenced the selection of sustainability criteria and system alternatives. At the second workshop, the stakeholders were asked to assign weights to the different criteria according to their relative importance. Each system alternative was evaluated for each sustainability criteria and the overall sustainability score was calculated as the weighted sum of criteria scores and weights.

For the Vantaanjoki case study, different systems for managing horse manure, waste-grass and source-separated blackwater from scattered settlements were assessed. The system alternatives evaluated were 1. Composting (baseline system representing current management), 2. Anaerobic digestion and 3. Pyrolysis + urea hygienization of source-separated blackwater. These systems were evaluated against the 9 criteria: global warming potential, eutrophication potential, nutrient recovery, effects on soil structure, total costs, local economy, risk of exposure to pollutants, acceptance and compatibility with existing infrastructure. The system anaerobic digestion system alternative got the highest sustainability score, although the Pyrolysis + urea hygienization got an only slightly lower score. Both systems received higher sustainability scores than the composting alternative.

For both the Fyriså and the Słupia case studies nutrient recovery from domestic wastewater was assessed. The same 8 sustainability criteria were used for both case-studies: global warming potential, eutrophication potential, nutrient recovery, total costs, risk of exposure to pollutants, acceptance, technical robustness and technical flexibility.

For the Fyriså case study, four system alternatives were evaluated: 0. Baseline system (representing current management), 1. Incineration of sludge and phosphorus extraction from ash 2. Anaerobic treatment in UASB-reactor and nutrient extraction through ammonia stripping and struvite recovery and 3. Source-separation (blackwater treated as in 2. and sludge treated as in 1.). The source-separation system got the highest score, followed by the nutrient extraction system and incineration system. All recovery systems received a higher sustainability score than the baseline system.

In the Słupia case study, four similar system alternatives were evaluated; 0. Baseline system (representing current management), 1. Ammonia stripping from reject water from dewatering anaerobic digestate 2. Anaerobic treatment in UASB-reactor and nutrient extraction through ammonia stripping and struvite recovery and 3. Source-separation (blackwater treated as in 2.) in all systems

sludge was composted. The system alternative with nutrient extraction (2) got considerably higher score than the other systems and source-separation got the lowest, compared to the baseline system. Results showed that the source-separation system could receive a sustainability score lower than the baseline system. The outcome of the assessment was different for the Fyrisån and Słupia cases, even though the system alternatives were composted of largely the same ecotechnologies. This shows that local context and stakeholder participation are important parts of sustainability assessments.

1 INTRODUCTION

The degradation of the Baltic Sea is an ongoing problem, despite investments in measures to reduce external inputs of pollutants and nutrients from both diffuse and point sources. Available technological and management measures to curb eutrophication and pollution flows to the sea have not been adapted adequately to the contexts in which they are being applied. Furthermore, measures are often designed based on single objectives, thereby limiting opportunities for multiple benefits.

In addition, there is a general sense that measures to address the deterioration of the Baltic ecosystem are primarily technologically-driven and lacking broader stakeholder acceptance – the "experts" who define these measures have little engagement with industry, investors, civil society and authorities. This problem is magnified by governance and management, taking place in sectoral silos with poor coordination across sectors.

As a result, research shows that regional institutional diversity is presently a barrier to transboundary cooperation in the Baltic Sea Region (BSR) and that actions to achieve national environmental targets can compromise environmental goals in the BSR (Powell *et al.*, 2013). The regional dimension of environmental degradation in the BSR has historically received weaker recognition in policy development and implementation locally. However, developments in recent years suggest a new trend with growing investments in environmental protection supporting social, economic, and territorial cohesion.

The BSR is an environmentally, politically and economically significant region and like other regions globally, its rapid growth needs to be reconciled with the challenges of sustainable development in a global setting that demands unprecedented reductions in GHG emissions. This poses a truly wicked problem exacerbated by the fact that many of the challenges in the BSR will also magnify in a changing climate. In order to navigate the uncertainties and controversies associated with a transformation towards a good marine environment, BONUS RETURN will enact an innovative trans disciplinary approach for identifying and piloting systemic eco-technologies.

The focus is on eco-technologies that generate co-benefits within other interlinked sectors, and which can be adapted according to geophysical and institutional contexts. More specifically, emphasis is placed on eco-technologies that reconcile the reduction of present and future eutrophication in marine environments with the regional challenges of policy coherence, food security, energy security, and the provision of ecosystem services.

1.1 Project Objectives

The **overall** aim of BONUS RETURN is to improve the adaptation and adoption of eco-technologies in the Baltic Sea Region for maximum efficiency and increased co-benefits.

The **specific objectives** of the project can be divided into six categories presented below. These categories are interlinked but for the purpose of providing a step-wise description, the following overview of each category proves useful. BONUS RETURN is:

1) **Supporting innovation and market uptake of eco-technologies by:**

- Contributing to the application and adaptation of eco-technologies in the BSR through an evidence-based review (systematic map) of the developments within this field.
- Contributing to the development of emerging eco-technologies that have the capacity to turn nutrients and carbon into benefits (e.g. bio-energy, fertilizers), by providing an encompassing framework and platform for rigorous testing and analysis.
- Developing decision support systems for sustainable eco-technologies in the BSR.
- Contributing to better assessment of eco-technology efficiency via integrated and participatory modelling in three catchment areas in Finland, Sweden and Poland.
- Contributing to methodological innovation on application and adaptation of eco-technologies.

2) Reducing knowledge gaps on policy performance, enabling/constraining factors, and costs and benefits of eco-technologies by:

- Assessing the broader socio-cultural drivers linked to eco-technologies from a historical perspective.
- Identifying the main gaps in the policy environment constraining the implementation of emerging eco-technologies in the catchments around the Baltic Sea.
- Informing policy through science on what works where and under which conditions through an evidence-based review (systematic map and systematic reviews) of eco-technologies and the regional economic and institutional structures in which these technologies evolve.

3) Providing a framework for improved systematic stakeholder involvement by:

- Developing methods for improved stakeholder engagement in water management through participatory approaches in the case study areas in Sweden, Finland and Poland.
- Enacting a co-enquiry process with stakeholders into opportunities for innovations in eco-technologies capable of transforming nutrients and pollutants into benefits for multiple sectors at different scales.
- Bringing stakeholder values into eco-technology choices to demonstrate needs for adaptation to local contexts and ways for eco-technologies to efficiently contribute to local and regional developments.
- Disseminating results and facilitating the exchange of learning experiences, first within the three catchment areas, and secondly across a larger network of municipalities in the BSR.
- Establishing new cooperative networks at case study sites and empowering existing regional networks by providing information, co-organizing events and engaging in dialogues.

4) Supporting commercialization of eco-technologies by:

- Identifying market and institutional opportunities for eco-technologies that (may) contribute to resource recovery and reuse of nutrients, micro-pollutants and micro-plastics (e.g. renewable energy).
- Identifying potential constraints and opportunities for integration and implementation of eco-technologies using economical models.
- Facilitating the transfer of eco-technologies contributing to win-win solutions to multiple and interlinked challenges in the BSR.
- Linking producers of eco-technologies (small and medium enterprises – SMEs), to users (municipalities) by providing interactive platforms of knowledge exchange where both producers and users have access to BONUS RETURN’s envisaged outputs, existing networks, and established methodologies and services.

5) Establishing a user-driven knowledge platform and improved technology-user interface by:

- Developing an open-access database that maps out existing research and implementation of eco-technologies in the BSR. This database will be intuitive, mapped out in an interactive geographical information system (GIS) platform, and easily managed so that practitioners, scientists and policy-makers can incorporate it in their practices.
- Developing methodologies that enact the scaling of a systemic mix of eco-technological interventions within the highly diverse contexts that make up the BSR and allows for a deeply interactive medium of knowledge.

1.2 Project Structure

BONUS RETURN is structured around six Work Packages that will be implemented in three river basins: The Vantaanjoki river basin in Finland, the Słupia river basin in Poland, and Fyrisån river basin in Sweden.

Work Package 1: Coordination, management, communication and dissemination.
Work Package 2: Integrated Evidence-based review of eco-technologies.
Work Package 3: Sustainability Analyses.
Work Package 4: Environmental Modelling.
Work Package 5: Implementation Support for Eco-technologies.
Work Package 6: Innovative Methods in Stakeholder Engagement.

1.1 Deliverable context and objective

The current deliverable (Del. No 3.3) is part of WP (3). The objectives of WP (3) are to evaluate sustainability aspects of eco-technologies selected from WP2 using a decision support-based framework for sustainability analysis for each catchment area. The application of sustainability analysis includes a step-wise systems analysis approach to be carried out together with local stakeholders by: 1) defining system boundaries; 2) selecting criteria covering health and hygiene, environmental issues, economy, socio-cultural dimensions and technical function; 3) selecting and formulating different system alternatives based on the review of eco-technologies from WP2; 4) comparing the different options using the criteria from step 2. The comparison is done by using substance flow-, cost-effectiveness and cost benefit analysis, energy analysis and qualitative assessments. In step 4, a multi-criteria analysis is used for an integrated assessment of all dimensions to reach a complete decision support system for municipalities or regions. A second objective of WP3 is to identify upcoming innovations for reuse (TRL 5 or higher), using the same sustainability criteria as above. The final results of WP3 are a selection of interesting eco-technologies for further development in WP5.

This deliverable summarizes the multi-criteria analysis performed, including description of the system alternatives, sustainability criteria chosen and results of the analysis for each of the three case-studies.

1.2 Outline of the report

This report is structured as follows: first, the general method used is presented together with a short description of the catchment areas and main learning points from the first scoping workshop held in each. Then, the framework and results of the analysis are presented for each case study separately, starting with Vantaanjoki (Finland) followed by Fyrisån (Sweden) and Słupia (Poland). Lastly, a general discussion and final conclusions are made.

2 REPORT FROM THE MULTI-CRITERIA ANALYSIS FROM WORKSHOP 2 WITH COMPARISONS OF THE DIFFERENT ALTERNATIVES IN EACH CASE STUDY AND SELECTION OF ECOTECHNOLOGIES FOR FURTHER USE IN WP5

2.1 General method

A sustainability analysis approach with multi-criteria analysis (MCA) was used to assess the different alternatives in the three case studies. This approach was mainly based on Strategic Planning of Sustainable Urban Water Management (Malmqvist *et al.*, 2006) and consists of the 8 steps: 1) Goal and scope definition, 2) Selection of criteria, 3) Selection of alternatives, 4) Analysis and evaluation, 5) Scoring, 6) Weighting 7) Interpretation of results and 8) Sensitivity analysis. This MCA-approach has been applied as decision support in more than 20 applications for urban and rural water, wastewater and solid waste management~~.~~

For the BONUS RETURN project, we have used this general method of MCA. The selection of criteria started with a literature review of criteria (see Appendix). Stakeholder engagement in the selection was included through a first workshop in each case study (see 2.2.1, 2.3.1 and 2.4.1). The criteria chosen for the assessment is the basis of the sustainability evaluation. Each system alternative chosen is assessed regarding its performance based on the criterion in question. Depending on its performance, it is given a representative score. In this way, the system alternatives are compared to each other in respect to the chosen sustainability aspects.

The selection of system alternatives started with the selection of which sector to focus on in each case study. The sectors relevant for the project were agricultural and wastewater. In both sectors, the focus would be on the sustainability of managing resources from wastes in a different way than current practice. In the agricultural sector, a typical resource could be manure whilst in the wastewater sector it would be domestic wastewater. The management of these resources is the function of the system and could include different ecotechnologies in various constellations. Furthermore, aspects of sustainability not only apply to the part where nutrients or carbon are extracted, but also before and after those steps. For example, collection and transport of manure is a source of both emissions and costs and should therefore be accounted for in the system. The same goes for transport of the product to the site where nutrients will be reused; different technologies could produce products of different densities leading to differences in emissions from transport. The system therefore consists of both collection, treatment and reuse of substrates and products. In order to make a comparison between the different systems, they all need to perform the same net function. If a certain amount of substrate is managed in one system, the same amount needs to be managed in some way in all the compared systems, otherwise they are not comparable. Furthermore, in order for the system to provide adequate functions, additional system components such as conventional management practices may need to be included. This could, for example, be additional, conventional treatment of wastewater after nutrients have been extracted in order to limit eutrophication.

There can be many different external inputs to the systems that have emissions, costs or other sustainability aspects accompanying them. Such external inputs can be electricity and chemicals. These resources need to be accounted for when comparing the systems, since they consume different amounts. This is done by adding e.g. the emissions from production of the amount of electricity needed in the system, even though electricity production is not included as an internal function of the studied system.

2.1.1 Selection of sustainability criteria and system alternatives

For all case studies, the same general method was used to conduct the sustainability assessment (see above). Two workshops were held in each case study. The aim of the first workshop was to gain insights into the local contexts, challenges, opportunities and stakeholders' interests. This was done during a one-day workshop with local stakeholders which included presentations of the BONUS RETURN project and group exercises to identify and discuss relevant sustainability criteria and eco-technologies for the area. The progress of the systematic mapping from WP2 (see Haddaway (2018)) was presented, as well as a list of example sustainability criteria. Since it was uncertain which sector, whether agriculture or wastewater, would be the focus of the study in the sites, a general list of sustainability criteria was used. The criteria are divided into five categories: environmental, economic, socio-cultural, health and hygiene, and technical function. Each category includes several criteria, as outlined in Table 1.

Table 1. Sustainability criteria presented as examples to stakeholders at the first workshops.

Environmental	**Economic**	**Socio-cultural**	**Health & hygiene**	**Technical function**
Climate effect	Life cycle cost	Acceptance	Work environment	Flexibility
Reuse of resources	Capital/investment costs	Laws and policy	Health risks	Reliability
Emission of pollutants	Work force demands	Encourage sustainability	Pathogens	Technical complexity
Biodiversity	Economic vulnerability	Cultural and aesthetic values	Toxic substances	Lifetime
Land use	Quality of products	Functioning organization		Compatibility with existing infrastructure/technol ogy
Use of resources (energy, water etc.)	Support local economy	Equity		Maintenance requirement

The criteria in each category identified as most relevant by the stakeholders were given priority in the final selection of criteria for the assessment. However, consideration of the suitability of the criteria to the scope of the assessment and system alternatives had to be considered. Criteria representing aspects that are not accounted for in the system alternatives are of no use. For practical reasons the aim was to have at most 10 criteria to assess across all categories. To maximize the usefulness of the assessment, redundant criteria were excluded. Therefore, the selection of criteria was done in relation to the selection of system alternatives.

The selection of specific ecotechnologies to be included in the different systems was primarily influenced by the systematic mapping done in WP2 (see Macura *et al.* (2018)) and the first workshop for each case study. Initially, the most common ecotechnologies found in the maps were screened for relevance to the case studies and compared in relation to the lessons learned from the first workshops. These ecotechnologies, most of which can be applied in both wastewater and agriculture sector, were the following:

- Anaerobic treatment (biogas production)
- Adsorption of nitrogen and/or phosphorus
- Composting
- Biomass production for energy or biofuel production
- Irrigation with treated wastewater
- Hydrothermal treatment
- Membrane filtration
- Microalgae cultivation
- Microbial fuel/electrolysis cells
- Ammonia stripping
- Struvite recovery
- Pyrolysis and biochar use
- Source-separation of wastewater
- Vermicomposting

Next, the relevant ecotechnologies were evaluated based on the feasibility of assessing them with the sustainability assessment framework used and the accessibility of data for modelling. The resource recovery technologies chosen from the maps were complemented as needed with conventional technologies, so that the systems would function adequately.

An initial suggestion of sustainability criteria and system alternatives was sent out to the BONUS RETURN consortium for feedback. It was also sent to the stakeholders who participated in the first workshop so they would have a chance to give feedback. Based on the feedback received, the suggestion was revised as needed. After the final criteria and systems were chosen, further revisions were made only if problems with data requirements or execution demanded it.

2.2 The Vantaanjoki catchment area

The Vantaanjoki River basin (1,680 km^2) flows through the Helsinki metropolitan area (ca. 1 million inhabitants) before discharging into the Baltic Sea. The catchment area consists of 23% agriculture, 56% forestry and 17% urban area. Over 90% of the population is connected to a sewage network. The estimated number of on-site treatments for wastewater is 10,000 households. Treated sewage water from this region is discharged into the open sea area in the Gulf of Finland. There are five municipal wastewater treatment plants, four of which discharge treated wastewater into the river. The level of treatment at the municipal plants is high, e.g. around 95% of the phosphorus in the wastewater is removed during treatment. In the upper reaches of the river there are two towns (Riihimäki and Hyvinkää) with their own wastewater treatment plants also discharging treated wastewater into the river. The Vantaanjoki River basin is characterized by a variety of water resource problems, of which the most serious is non-point source pollution from agricultural fields and the point source pollution coupled with stormwater runoff from the urban areas.

2.2.1 First workshop

The stakeholders identified several ecotechnologies they deemed interesting for their catchment area. The ecotechnologies included the following:

- Forestation/restoration of riparian areas for recreational use, nutrient retention, etc.
- Increase in water-protection methods, e.g. naturalistic drainage systems
- Consideration of water and protection of it in planning and under construction
- Termination of wastewater overflow
- Production of biogas from grass, horse manure, manure and other agricultural residues and return nutrients to agriculture
- Maintaining fertility and soil structure of agricultural lands, reducing nutrient loads
- Holistic management of drainage
- Source-separation of wastewater for scattered settlements, greywater treated on-site and blackwater stored and then transported to treatment plant where it could be used in small-scale cultivation after lime-stabilization. Concern about transporting distances and responsibility
- Water management in agriculture and forestry, e.g. water retention on non-productive lands
- Management of leakages in urban stormwater network, biochar improved infiltration, urban wetlands

2.3 The Fyrisån catchment area

The Fyrisån River basin (1,982 km^2) is located in the south-eastern part of Sweden. The Fyrisån River is a tributary of Lake Mälaren, which has its outlet through Stockholm into the Baltic Sea. The catchment area is distributed among forests (60%), agriculture (32%), wetlands (4%), lakes (2%) and urban areas (2%). The urban area is dominated by the city of Uppsala, the fourth largest city in Sweden, whose wastewater treatment plant discharges treated wastewater into the river. The total number of people living within the catchment area is difficult to assess since it covers parts of 6 different municipalities. The Fyrisån River basin covers a quite diverse set of landscapes. The water quality status of the river has also been very well documented for a long time, making it possible to e.g. trace effects of historical implementations of ecotechnologies in wastewater treatment plants in the basin. There are several smaller treatment plants, most operated by municipal water companies. Around 83% of households are estimated to be connected to a sewer network.

2.3.1 First workshop

The following points were discussed by local stakeholders at the scoping workshop:

- Increasing the buffering capacity (of water flow) in the river, for example by introducing productive wetlands
- Addressing the spreading of pathogens in smaller communities (from small sewage systems)
- Activity-based actions, e.g. phosphorus capture
- Recovery at decentralized wastewater treatment plants, e.g. by liquid composting, treatment outdoors, wetlands
- Source-separated sewage at small and on-site treatment systems
- Biochar production from forestry waste
- Reduce use of phosphorus chemical fertilizer by substituting with sludge and other sources of recovered phosphorus, such as from phosphorus traps at fields
- Urine-diversion toilets
- Not connecting new residential areas to the central treatment plant but instead building decentralized treatment
- Membrane filtration of reject water from anaerobic digestion to capture pharmaceuticals
- Pyrolysis of sewage sludge and use of the biochar as soil improver, possibly mixed with treated source-separated blackwater
- Reuse of treated wastewater for industry e.g. as cooling water or for irrigation
- Recognize (gravity-based) combined sewers, employing drinking water as transport medium for excreta, as unsustainable
- Address the problem at source, not at the end of the pipe

2.4 The Słupia catchment area

The Słupia River basin (1,623 km^2) is a diverse coastal catchment with an expansive area of dunes stretching along the coast. Agricultural land and forest represent 54% and 42% of the basin, respectively. Urban areas constitute around 3%, of which the largest portion is taken by the city of Słupsk with 95,000 inhabitants, and two smaller towns (Bytów and Ustka). All of them have their own wastewater treatment plants discharging treated wastewater into the Słupia River system. The Słupia catchment is one of the largest catchments on the Polish coast that includes a large city (Słupsk) and thus it offers a unique opportunity to study the pressure on water quality from both rural and urban areas, which are predominant in this part of the BSR.

2.4.1 First workshop

The following ecotechnologies and measures were discussed by stakeholders in Słupia:

- Enhanced wastewater treatment level, e.g. through ultrafiltration and UV-disinfection
- Mitigate agricultural nutrient emissions and improve stormwater management, the second being a problem due to increase in area that is paved
- Small retention reservoirs and river restoration for increased self-purification

- The awarded winners of the BR innovation competition (Deliverable 3.7) concerned with phosphorus recovery are interesting and seem implementable
- Either 100% of population are to be connected to wastewater treatment plants, or on-site treatment needs to be improved
- Improving the liming and drainage management on farms
- Increasing use of renewable energy
- Optimizing fertilization rates based on soil parameters using geo-location systems
- Improved on-farm composting practices
- Crop rotation and optimization of livestock density for better nutrient management
- Introduce micro-strainer technologies at fish farms to reduce the environmental impact
- Increase environmental monitoring, both coverage and parameters measured

2.5 General learning points and issues

There was no agreement about which sector, i.e. agriculture or wastewater, that was most important to focus on in the context of this MCA in any of the catchment areas. There is evidence that the agricultural sector is a larger source of eutrophying emissions than the wastewater sector (HELCOM, 2018). The agricultural emissions are to a large extent diffuse, e.g. nutrient leaching from arable lands. The aim of this assessment is to compare different systems for recovering and reusing nutrients and carbon. There have been few ecotechnologies identified by WP2 that recover nutrients or carbon from diffuse sources in a form that is possible to reuse. Measures for dealing with diffuse sources are for example practices leading to better nutrient management and retention of nutrients in the soil, such as reduced tillage, crop rotation or cover crops. These measures do not provide a nutrient or carbon product that can be reused. In WP5, however, the awarded eco-innovation, BioPhree, is designed to capture and recycle nutrients from receiving waters so in the future also this type of ecotechnology could be included in MCAs. But here the focus was on wastewater and agricultural waste, where more data are available from full-scale applications. These are point-sources and more concentrated, making the recovery potential from them higher. The possibility of combining measures for diffuse and point sources has been considered, however the combination would be too difficult and possibly not meaningful in a systems analysis with aim and scope as this. In all catchment areas, stormwater management and pollution were an issue, but few ecotechnologies for recovering nutrients or carbon from stormwater have been identified in WP2. Therefore, management of stormwater is not included in any system alternative.

2.6 Assessment of the sustainability criteria

For the Vantaanjoki catchment area it was decided that resource recovery from mainly agricultural wastes and residues was to be assessed (described in detail in chapter 3). Three systems were assessed containing the following main ecotechnologies: composting, anaerobic digestion, pyrolysis, source-separation at on-site wastewater systems and blackwater hygienization. In the Fyris and Słupia catchment areas domestic wastewater was the focus. Similar systems were set up for Fyris and Słupia (described in detail in chapters 4 and 5), therefore the same criteria were used for both case-studies. For each of these two case-studies, four system alternatives were assessed. The main ecotechnologies included were: conventional treatment and anaerobic digestion of sludge (baseline), ammonia stripping, struvite recovery, anaerobic treatment of wastewater, phosphorus extraction from sludge incineration ashes and source-separation. All criteria assessed in this report are presented in Table 2, including which case-studies they were used in. Each criterion is described below.

Table 2. The sustainability criteria used for each case study.

Sustainability criteria	Vantaanjoki	Fyris	Słupia
Global warming potential	X	X	X
Eutrophication potential	X	X	X
Nutrient recovery	X	X	X
Total costs	X	X	X
Effects on soil structure	X		
Impacts on local economy	X		
Acceptance	X	X	X
Risk of exposure to pollutants	X	X	X
Compatibility with existing infrastructure	X		
Technical robustness		X	X
Technical flexibility		X	X

Global warming potential is calculated as the systems net emissions of CO_2 equivalents. There are several inputs to the systems in the form of electricity, heat and chemicals. In the systems, several sources of greenhouse gas emissions can occur such as from transport or from the treatment processes. Emissions from spreading and use of fertilizers are not included in the greenhouse gas calculations. The reasoning behind this is that we assume that the new fertilizer products replace mineral fertilizers, so in total no more fertilizers are used in agriculture compared to previously. Most greenhouse gas emissions from use of fertilizers (nitrous oxide) are connected to nitrogen load and as the nitrogen load will be the same we can assume that the greenhouse gas emissions will be similar. This is of course a simplification, as emissions of indirect nitrous oxide emissions also occur, however we think this simplification will not matter greatly for the interpretation of the results. The systems can provide benefits and products which replace other resources, thereby “saving” emissions. An example is replacing mineral fertilizer with recovered nutrients. This constitutes a negative emission for the system, and so the net emissions are reduced accordingly. More detail on which processes and emissions that are included in the *global warming potential* calculation for each case study is found in chapters 3, 4 and 5.

Eutrophication potential was assessed through a similar modelling as was done to calculate *global warming potential* for Fyris and Słupia. The indicator for this criterion was PO_4^{3-} equivalents, calculated with the CML method (Heijungs *et al.*, 1992). The calculated eutrophication potential is a “worst case” scenario where all emissions of nitrogen and phosphorus contribute to eutrophication. The sources of PO_4^{3-} eq. in these cases were nitrogen and phosphorus released directly to water, air emissions of ammonia and NOx emissions from transports. For the Fyris and Słupia cases, eutrophying emissions from soil which has received fertilizer is not accounted for. The system boundary ends where the fertilizer is applied to the soil. For the Vantaanjoki case the assessment of this criterion was done qualitatively based on nutrient leakage using early modelling results from WP4.

The *nutrient recovery* criterion was based on substance flow calculations of nitrogen and phosphorus recovered and returned to agriculture in each system. The criteria effects on soil structure were based on substance flow calculations of the amount of carbon returned to agriculture in each system. The *total costs* calculated included costs for investments, maintenance and operation. The investment costs included for example costs of reactors and construction of facilities. Annual capital cost was calculated with the annuity method, using 3% interest. The maintenance cost was calculated as 3% of the total investment cost. The operations costs included costs for energy, chemicals, staff, etc. Revenues for fertilizer products and surplus energy produces were subtracted, resulting in a net cost for the system studied. In Vantaanjoki, the criteria *impacts on local economy* was applied assessing the pros and cons of the different alternatives for the people who lives or have their businesses within the catchment area.

The *criterion acceptance* was qualitatively based on the general acceptance of using the recovered nutrient products as fertilizers in agriculture. This criterion was assessed by stakeholders at the second workshop for the Fyris and Słupia case-studies. For the Vantaanjoki case study, *acceptance* was based on a local study of acceptance in the area.

Risk of exposure to pollutants was assessed based on the content of heavy metals, pharmaceuticals, microplastics and visible contaminants in the fertilizer products and possible other outputs produced in the systems.

The *compatibility with infrastructure* criterion was assessed by local stakeholders at the second workshop in the Vantaanjoki catchment area.

Technical robustness was assessed based on the systems risk for operational stops, sensitivity for overflows and severity of consequences if either were to occur.

Technical flexibility was assessed based on the systems flexibility to changes in load, due to increase or decrease in population, and ability to adapt to new technologies or new treatment requirements.

Data for calculations were firstly collected from local sources, such as wastewater treatment plants or national institutes. Secondly, scientific literature and previous projects were used for data acquisition. If no data were found, estimations and assumptions made by experts were used. Quantitative criteria were evaluated for the systems based on literature, expert knowledge and in some cases the opinions of local stakeholders.

For each system, each criterion was given a score based on the systems performance in that sustainability aspect. The score given was between -2 and +2, where +2 is highest performance and -2 is poorest performance. Each case study had one system alternative representing the baseline system; this system was given the score 0 for all criteria. The other systems were then given a score higher or lower depending on whether the performance on the criterion in question was higher or lower than that for the baseline system. The criteria *global warming potential*, *eutrophication potential*, *nutrient recovery* and *total costs* were scored based on the following:

Over 40% worse than baseline:	score -2
Up to 40% worse than baseline:	score -1
Within 20% of baseline:	score 0
Up to 40% better than baseline:	score 1
Over 40% better than baseline:	score 2

Important to keep in mind is that the score 0 does not mean that the performance of the system regarding the criterion in question is 0. For example, if the baseline is given the score 0 for *Total costs* this does not mean that the costs are 0; it means that the cost for the baseline system has a middle value. The performance of the baseline system is neutral in comparison to itself. The other systems are compared in relation to the performance of the baseline system. So, a system alternative that has a 30% higher total cost than the baseline system is assigned the score -1.

At the second workshop, the main aim was to assign weights to the different criteria. This was done by the local stakeholders participating at the one-day workshop. Participants were divided into groups and asked to first individually give weights to the previously mentioned criteria so that the sum of weights was 100. After individual weighting, each group's facilitator collected the individual weightings and typed them into an Excel-sheet where group averages were calculated. The group averages were then discussed within the whole group and changed in consensus if necessary.

Another purpose of the workshop was to get input on locally anchored criteria where stakeholder opinions were of great importance for the score. When all criteria were scored and weights assigned, a weighted sum was calculated for each system with equation (1). The result was an overall sustainability score for each system to be compared to the others.

$$Total\ score = \sum_{i=1}^{n} weight_i \times criterion_i \qquad (1)$$

In equation (1), $weight_i$ is the weight assigned to the criterion *i* and $criterion_i$ is the score assigned to criterion *i*.

3 MULTI-CRITERIA ANALYSIS IN THE VANTAANJOKI CASE

For the Vantaanjoki case study, the focus was the agricultural sector with an addition of source-separated blackwater from scattered settlements (on-site sewage systems). Residual flows from agriculture studied as input biomass for alternative systems was horse manure and non-utilized grass such as set-aside grass and buffer zones grass. The substrates (horse manure, grass and source separated blackwater) were all discussed by local stakeholders as potentially interesting for resource recovery, see actual quantities presented in Table 3.

The case study consisted of three different system alternatives (see chapter 3.1 below, for description and illustration of each system alternative):

1. Composting
2. Anaerobic digestion
3. Pyrolysis + urea hygienization of source-separated blackwater

Table 3. Quantities of biomass used as input for the system alternatives in the Vantaanjoki case study

Biomass	Tonnes/year	tonnes dry matter/year	N (tonnes/year)	P (tonnes/year)	C (tonnes/year)
Horse manure	35 000	12 157	172	35	5 471
Grass, set-aside	33 993	10 198	255	71	4 691
Buffer zone grass	4 177	1 253	21	5	564
Blackwater	63 887	375	93	11	164
Sum	**137 057**	**23 983**	**541**	**122**	**10 890**

The sustainability criteria used for the assessment are presented in the previous chapter 2.6.

3.1 System alternatives

For all system alternatives horse manure and grass are collected and transported to a centrally located plant co-located with the waste incineration plant in Vantaa. In system alternative 1. Composting and 2. Anaerobic digestion, also source-separated blackwater is treated in a central facility in Vantaa. For system alternative 3. Pyrolysis + urea hygienization of blackwater, the source-separated blackwater is treated locally in 32 basins for urea hygienization placed on farms with very short or no distance to the fields. 1. Composting was the baseline system, against which the other two systems were compared.

3.1.1 System alternative 1: Composting

In this system alternative, horse manure and grass are co-composted with 23% of the source-separated blackwater. The rest of the collected blackwater is treated in a thermal hygienization unit. All treatment is done in one central plant located in Vantaa. The system is illustrated in Figure 1.

The solid feedstock, horse manure and grass for composting, is crushed in a shredder, then blackwater is added to achieve appropriate dry matter content. After that, the material is fed into a reactor composting step. The main function for the reactor composting, is to ensure that the mixture is hygienized and to generate the heat (60^{o}C) to hygienize the source-separated blackwater. The retention time in the vessel is about seven days. Air is supplied to ensure that aerobic conditions exist in the whole compost pile. The temperature in the composting material is expected to reach 60°C within two days, then the amount of supplied air is adjusted to retain that temperature. The air leaving the vessel will also be close to 60°C and saturated with moisture and is passed through a heat recovery step. The temperature of the compost air falls in the heat exchanger and a condensate water is generated. Most of the recovered heat from the compost air comes from this condensation. Condensate water is collected in a storage tank and used as nitrogen fertiliser. The compost air from the vessel is treated in a biofilter to reduce odours, before atmospheric dispersion. Most of the ammonia emissions will be trapped in the condensate water. The recovered heat is mainly used for the thermal hygienization unit, where the source-separated blackwater, that is not used in the substrate mix, is heated to 53°C with a guaranteed retention time of 15 hours in the hygienization chambers, operated batch-wise. Excess heat is assumed to be used for heating buildings at the composting plant.

After reactor treatment, the composted material goes for post-composting treatment in turned windrows for approximate four weeks. Afterwards the compost is shredded and moved to an area for compost maturing and storage. The matured compost is used as soil conditioner/amendment. Hygienized blackwater is spread as liquid fertilizer or used as nutrient irrigation on agricultural land.

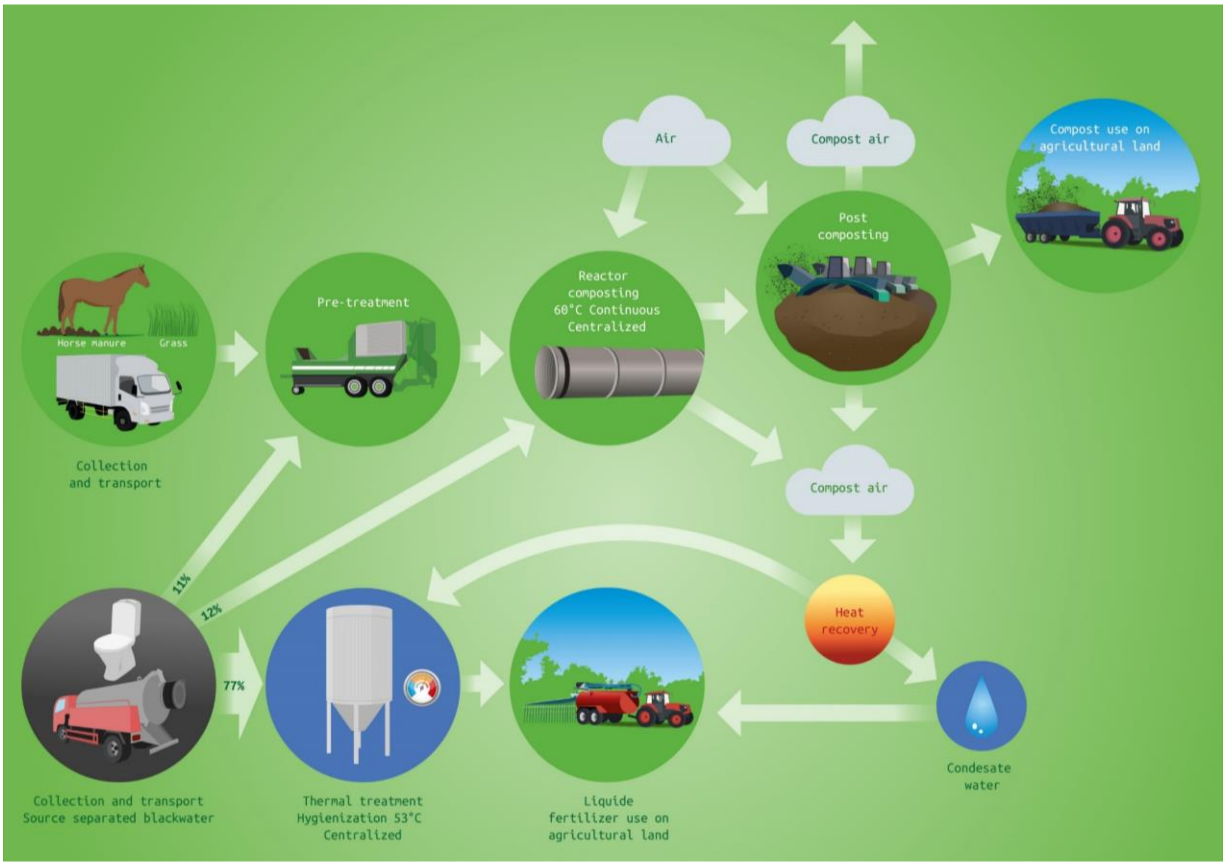


Figure 1. Illustration of system alternative 1: Composting, where horse manure, grass and blackwater undergo reactor composting in one centrally located plant. The unused blackwater is treated in a thermal hygienization unit.

3.1.2 System alternative 2: Anaerobic digestion

In this system alternative, horse manure, grass and part of the collected blackwater undergo anaerobic digestion with production of biogas and digestate. Horse manure and grass are co-digested with 57% of the source-separated blackwater. The rest of the collected blackwater is treated in a thermal hygienization unit. All treatment is done in one central plant located in Vantaa. The system is illustrated in Figure 2.

The solid substrate is, after weighing, received on a concrete slab which provides capacity for short term storage up to five days. It is then fed into the pre-treatment equipment by a wheel loader. Pre-treatment consists of cutting equipment in order to simplify material handling and to improve digestibility. Incoming source-separated blackwater enters a short-term liquid storage and is divided into two streams. The main stream is pre-heated with recovered heat from digestate (see below) and mixed with the solid substrate in proportions resulting in an appropriate humidity for dry fermentation (approx. 22% DM). The mix is fed into plug-flow digesters operated at thermophilic temperature (55°C) where biomass will decompose anaerobically, resulting in the formation of raw biogas. The high operating temperature together with a verified minimal retention time due to the plug-flow setup ensures the hygienization of the material. The remaining material after digestion (digestate) leaves the digesters after a retention time of 25-30 days and is fed into a dewatering step producing a solid and a liquid fraction.

The solid fraction is stackable and contains the majority of phosphorus from the substrate. It is stored on a concrete slab and is transported to external long-term storage facilities and can be used as fertilizer since it is rich in phosphorus and fibres. The liquid portion of the digestate passes a heat exchanger for the recovery of some heat energy used to pre-heat incoming source-separated blackwater and/or substrate mix. Finally, it enters the short-term liquid digestate storage which is a concrete or steel tank with gas tight roof. Minor amounts of biogas may be formed in that storage and will be led to the digesters' gas system.

The source-separated blackwater not used in the substrate mix is fed into a separate hygienization unit consisting of three chambers operated batch-wise. The water is first pre-heated by heat exchange with water leaving the unit, and then heated to 70°C. It is further fed into one of the chambers where it remains for 1 hour at controlled temperature (70°C). Finally, it is pumped out of the hygienization chamber and through a heat exchanger where heat is recovered and used to preheat the next batch of blackwater, and then fed into a concrete vessel with roof acting as short-term storage for outgoing blackwater. Hygienized blackwater is spread as liquid fertilizer or used as nutrient irrigation on agricultural land.

Formed biogas from the main digesters as well as the liquid digestate storage enters a gas upgrading plant where unwanted components such as carbon dioxide, hydrogen sulphide and water vapor are removed. A chemical scrubber using amines is applied which provides large amounts of excess heat used to heat the digesters and hygienization of source-separated blackwater. Finally, the upgraded biomethane is compressed and fed into the natural gas grid.

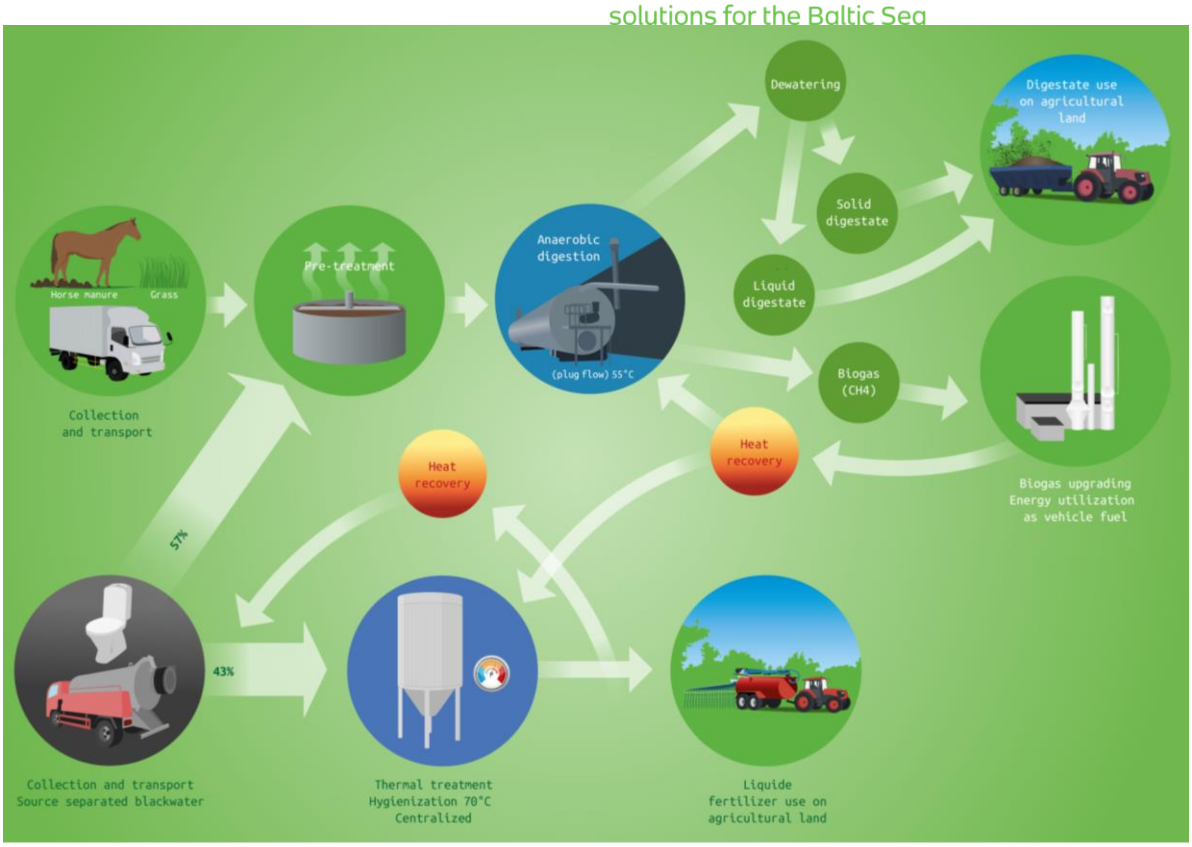


Figure 2. Illustration of system alternative 2: Anaerobic digestion, where horse manure, grass and source-separated blackwater undergo anaerobic digestion with production of biogas and digestate in a centrally located plant. The unused blackwater is treated in a thermal hygienization unit.

3.1.3 System alternative 3: Pyrolysis + urea-hygienization of source-separated blackwater

In this system alternative, horse manure and grass are converted to biochar by pyrolysis, a chemical transformation at high temperatures in an oxygen-free environment, in a central plant. Since a prerequisite for the pyrolysis process is dry material, no source-separated blackwater is added but instead treated locally in covered basins by adding urea for hygienization, see Figure 3.

For pyrolysis to occur, high temperatures are needed, in this case 700°C. The input material therefore needs to be dry, here estimated as 95% dry matter. The pyrolysis process generates char, gas and tar. The distribution between these products can be controlled by the pyrolysis temperature and retention time. In this case, the process is optimized towards char production. Typical product gases from pyrolysis (syngas) are CO, CO_2, H_2, CH_4, N_2 and other light hydrocarbons. These are incinerated for heat production which primarily is used to run the process and drying of biomass. Excess heat can be used in district heating. Flue gas cleaning to meet the limit values for current legislation is installed. The drying step is energy-intensive and heat-demanding, since the dry matter of incoming biomass is only 30-35% DM. Measures such as letting grass pre-dry on fields, with a potential to increase dry matter up to 70%, would for example radically change the energy balance.

Generally, phosphorus will be recovered in the biochar (tightly bound) and most of the nitrogen will be converted to gas phase during the pyrolysis process. However, nitrogen from horse manure may partly be released as ammonia during drying; a process for utilizing nitrogen from condensate is therefore included in the alternative. Biochar is primarily used as soil improver in agricultural land. Benefits seen are also storage of biogenic carbon and recycled phosphorus as stored fertilizer.

When adding urea to blackwater it becomes NH_3 that, together with increasing pH, is toxic to pathogens. In this alternative, it is assumed that source-separated blackwater is treated with liquid urea (1%) in 32 containers with a volume of 2000 m^3 each. The containers are built with waterproofing cloth (including an external filling/emptying well)[1], and with a floating blanket to prevent emission of ammonium. For mixing, a tractor-driven propeller stirrer with protective carriage are used. The containers are locally placed on farms so the hygienized blackwater can be spread on nearby fields. The 32 basins are placed in areas with many septic tanks or geographically in the catchment area so that transport can be minimized. The transport from a septic tank to a local container is calculated based on data about areas with high numbers of septic tanks, geographical location of fields, the size of transport vehicles (12 m^3) and the approximate size of septic tanks in Finland (10 m^3). Since urea increases the nitrogen content in the blackwater, it is usually used as a nitrogen fertilizer. Due to the high amount of water (0.6% DM) it can also be used as nutrient irrigation.

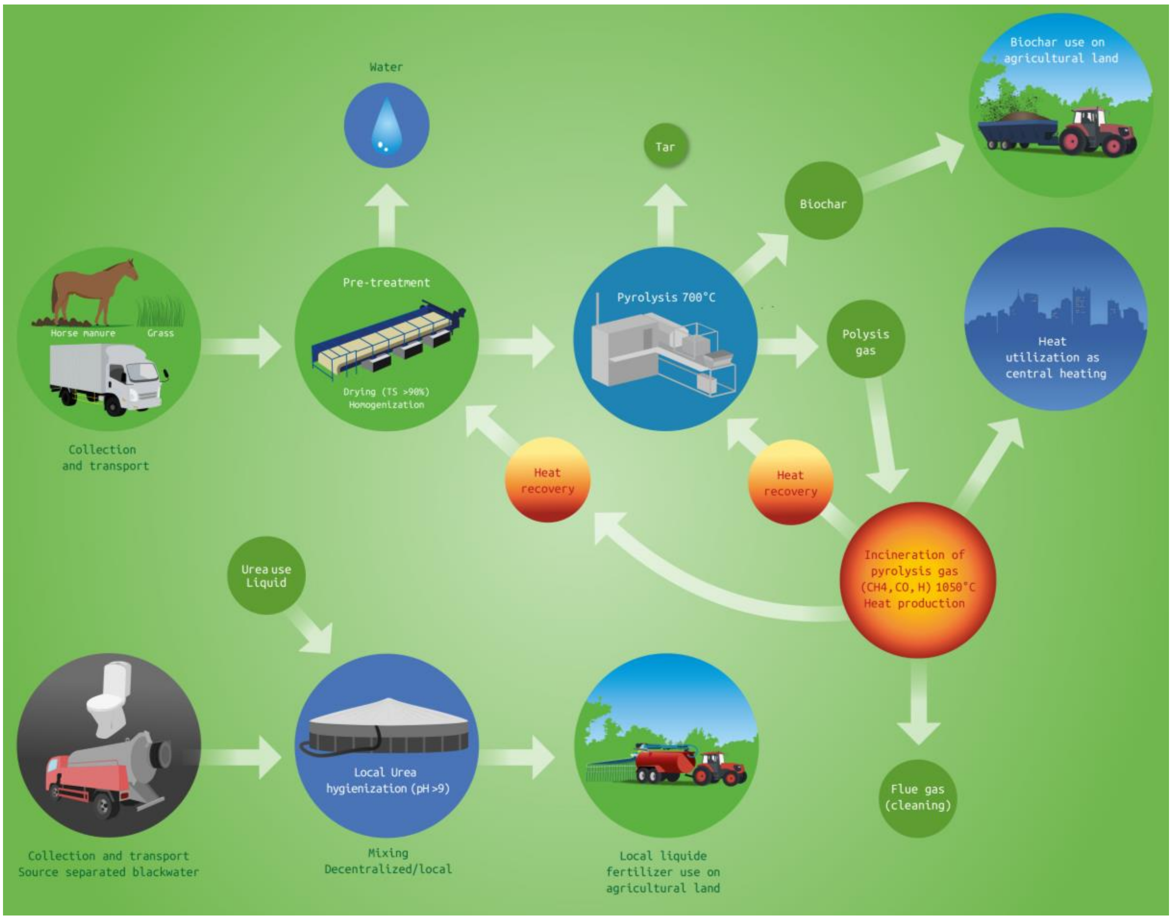


Figure 3. Illustration of system alternative 3, where horse manure and grass are converted to biochar by pyrolysis in a centrally located plant and source-separated blackwater is treated locally by urea hygienization.

[1] *Information about the intended product types can be found at MPG Miljöprodukter AB (https://www.mpg.se/)*

3.2 System boundaries and assumptions

The system boundaries of the calculations of *global warming potential* are presented in Figure 4. The climate impact calculations start with the treatment of biomass. The cultivation, harvesting and collection of the biomass are not included, as we focus here mainly on comparing different treatment options and we have the same amount of input biomass in each scenario.

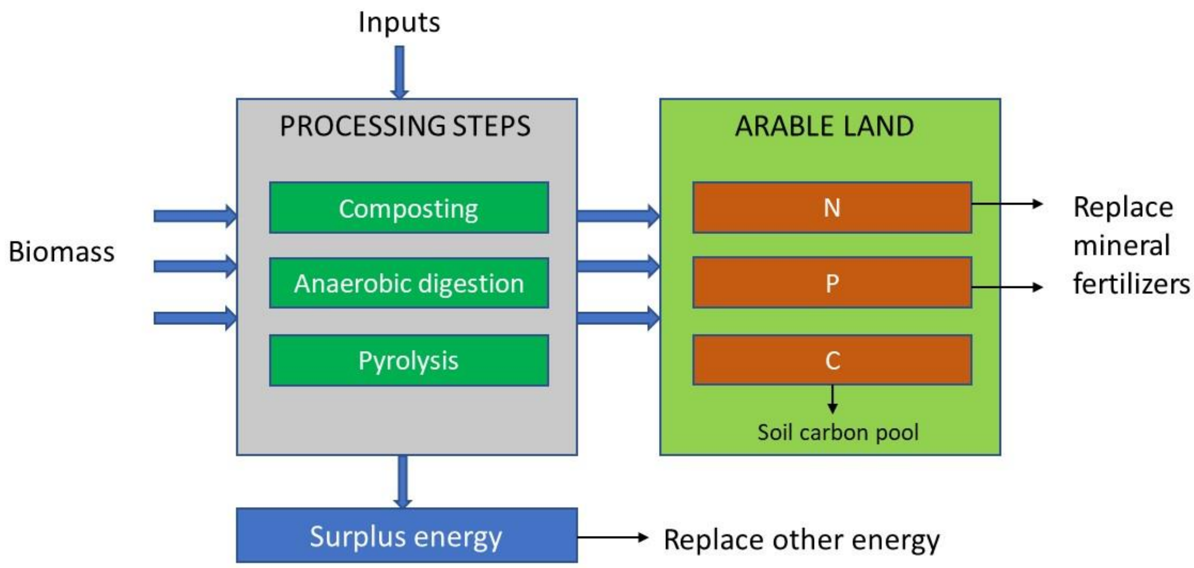


Figure 4. System boundaries for calculation of global warming potential in the Vantaanjoki case study.

The products that come out of the treatment are used as fertilizers and soil amendments on arable land. For products containing nitrogen and phosphorus, we assume they can replace mineral fertilizer alternatives, giving the systems a climate credit by reducing the emissions from mineral fertilizer production. In the pyrolysis case, most nitrogen will be lost. However, in the pyrolysis scenario, the blackwater is treated with urea and the urea together with the blackwater is spread on the fields. The urea is however not seen as a credit to the system as it is an external input and does not mean a reduced use of mineral fertilizers.

Systems that generate surplus energy such as heat and biogas fuel will be credited the replacement of other energy, e.g. biogas can replace natural gas. For biochar, there is no replacement product; we assume that biochar will increase soil carbon content giving a climate benefit of carbon sequestration. Of the carbon that is applied to fields, only a share is transferred to the long-term soil carbon pool. In this study we assumed 15% of the carbon in compost and digestate becomes stable soil carbon and is given climate credit. For blackwater we assume 5%, and for biochar 30%. A higher soil carbon content could lead to higher yields, especially in degraded soils. However, the effects in northern Europe are uncertain and therefore we did not include potential yield improvements in this study.

Transport distances were estimated based on maps of the Vantaanjoki region in combination with occurrences of activities in different areas of the region. The estimated distances are presented in

Table 4. Transport emissions were modelled to include positions of empty truck and empty return (by assuming a load factor of 50% and double distance) and with GHG emissions data from Network for Transport Measures (NTM Calc, 2019). Transport was assumed to be carried out with rigid trucks with varying capacities between 7 and 26 tons.

Table 4. Estimated transport distance for the different substrates and products in the Vantaanjoki area.

Transport type	Distance
Grass from set-aside fields to central treatment (compost/AD/pyrolysis)	35 km
Buffer zone grass to central treatment (compost/AD/pyrolysis)	30 km
Horse manure to central treatment (compost/AD/pyrolysis)	26 km
Blackwater to central heat treatment (compost/AD)	27 km
Solid fertilizer products to field (compost, solid digestate, biochar)	27 km
Liquid fertilizer products to field (liquid digestate, heat-treated blackwater)	10 km
Blackwater to urea treatment	6 km
Blackwater from urea treatment to field	0 km

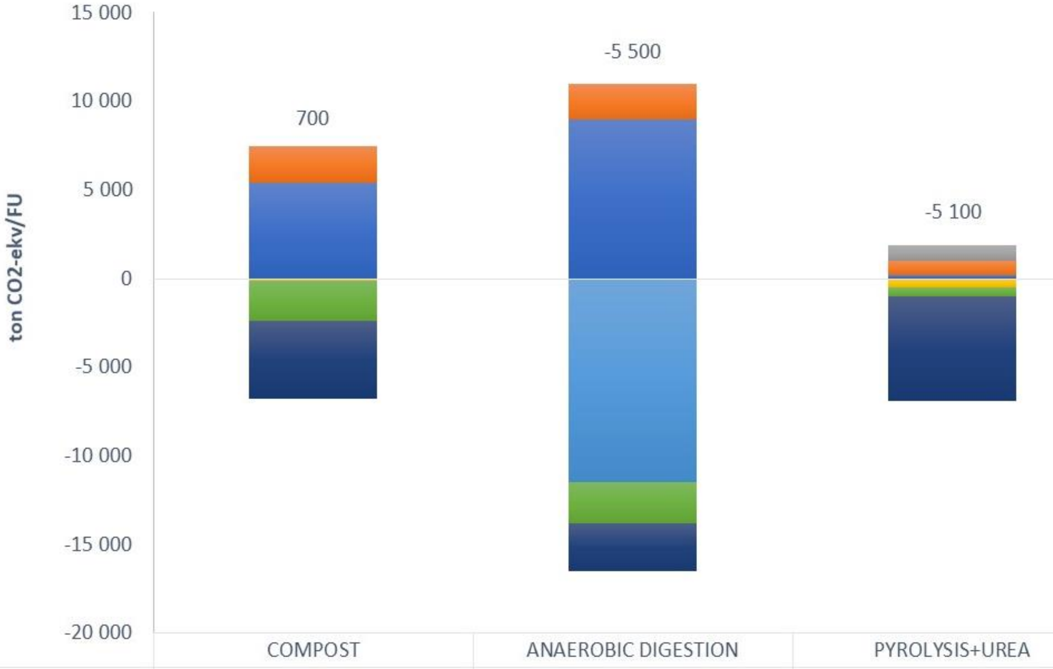
The total annual cost for the system alternatives was calculated using the annuity method. The revenue from selling biogas was included but not for other residuals such as biochar, or fertilizer products. The total costs for the composting, anaerobic digestion and blackwater hygienization were based on data from earlier applications while data for the pyrolysis plant was based on information from a company that deliver these plants. General Finnish data were collected for energy and transport costs.

3.3 Results

3.3.1 Global warming potential

The results of the modelling are presented in Figure 5. As can be seen, each scenario has both contribution to global warming as well as climate benefits/credits. These contributions consist of process emissions and transports. The process emissions include electricity use, but for the composting and anaerobic digestion alternatives, process emissions come mainly from storage of compost/digestate.

Regarding climate benefits, we can see that soil carbon, i.e. carbon sequestration by applying organic fertilizers has a large impact on the net emissions. Replacement of mineral fertilizers also contributes to benefits; where recovered nitrogen plays the major role as mineral nitrogen fertilizer production produces considerable greenhouse gas emissions. The production of biogas which replaces natural gas constitutes a large climate benefit for the anaerobic digestion system.



	COMPOST	ANAEROBIC DIGESTION	PYROLYSIS+UREA
Urea production			900
Transports	2 100	2 000	800
Emissions from process/storage	5 400	9 000	200
Soil carbon	-4 400	-2 700	-5 900
Replacement mineral N & P	-2 300	-2 300	- 500
Biogas replacing NG		-11 500	
Surplus heat	- 100		- 500

Figure 5. Results for GHG-calculations of Vantaanjoki region scenarios. FU= Functional unit, in this case treatment of 137 057 tons biomass per year. Numbers above each bar are the total value.

The scores for *global warming potential* are:

1. Composting 0
2. Anaerobic digestion 2
3. Pyrolysis + urea hygienization 2

3.3.2 Total costs

The result of the costs analysis showed that the Composting alternative has an annual cost of 3 MEuro, while Anaerobic digestion actually has such a projected revenue from selling biogas that the alternative ends up with a negative cost of 1 MEuro (i.e. a yearly profit of 1 MEuro). This means, the anaerobic digestion alternative is economically more effective than composting, despite having higher maintenance/investment costs in our assessment. The pyrolysis alternative had the largest cost: 8 MEuro. This may be due to fact that the cost estimation is based on data from smaller pyrolysis plants (a number of plants are built in parallel in the system alternative). Considering economy of scale, the estimated costs could be overestimated for the pyrolysis plants.

The scores for *Total costs* are:

1: Composting	0
2: Anaerobic digestion	2
3: Pyrolysis + urea hygienization	-2

3.3.3 Eutrophication potential

For the assessment of eutrophication potential, both diffuse and point-source emissions were considered. In terms of agricultural residues, eutrophication potential can be decreased if more residues from buffer zones and green fertilizing (crop rotation) are incorporated into the arable soils of the Vantaanjoki catchment. Thereby the soil structure will become more resilient to surface runoff and erosion and particle-bound P loading will thus decrease. Moreover, the increased carbon content of soil will enhance denitrification which, in turn, will decrease N loading. This process was clearly demonstrated by the first SWAT scenario simulations, where 50% increase of soil carbon (% of weight unit) led to 10% decrease in total N loading (upcoming project deliverable D 4.4).

Horse management, particularly in larger stables, may induce point-source type nutrient loading, which could be alleviated by wise utilization of the energy and fertilization potential of the horse manure. When applied to arable land and used instead of mineral fertilization, horse manure may decrease nutrient loading for the same reason as in the case of plant residues, i.e. by improving the soil structure.

Because of a lower amount of carbon to soil, anaerobic digestion received a lower score than the other alternatives.

The scores for *Eutrophication potential* are:

1. Composting: adds 8012 tonnes of C to soil/year	0
2. Anaerobic digestion: adds 4872 tonnes of C to soil/year	-1
3. Pyrolysis + urea hygienization: adds 5527 tonnes C to soil/year	0

3.3.4 Nutrient recovery

The indicator chosen was the recycling of nitrogen and phosphorus (tonnes/year). The major part of phosphorus is recycled in all alternatives, and almost all nitrogen is recycled in alternatives 1 and 2. Only 80% of phosphorus and 17% of nitrogen is recycled in alternative 3.

The scores for *nutrient recovery* are:

1. Composting (122 tonnes P, 550 tonnes N per year)	0
2. Anaerobic digestion (122 tonnes P, 540 tonnes N per year)	0
3. Pyrolysis + urea hygienization (99 tonnes P, 93 tonnes N per year)	-2

3.3.5 Risk of exposure to pollutants

The criterion *risk of exposure to pollutants*, includes a discussion around the content of heavy metals, pharmaceuticals, microplastics[2] and visible contaminants[3], both in the incoming substrates and in the treated fertilizers. The risk of pollutants in the fertilizer depends on the content in the incoming substrates and whether these pollutants are retained, transformed or lost in the process.

Agricultural residues and horse manure generally have a low content of pollutants. The agriculture residues may be affected by pollutants in the soil or air, and by foreign objects which may have landed on the fields (source for any visible contaminants). The horse manure composition may be affected by various sources in the stables, such as bedding material, stable furnishing and human impact and objects that follows when collecting the horse manure (for example stones, rope and metal objects). Pharmaceutical residues may be the result of medicating the horses, and visible contaminants and microplastics can be present in the horse manure as a result of the use of plastic for conservation of silage. Source-separated blackwater can contain pharmaceutical residues from our intake of medicines. Visible contamination is not expected in blackwater, however, there is a risk that for example ear swabs, sanitary napkins and tampons are flushed down the toilet. There is also a risk of general contamination from the trucks transporting the blackwater, if they are not washed between uses.

The composting and the digestion processes are not expected to contribute to additional pollutants, although degradation of pollutants by bioremediation can generate new hazardous byproducts in the form of metabolites. Little degradation of microplastics and pharmaceuticals are expected, but fragmentation of visible contaminants can occur (e.g. fragmentation of plastic particles into microplastics). In the pyrolysis process, hormones, pharmaceuticals and other organic compounds be degraded. It is also possible at high temperatures to remove heavy metals, for example cadmium. Adding urea as a hygienization process is not expected to affect the incoming content of pollutants.

This means that the biochar will have a lower risk for pollutant content than the other fertilizer products. Though, looking at the system alternatives including urea hygienization, the risk for source-separated blackwater is similar in all alternatives.

The scores for r*isk of exposure to pollutants* are:

1: Composting	0
2: Anaerobic digestion	0
3: Pyrolysis + urea hygienization	1

[2] *Plastic particles < 5 mm. Definition from The Swedish Environmental Protection Agency: " by humans made polymers from either oil or by-products from oil, or from biomaterials (bio-based sites)".*

[3] *Foreign objects such as plastic, glass, metal and composite materials with a size > 2 mm. Note that there is overlap between "visible contaminants" and "microplastics" since the limit for visible contaminants is> 2 mm and microplastics <5 mm.*

3.3.6 Effects on soil structure

For this criterion it was assumed that addition of carbon to agricultural soil improves the soil structure. Because of a lower amount of carbon additions to soil, alternative 2 got a lower score than the other alternatives.

The scores for *effects on soil structure* are:

1. Composting: 8012 tonnes C/year	0
2. Anaerobic digestion: 4872 tonnes C/year	-2
3. Pyrolysis + urea hygienization: 5527 tonnes C/year	0

3.3.7 Acceptance of using recycled fertilizer products

This criterion assesses stakeholder acceptance for spreading recycled products on farmland. A study on the acceptance of using wastes as fertilizers was conducted in Finland in 2018. The study found that farmers had a more negative opinion towards the use of sewage sludge and other products with origin from human excreta compared to food waste and agricultural waste (Myllyviita & Rintamäki, 2018).

Across the three system alternatives, it is assumed that treated horse manure, grass and blackwater are spread on farmland. In the pyrolysis alternative, agricultural wastes are not mixed with blackwater which means that the products generated from human excreta can be handled separately if so wanted.

The scores for *acceptance* of using recycled fertilizer products are:

1: Composting + heating of BW	0
2: Anaerobic digestion + heating of BW	0
3: Pyrolysis + urea hygienization	1

3.3.8 Local economy

This criterion assesses the potential for creating new businesses in Vantaanjoki area. All the suggested alternatives will be adding new activities i.e. collection of horse manure, grass and blackwater, and treatment, storage and recycling of products on farmland. In the pyrolysis alternative, the blackwater treatment is decentralized in 32 places which means more activities within the catchment area.

The scores for *local economy* are:

1: Composting + heating of BW	0
2: Anaerobic digestion + heating of BW	0
3: Pyrolysis + urea hygienization	1

3.3.9 Compatibility with existing infrastructure

Vantaa is the location of the centralized process facility and it is assumed that the facility is newly built for all the alternatives. This is 1) to have access to professional operations and maintenance staff, 2) so that heat use and excess heat produced can be integrated with the existing Vantaa heating plant.

In the second workshop the stakeholders considered that less traffic in the Vantaa area would be prioritized and therefore they gave alternative 3, which includes decentralized blackwater treatment a higher score.

The scores for *Compatibility with existing infrastructure* are:

1: Composting + heating of BW	0
2: Anaerobic digestion + heating of BW	0
3: Pyrolysis + urea hygienization	1

3.3.10 Second workshop in Vantaanjoki

Participants were divided into three groups. To start with, they individually gave weights to the previously mentioned 9 criteria so that the sum of weights had to be 100. The 3 group averages were then discussed within the whole group and adjusted through consensus if necessary. The results of the three groups varied. The results by criterion categories are shown in Table 5.

Table 5. Weights assigned by the three groups and the average weights for the Vantaanjoki case study.

Criteria	Group 1	Group 2	Group 3	Average weight
Global warming potential	21	10	18	16
Eutrophication potential	5	5	4	5
Effects on soil structure	8	10	20	13
Nutrient recovery	5	5	6	5
Local economy	8	5	7	7
Total costs	16	25	9	17
Acceptance	13	15	12	13
Risk of exposure to pollutants	10	15	13	13
Compatibility with existing infrastructure	14	10	11	11

3.3.11 Sustainability scores for all systems

In the scoring, the composting alternative was set as the baseline with score 0 for all criteria. The final scores are presented in Table 6.

Table 6. Scores for each criterion for each system alternative for the Vantaanjoki case study.

Criteria	Composting	Anaerobic digestion	Pyrolysis + urea hyg.
Global Warming potential	0	2	2
Eutrophication potential	0	-1	0
Nutrient recovery	0	0	-2
Effects on soil structure	0	-2	0
Local economy	0	0	1
Total costs	0	2	-2
Acceptance of using recycled fertilizer products	0	0	1
Risk of exposure to pollutants	0	0	1
Compatibility with infrastructure	0	0	1

Based on the average of weights from Table 5, the weighted sum of the three alternatives was calculated in Figure 6. The results show that alternative 2, Anaerobic digestion got the highest weighted score followed by alternative 3, Pyrolysis. Alternatives 2 and 3 reach almost the same sum but considerably higher than alternative 1, Composting. Both alternatives 2 and 3 have a large advantage compared to alternative 1 because of a lower impact on climate change. Alternative 3, Pyrolysis, also has other strengths in terms of *local economy*, *acceptance*, *risk of exposure to pollutants* and *compatibility with infrastructure*. Alternative 3 has, however, one disadvantage which is the considerable annual costs.

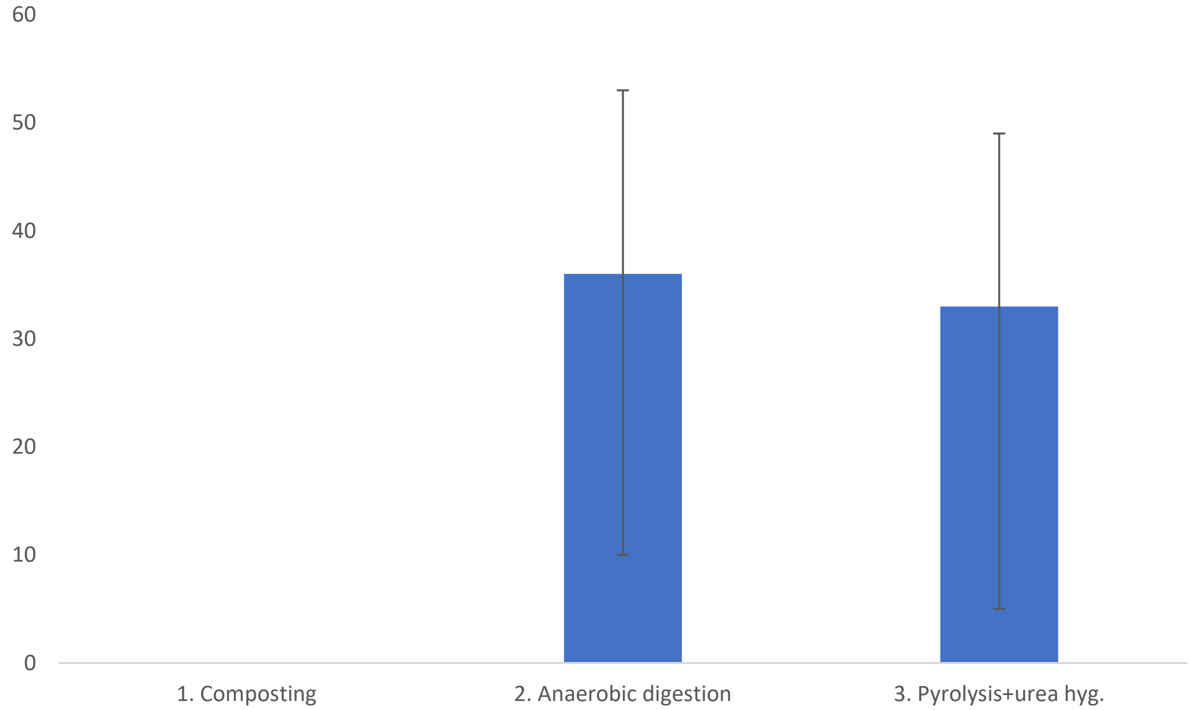


Figure 6. Total sustainability score for each system alternative in the Vantaanjoki case study. The error bars show the scores based on the different weighting of criteria from the three stakeholder groups at the second workshop.

3.4 Discussion of results

For the *Global warming potential,* soil carbon had a major influence on the results because carbon is sequestered in the soil and thereby contributes to a reduction in global warming. However, soil carbon dynamics are complicated and depend on many site-specific factors such as soil properties and temperature. The climate benefits must therefore be interpreted with great caution. Biochar has in the literature been pointed out as being especially promising for carbon storage. However, there are large variations in the conclusions reached in the literature regarding carbon storage potential. Pyrolysis conditions alter the properties of the biochar and carbon storage ability, and so does the pyrolysis feedstock and the type of soil where the biochar is added. More in-depth site-specific analysis and soil carbon modelling are needed to draw accurate conclusions.

For the *compost and anaerobic digestion* alternatives, processing and storage make up the majority of the emissions. During the drum composting and storage, emissions of ammonia, methane and nitrous oxides can occur. For anaerobic digestion, we include emissions from storage of liquid and solid digestate and from leakage of methane during biogas upgrading. However, the positive side is that these emissions can be reduced through improved processes or handling and storage, e.g. by covering tanks and reducing the storage time.

The high weights participants assigned to environmental impacts were justified e.g. by the fact that the idea behind circular economy is to reduce the environmental impacts and make the economy more sustainable. On the other hand, high weights on economic impacts were justified by the large impact range in *total costs*, and the overall importance of the economic impacts. If the benefits and costs are not balanced, the measures won't be feasible. However, in one group, a strong opinion was stated that the environmental impacts are so crucial that regardless of costs, actions must be taken.

Eutrophication received the lowest weights in all groups for two main reasons; i) the improved soil structure was seen to decrease nutrient loading already, and ii) the impact range between the ecotech-alternatives was small and the assessment uncertain.

The *acceptance* and the *risk of exposure to pollutants* were seen to be connected to each other, and the participants (at least in Group 2) thought that these impacts together have enough weight even though the weight is divided between the criteria. *Technical feasibility* was seen as least important.

In general, participants thought that blackwater should not be mixed with agricultural residues in any of the alternatives. This would improve the performance of compost and digest compared to the pyrolysis option. In addition, at least some participants considered that also composting and anaerobic digestion would be maybe more feasible in the decentralized option.

3.5 Conclusions

In the Vantaanjoki case study, the system alternative with anaerobic digestion of substrates got the highest sustainability score using average weights from the stakeholder workshop. However, the pyrolysis of horse manure and grass and urea hygienization of blackwater got almost as high score. Both these alternatives got much higher scores than the alternative with composting, which was the baseline system. This suggests both of these alternatives are more sustainable options than the composting alternative.

4 MULTI-CRITERIA ANALYSIS IN THE FYRISÅN CASE

In the Fyrisån catchment area, different technical systems for recovering nutrients and energy from domestic wastewater were assessed. The sustainability criteria used in the assessment are described in chapter 2.6. In all system alternatives, the same amount of wastewater is treated, i.e. the systems perform the same functions.

4.1 System alternatives

4.1.1 Alt 0F Baseline

The baseline system (Alt 0F: Baseline) represents the conventional wastewater treatment currently in use in the area. Figure 7 shows a flow chart for the system. For this alternative, treatment efficiencies, energy recovery and sludge reuse were mostly based on environmental reports from the four largest treatment plants. In this system alternative, sludge from septic tanks from all on-site systems are transported to Kungsängsverket for treatment. Dewatered sludge from all treatment plants are transported to a local facility for storage. After storage, half of the sludge is returned to agriculture and the other half is used for soil production. The soil production is outside of the system boundary, only the transport to the site is considered. The products from this system alternative are electricity, heat and biofuel from biogas and organic fertilizer from sludge.

Figure 7. System illustration of Alt 0F Baseline system in the Fyriså case study. Note that it is the treatment at Kungsängsverket treatment plant that is illustrated.

4.1.2 Alt 1F Incineration

In the first recovery alternative, Alt 1F Incineration, wastewater is treated by conventional treatment as in the *Baseline* system, but all sludge is mono-incinerated instead of being stored. Figure 8 shows a flow chart for the system. The phosphorus is recovered from the incineration ashes by chemical treatment where phosphorus is leached and precipitated from the ashes. The incineration plant is located at the same site as the sludge storage in the *Baseline*. All sludge produced in the system is transported to Kungsängsverket where it is dewatered. From there, it is transported to the incineration plant where it is dried and incinerated. The remaining ashes are then transported to another, regional, site for phosphorus extraction. The landfilling of the waste ashes is outside of the system boundary and not considered. It is assumed that the recovered phosphorus has the same plant availability as mineral phosphorus (this will be assessed in a forthcoming project report D 2.7, December 2019). The wastewater treatment is the same as in the baseline system. The products from this system alternative are electricity, heat and biofuel from biogas and fertilizer in the form of calcium phosphate.

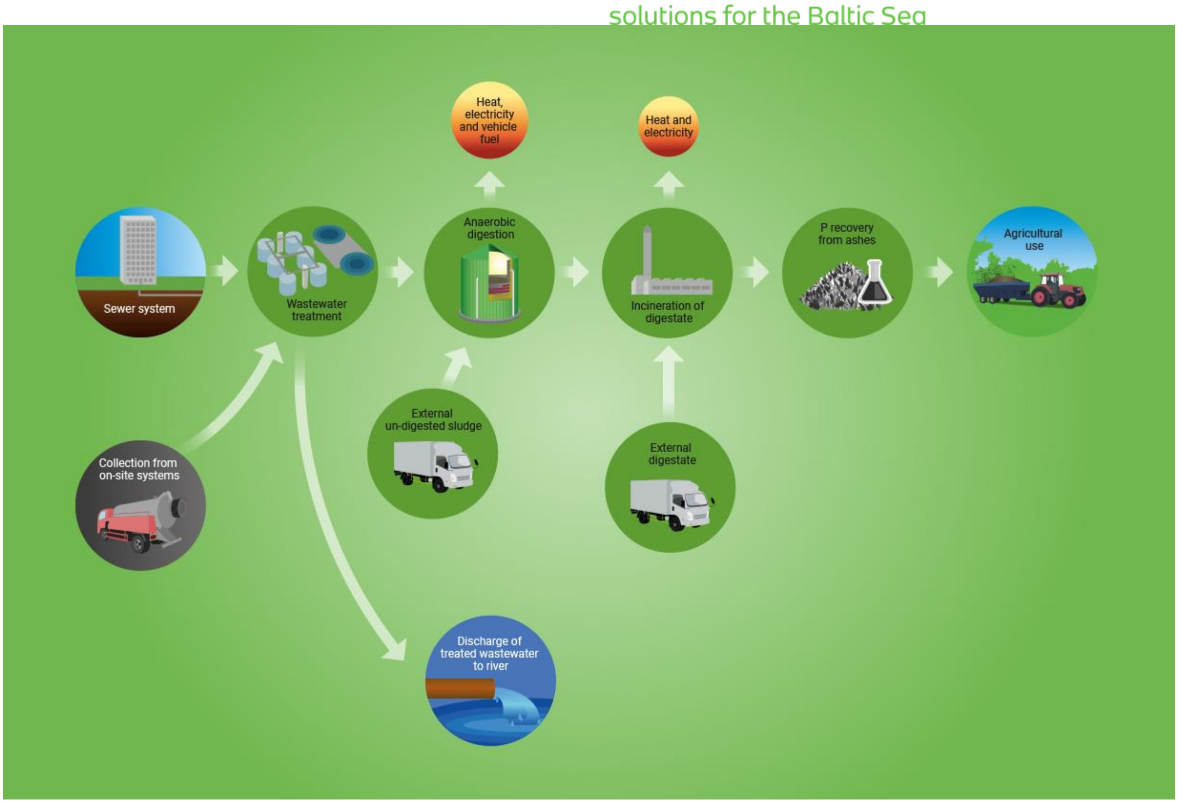


Figure 8. System illustration of Alt 1F Incineration system in the Fyriså case study. Note that it is the treatment at Kungsängsverket treatment plant that is illustrated.

4.1.3 Alt 2F Nutrient extraction

In the second recovery alternative, Alt 2F Nutrient extraction, the wastewater treatment at Kungsängsverket is redesigned. Figure 9 shows a flow chart for the system. Instead of the conventional treatment, pre-screened raw wastewater is fed directly into an Upflow Anaerobic Sludge Blanket reactor (UASB). In the UASB reactor, biogas is produced and recovered. Additionally, sludge and effluent are separated in the reactor. The effluent goes through precipitation and recovery of struvite, followed by ammonia stripping for nitrogen recovery. The effluent is then polished by conventional treatment, same as in the *Baseline* system, before being discharged. At the smaller treatment plants the treatment is the same as in the *Baseline* system. Sludge from septic tanks in on-site systems are treated at Kungsängsverket by the redesigned treatment. In this system all the sludge is stored for 6 months, after which 50% is returned to agriculture and 50% is used for soil production. This part of the system is the same as in the *Baseline* system. The products from this system alternative are electricity, heat and biofuel from biogas, organic fertilizer from sludge and fertilizer in the form of struvite and ammonium sulphate.

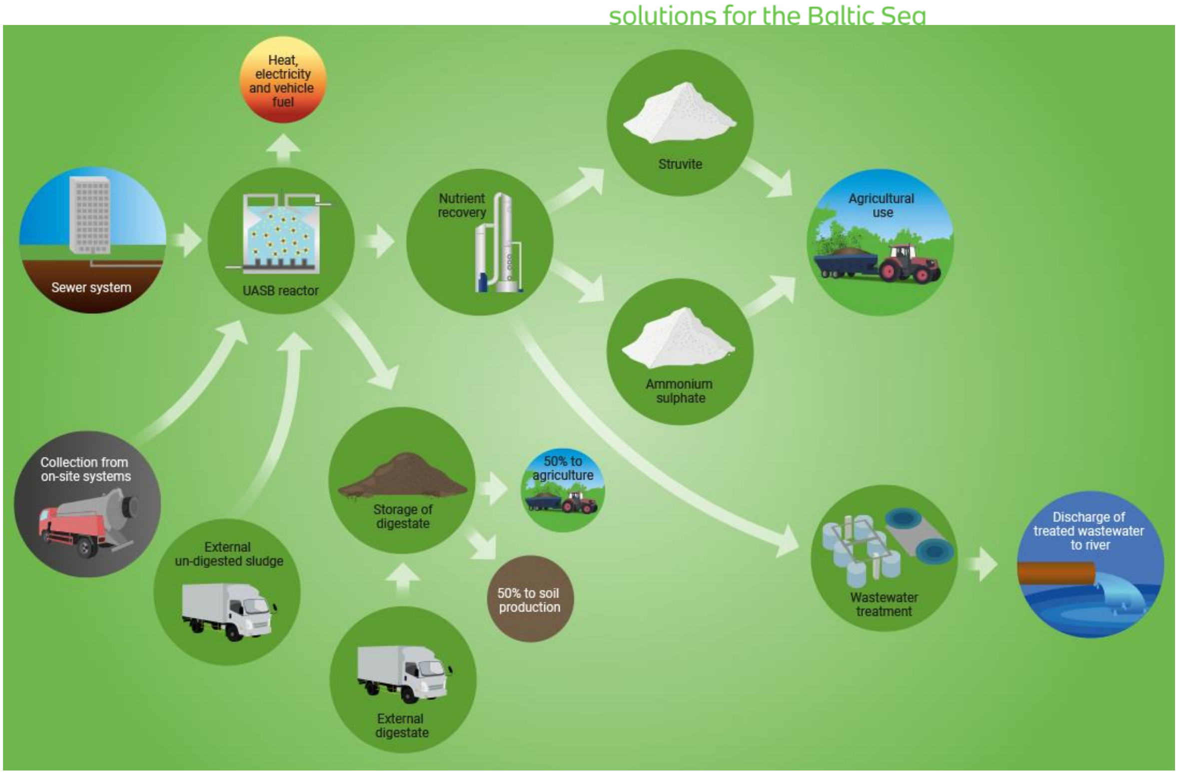


Figure 9. System illustration of Alt 2F Nutrient extraction system in the Fyriså case study. Note that it is the treatment at Kungsängsverket treatment plant that is illustrated.

4.1.4 Alt 3F Source-separation

In the third recovery alternative Alt 3F Source-separation system, a fraction of all households have separation of blackwater and greywater. Figure 10 shows a flow chart for the system. It is assumed that all new housing gets a source-separated system plus renovated sewage systems. In this system, there are different sources of wastewater to handle. There is blackwater and greywater from households connected to the sewer network, and mixed wastewater from the households connected to the sewer network that do not have source-separation. Then there is sludge from septic tanks from on-site systems without source-separation, sludge from septic tanks fed with only greywater from households with source-separation, and finally blackwater stored in tanks at households with source-separation. As in the other alternatives, all sludge from on-site systems are transported to and treated at Kungsängsverket.

The blackwater from households with source-separation that are connected to Kungsängsverket is transported by separate pipes to the treatment plant. The mixed wastewater is transported by conventional sewers, together with the greywater. At the treatment plant, the blackwater is treated by the same process as in the *Nutrient extraction* alternative (Alt 2F Nutrient extraction). The greywater and mixed wastewater are co-treated conventionally as in the Alt 0F Baseline system. The blackwater, greywater and mixed wastewater from on-site systems are added into corresponding treatment processes. Blackwater from households connected to the other treatment plants is stored in closed tanks and transported to Kungsängsverket for treatment, just as the on-site systems. The greywater from the same houses and mixed wastewater from houses without source-separation are transported by the sewer systems to conventional treatment as in the baseline system. The sludge originating from the blackwater treatment at Kungsängsverket is stored as in the *Baseline* system and all of it is returned to agriculture. All other sludge is incinerated, and phosphorus is recovered from the ash just as in the *Incineration* alternative. The products from this system alternative are electricity, heat and biofuel from biogas, organic fertilizer from blackwater sludge and fertilizer in the form of struvite, ammonium sulphate and calcium phosphate.

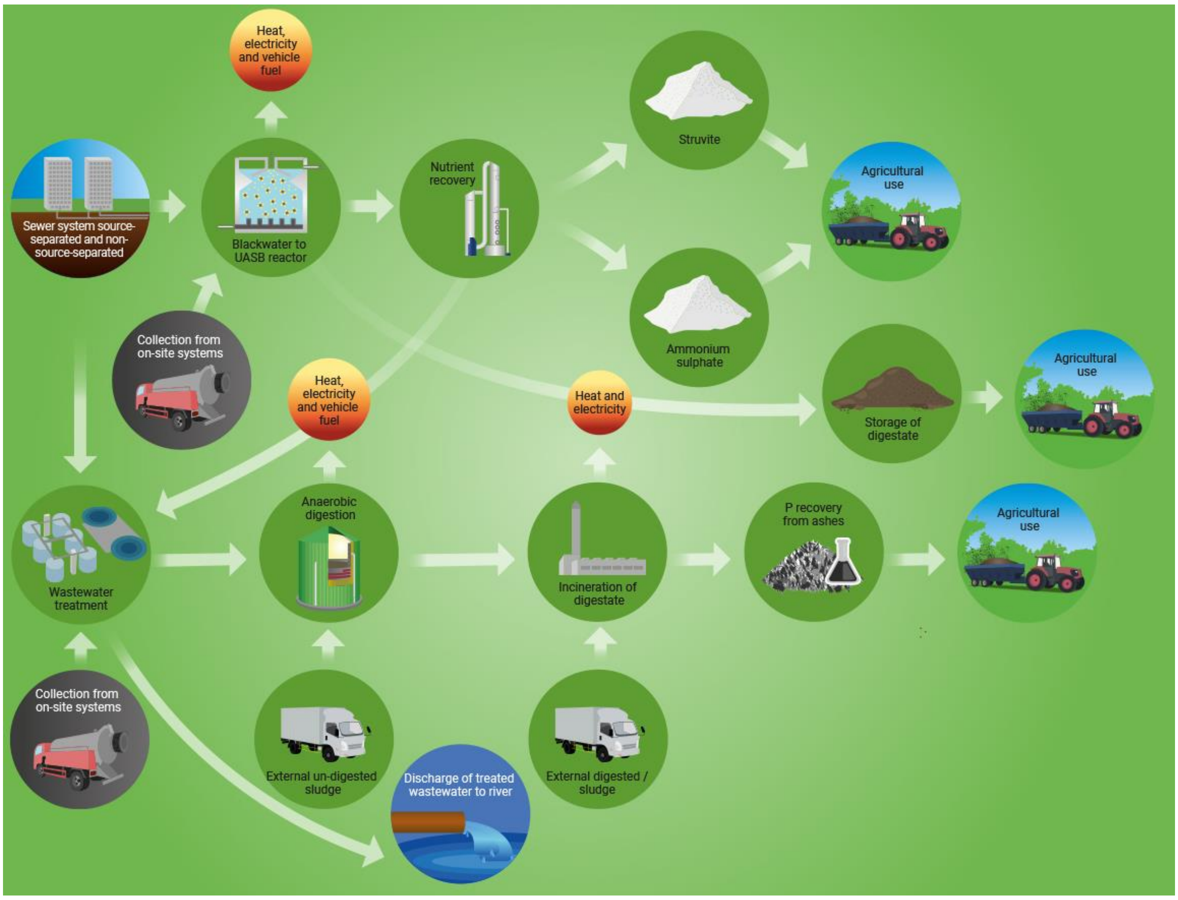


Figure 10 System illustration of the Alt 3F Source-separation system in the Fyriså case study. Note that it is the treatment at Kungsängsverket treatment plant that is illustrated.

4.2 System boundaries and assumptions

Seven wastewater treatment plants and on-site systems within the catchment area were considered. The number of people being served by each is shown in Table 7. According to a prognosis for population growth, there will be an increase of 30,400 people within the Uppsala municipality by 2025 compared to 2016 (Uppsala kommun, 2017). The year 2016 was used as comparison because most data from the treatment plants used for modelling the environmental criteria were from that year. The catchment area covers additional municipalities. Uppsala municipality was chosen for the prognosis because it is uncertain how many people in the other municipalities live within the catchment area. Additionally, Uppsala is the largest city and it can be expected that most of the population growth will be in its municipality. It was assumed that “new inhabitants” would move into new housing, connected to the sewer network of the closest treatment plant. The increase in number of people connected to each treatment plant is proportional to the size of the plant in 2016 or 2017.

Table 7. Treatment plants and on-site systems considered in the Fyriså case study.

Treatment plant	**Estimate of persons connected by 2025**
Kungsängsverket	229 813
Storvreta	8 329
Björklinge	4 874
Österbybruk	3 496
Vattholma	1 885
Skyttorp	780
Gåvsta	897
On-site systems	25 000*

* Based on an estimated 10,000 households within the catchment area with on-site systems and on average 2.5 people per household

Only domestic wastewater generated by the people connected to the treatment plants was considered. Some of these people do live outside of the catchment area, but there are also some people living within the catchment area that are connected to treatment plants outside of it. The Kungsängsverket treatment plant receives sludge from several smaller plants outside of the catchment area; this contribution was not considered in this study. The contribution of industrial wastewater, which is co-treated with domestic wastewater at some of the treatment plants was also not considered. Two small treatment plants, Lagga and Husby, were excluded because there were only 30 and 48 people connected to each, respectively.

Global warming potential was defined as CO_2 equivalents from emissions of CO_2, CH_4 and N_2O. The sources considered of CO_2 equivalents considered were CH_4 and N_2O emissions during the treatment at the plants, from transport and production of energy and chemicals. The recovery of energy leads to a lower net energy of the system and therefore lower external input is needed. The use of recovered nutrients leads to an offset of CO_2 equivalents for production of an equal amount of mineral fertilizers and applying organic fertilizer on soil leads to carbon sequestration. The upgrading of biogas to biofuel leads to an offset of emissions, assuming that the biofuel replaces diesel fuel. These offsets are subtracted from the emitted CO_2 equivalents, resulting in a net emission for the system. Emission factors for the different processes were mainly based on Tumlin *et al.* (2013). For the *Source-separation* system, the energy use of vacuum pumps in the sewer network where source-separation is introduced is included in the environmental criteria. Apart from this, the sewer network is identical in all systems and therefore its emissions are not accounted for in the comparison.

Nutrient recovery is defined as the amount of plant-available nitrogen and phosphorus returned to agriculture and calculated from substances flows. *Eutrophication potential* is defined as PO_4^{3-} equivalents from emissions of total nitrogen, ammonia, total phosphorus and NOx. The sources considered are emissions of ammonia during the wastewater treatment and sludge storage, phosphorus and nitrogen discharged with treated effluent and NOx emissions from transports. The different emissions were converted to PO_4^{3-} equivalents (Heijungs *et al.*, 1992).

The *Total costs* were based on investment costs, operation and maintenance (O&M) and revenues from products. The investment costs considered were for conventional treatment plants (Kärrman *et al.*, 2012), mono-incineration plant (Balmér *et al.*, 2002), ash processing facility (Nättorp & Remmen, 2015), sewer network (Kärrman *et al.*, 2017), on-site systems (Kärrman *et al.*, 2012; Avloppsguiden, 2018), sludge storage facility (calculated based on compost facility estimations for Vantaanjoki, see 3.2) and investments for UASB-reactor, ammonia stripping and struvite recovery reactors (Kärrman *et al.*, 2017). The annuity method was used to calculate the annual costs for investments based on an interest rate of 3%. Maintenance costs were calculated as 3% of total investment costs. Staffing costs were based on average salary of technicians and estimated number of employees needed for operation (Nättorp & Remmen, 2015; Balmér, 2018). The price of heat and electricity was based on Swedish statistics (Energiföretagen) and price of chemicals was based on Nättorp & Remmen (2015). Revenues for the fertilizer products were based on Nättorp & Remmen (2015) and Biototal (2019).

The treatment efficiencies were for conventional treatment and based on the environmental reports from the four largest treatment plants in the area (Uppsala Vatten och Avfall AB, 2017b; c; a; Gästrike Vatten, 2018). For the on-site systems, it was assumed that they all had the same average removal efficiencies (Olshammar *et al.*, 2015). It was assumed that the treatment in the Baseline system complies with discharge limits and pathogen removal. For the UASB, struvite and ammonia stripping, efficiencies were mainly based on Kjerstadius *et al.* (2017) and Nättorp & Remmen (2015).

The transport distances were estimated based on maps of the area. The average distance from the treatment plants without anaerobic digestion to Kungsängsverket was estimated to be 34 km and from Kungsängsverket to the sludge storage facility 15 km. The distance from Storvreta to the sludge storage facility was estimated to be 18 km and to Kungsängsverket 20 km. The transport distance for fertilizer products to a reuse site was assumed to be 25 km, and for sludge to soil production 50 km. The incineration plant was assumed to be at the same site as the sludge storage facility and the distance from there to the ash processing facility was assumed to be 100 km. Transport of chemicals to the treatment plants was not included in the systems.

4.3 Results

Results for the qualitative criteria are presented with a short motivation for each system. The criterion *Acceptance* was mostly assessed by the stakeholders at the second workshop and is therefore presented in 4.4.1.

4.3.1 Global warming potential, eutrophication potential and nutrient recovery

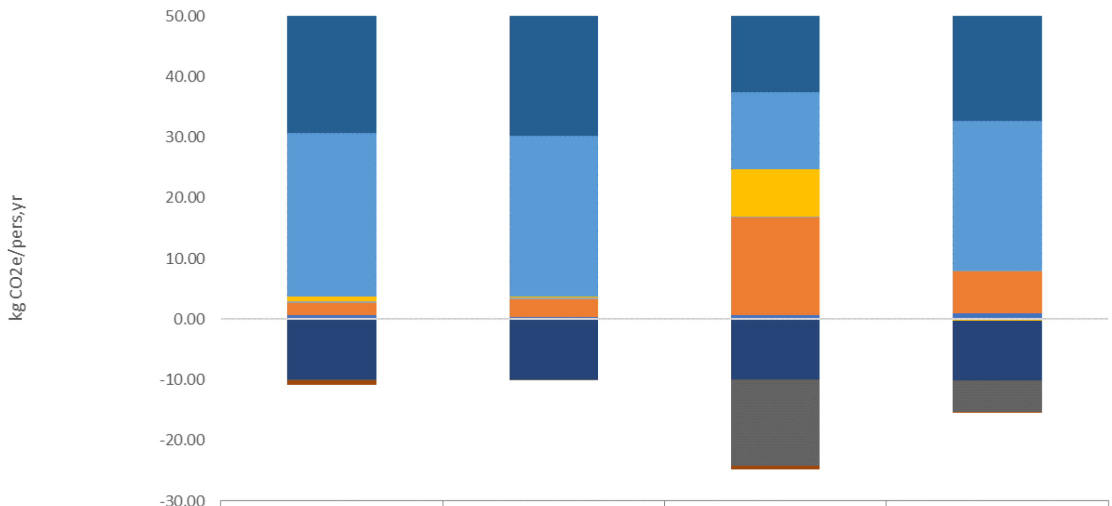
The environmental criteria that were modelled were *Global warming potential, Eutrophication potential* and *Nutrient recovery*. The results for these criteria are shown in Table 8 for each system alternative. The functional unit used is per person and year (/pers/yr), where the number of persons are the total number of persons considered in the study (i.e. the sum from Table 7). Figure 11 and Table 9 show the *global warming potential* and the *eutrophication potential*, respectively, divided into the sources of emissions.

Table 8. Global warming potential, eutrophication potential and nutrient recovery for each of the system alternatives in the Fyriså case study.

	Global warming potential	**Eutrophication potential**	**Nutrient recovery**	
	kg CO_2 eq./pers/yr	**kg PO_4^{3-} eq./pers/yr**	**kg N/pers/yr**	**kg P/pers/yr**
Alt 0F: Baseline	19.8	0.67	0.022	0.25
Alt 1F: Incineration	20.0	0.68	0.00	0.46
Alt 2F: Nutrient extraction	12.6	0.36	3.6	0.14
Alt 3F: Source-separation	17.3	0.48	1.3	0.47

Table 9. Eutrophication potential expressed in total tonnes of PO_4^{3-} equivalents from different sources in each system alternative in the Fyriså case study.

	Alt 0F Baseline	**Alt 1F Incineration**	**Alt 2F Nutrient extraction**	**Alt 3F Source-separation**
	Tonnes PO_4^{3-} eq./yr	**Tonnes PO_4^{3-} eq./yr**	**Tonnes PO_4^{3-} eq./yr**	**Tonnes PO_4^{3-} eq./yr**
Sludge storage	0.67	0.00	1.04	0.28
Direct to water	183	186	97.0	131
Transport	0.43	0.38	0.42	133



	Alt 0F: Baseline	Alt 1F: Incineration	Alt 2F: Nutrient extraction	Alt 3F: Source-separation
Sum	19.8	20.0	12.7	17.3
Carbon sequestration	-0.68	0.00	-0.55	-0.15
Mineral fertilizer offset	-0.21	-0.23	-14.27	-5.18
Fuel offset	-9.90	-9.90	-9.90	-9.90
Treatment	26.84	26.48	12.65	24.70
Heat	0.79	0.11	7.88	-0.20
Electricity	0.39	0.34	0.22	0.13
Chemicals	1.99	2.81	16.09	6.91
Transport	0.61	0.42	0.59	0.99

Figure 11. Global warming potential for each system alternative divided into sources for the Fyriså case study.

The major part of greenhouse gas emissions originates from the treatment processes in all alternatives except Alt 2F Nutrient extraction. The treatment process emissions are CH_4 and N_2O, originating mostly from digestion processes and nitrogen removal, respectively. For Alt 2F Nutrient extraction, the major source of emission is production of chemicals, which corresponds to the systems' high chemical consumption. The treatment emissions in Alt 2F Nutrient extraction are lower since there is more anaerobic treatment of the wastewater than in the other alternatives, reducing the N_2O emissions. The emissions of CH_4 are similar in Alt 2F Nutrient extraction as in Alt 0F Baseline. The highest offset of CO_2 equivalents occurs in Alt 2F Nutrient extraction, due to high nutrient recovery which leads to large replacement of mineral fertilizer and avoided emissions. The Alt 2F Nutrient extraction has the highest CO_2 emissions, but also the largest emission offsets, resulting in the lowest net emissions.

For eutrophication, direct emissions to water through discharge of treated wastewater is the main source. Due to all sludge being incinerated in Alt 1F Incineration, there are no emissions from sludge storage. In Alt 3F Source-separation, only the sludge from blackwater is stored, the rest is incinerated, leading to considerably lower storage emissions than in the baseline system. The ammonia emissions from sludge storage were calculated based on the total amount of nitrogen in the sludge, which is different in Alt 2F Nutrient extraction compared to Alt 0F Baseline, due to different treatment processes. The amounts of dry matter of sludge produced are similar in both systems, but the nitrogen fraction is higher in the sludge in Alt 2F Nutrient extraction, leading to higher storage emissions for that alternative. The magnitude of NOx emissions from transport is directly proportional to the fuel consumption, which is why Alt 3F Source-separation has the highest emissions due to more transport. In Alt 1F Incineration, some of the sludge transport is replaced with transport of incineration ashes and extracted phosphorus, much lighter materials leading to lower fuel consumption and lower NOx emissions.

In the Alt 1F Incineration system no nitrogen is recovered, only phosphorus. which corresponds to about 60% of incoming phosphorus. Alt 2F Nutrient extraction has the highest nutrient recovery of all systems, mainly due to high recovery of nitrogen. The Alt 3F Source-separation has a lower nutrient recovery than Alt 2F Nutrient extraction because ammonia stripping and struvite recovery are done only on blackwater.

For *global warming potential* the Alt 2F Nutrient extraction has the best performance. The other systems perform similarly to the baseline system. For both *eutrophication potential* and n*utrient recovery*, again the Alt 2F Nutrient extraction performs the best, followed by Alt 3F Source-separation. The Alt 1F Incineration has almost the same *Eutrophication potential* as the baseline system.

4.3.2 Risk of exposure to pollutants

In this assessment we focused on heavy metals, pharmaceuticals, microplastics and visible contaminants. Since the same amounts of all pollutants enter all systems, the assessment is based on the content of these pollutants in the different outputs from the systems and the amounts of each output (Table 10). The outputs from the systems, where pollutants may be present, are:

Alt 0F Baseline: Sludge and effluent water
Alt 1F Incineration: Recovered phosphorus product from ash and effluent water
Alt 2F Nutrient extraction: Struvite, ammonium sulphate, sludge and effluent water
Alt 3F Source-separation: Struvite, ammonium sulphate, recovered phosphorus product from ash, sludge from blackwater and effluent water

Heavy metals can be incorporated into the struvite crystals as they form, by both nucleation and crystal growth processes. However, the levels per kg can be expected to be much lower for struvite than for conventional sludge (Rahman *et al.*, 2014). Some pharmaceuticals can adsorb to the struvite crystals (Harder, 2019). It can be assumed that slightly larger amounts of heavy metals are retained in the phosphorus product from ash than in struvite (Harder *et al.*, 2019). Since the sludge is incinerated before phosphorus is extracted, one can assume that the product will not contain any visible contaminants, microplastics or pharmaceuticals. Ammonium sulphate from ammonia stripping is assumed to contain none of the pollutants considered. The effluent i.e. treated wastewater, in all systems is assumed to contain similar amounts of all pollutants (except visible contaminants, which are assumed to be absent in the effluent) due to the same levels of treatment. The blackwater sludge is assumed to contain all pollutants, but in smaller amounts than conventional sludge because it does not contain greywater. The amounts of each output/product in each system are presented in Table 10. Note that for conventional sludge only the amount used for agricultural purposes is considered, i.e. 50 % of the sludge produced.

Table 10. Amounts of the different products from each system alternative in the Fyriså case study.

	Alt 0F Baseline	Alt 1F Incineration	Alt 2F Nutrient extraction	Alt 3F Source-separation
Conventional sludge (tonnes dry matter/yr)	1 602	0	1 559	0
Blackwater sludge (tonnes dry matter/yr)	0	0	0	440
Struvite (tonnes P/yr)	0	0	133	35.8
Ammonium sulphate (tonnes N/yr)	0	0	906	328
Calcium phosphate (tonnes P/yr)	0	125	0	89.5

Based on the assumptions above, and the amounts of the different products, the *Baseline* and *Nutrient extraction* alternatives contribute the most pollutants, due to the spreading of conventional sludge. The lowest amounts of pollutants are spread in the *Incineration* alternative, and the *Source-separation* alternative has a moderate contribution of pollutants.

4.3.3 Total costs

The *total costs* are expressed in the functional unit per person and year, like the environmental criteria. The total costs for investments, operation and maintenance (O&M) and revenues from the fertilizer products is presented in Table 11. Alt 3F: Source-separation is a net producer of heat, which is assumed to be sold for the same price as heat is purchased in the other systems.

Table 11. Costs for each system alternative divided into investments, operations and maintenance (O&M) and revenues for the Fyriså case study.

	Alt 0F Baseline SEK/pers/yr	Alt 1F Incineration SEK/pers/yr	Alt 2F Nutrient extraction SEK/pers/yr	Alt 3F Source-separation SEK/pers/yr
Investments	1 023	1 034	1 079	1 219
O&M	791	791	877	892
Revenues	0	4	19	12
Total	1 814	1 821	1 937	2 100

There is an increasing cost for each alternative compared to the baseline system. The highest investment costs are found in Alt 3F Source-separation, which includes both incineration plant, ash processing facility, new treatment technology at the Kungsängsverket plant, storage of blackwater sludge, additional pipe and pumps in the sewer network and conventional treatment plants. The sizes of these facilities are smaller than in the other alternatives, for example the new treatment technology is only used for treating the blackwater whereas in the Alt 2F Nutrient extraction it is treating all wastewater at Kungsängsverket, but the sum of investment costs is still higher. Due to the higher energy recovery in Alt 1F Incineration compared to the baseline, the O&M costs are the same for both systems even though the maintenance costs are higher in Alt 1F Incineration due to higher investment costs.

4.3.4 Technical robustness

The indicators used for *technical robustness* were likelihood of operational stops and sensitivity to overflows, including the severity of consequences if either occurs.

Alt 0F: Baseline The baseline alternative includes conventional wastewater treatment and anaerobic digestion and therefore is considered the standard to which the other systems are compared to. Conventional wastewater treatment is a well-known treatment process and considered robust, as is conventional anaerobic digestion.

Alt 1F Incineration: This alternative has the addition of mono-incineration of sludge. This is considered a well-known and robust technology, with similar performance in this aspect as the baseline. It also includes extraction of phosphorus from ash. This is considered a less-known technology; however, the consequences of operational stops are considered minor since ash can be stored. In the worst case, more can be landfilled than recovered. The risk of overflow is mostly influenced by the sewer system and maximum capacity of the wastewater treatment plants. This is similar to the baseline system.

Alt 2F Nutrient extraction: In this alternative, there are new treatment technologies (UASB-reactor, ammonia stripping and struvite recovery) at the Kungsängsverket treatment plant which treats the majority of wastewater in the area. It is assumed that digestion in the UASB-reactor is done at lower temperatures (less than 30°C) to be energetically favourable, compared to conventional mesophilic digestion (37°C). Due to operation at lower temperatures, stable operation is more challenging to achieve than in conventional anaerobic digesters. This is due to the slow growth of anaerobic microorganisms, which is even slower at lower temperatures (Kjerstadius, 2017). However, stable operation can be achieved but the risk of operational problems is assumed to be higher than in the baseline. Additionally, due to the low COD concentration of the wastewater and low temperature, a considerable fraction of the CH_4 produced will be dissolved in the effluent. Because of this, the system alternative includes an extraction and oxidation of the dissolved methane. The consequence of this process not operating satisfactorily is considered serious since CH_4 is a potent greenhouse gas. The Alt 2F Nutrient extraction also includes ammonia stripping and struvite precipitation and recovery. Both of these technologies exist elsewhere at full-scale operation and are assumed to be fairly robust. The consequences of malfunction are minor, since the wastewater is further treated after the extraction of ammonia and struvite. In case of an operational stop, the *eutrophication potential* should not be significantly affected. One could assume that the UASB-reactor is less flexible to large increases in flow due to having the digester first and not following several basins. Otherwise, the risk of overflows is similar as in the baseline.

Alt 3F Source-separation: The sewer network for source-separation is considered robust (Kärrman *et al.*, 2017). This alternative is considered having the lowest risk for overflows, and mildest consequences. Having separate collection of the blackwater, by pressurized sewer or by truck, means that there is less risk for overflows. Additionally, the environmental effect of overflow is reduced because of the polluted blackwater being handled separately. This is especially true for the risk of spreading pathogens in the case of overflows, because these are mainly found in blackwater. The blackwater is treated with the same technologies as in Alt 2F Nutrient extraction, which was considered less robust than baseline. However, in Alt 3F Source-separation it is only the blackwater that is treated by these technologies. This is a considerably lower flow than in Alt 2F Nutrient extraction, and it has a higher COD concentration which should make a stable operation of the UASB-reactor less difficult and lead to less dissolved CH_4 in the effluent.

4.3.5 Technical flexibility

Technical flexibility was determined by two aspects: 1) the systems' capacity to handle changes in load due to increasing or decreasing population and 2) the possibility to change or add new technologies to meet new requirements on treatment, such as demand for resource recovery or stricter discharge limits.

Alt 0F Baseline: The baseline system is considered the standard.

Alt 1F Incineration: This alternative is comprised of the same wastewater treatment, only sludge management differs. There is a recovery of phosphorus, which might become a requirement for wastewater systems in the near future. In the case of prohibiting sludge application in agriculture, the *Incineration* alternative would perform better than baseline. For both alternatives, nutrient recovery could be enhanced by applying nutrient extraction on the reject water from dewatering digestate. Otherwise, the treatment system is rather inflexible.

Alt 2F Nutrient extraction: This alternative does offer more potential to modify treatment than the baseline alternative. For example, a membrane could be coupled to the UASB-reactor. However, since conventional treatment is used to polish the effluent, flexibility is not very high since this requires significant infrastructure. This could be rebuilt, just as in the baseline alternative, but it would be costly.

Alt 3F Source-separation: *This* alternative has the same treatment as the previous alternative, but only on a fraction of the wastewater. Conventional treatment of almost the same size is still required, since the blackwater that is separated is only a small volume compared to the greywater and mixed wastewater in the system. However, source-separation offers more alternatives to treatment and is considered an advantage over the other systems. Building a separate greywater treatment offers many possibilities for water reclamation, for example.

4.3.6 Second workshop in Fyris

The criterion *Acceptance* was scored by the stakeholders. The stakeholders were divided into two groups and asked to score the criterion based on the amounts of different fertilizer products produced in each system alternative. The scores chosen by each group is presented in Table 12 together with an average score for each system.

Table 12. Scoring of acceptance for each system alternative by stakeholders at the second workshop for the Fyriså case study.

	Alt 0F Baseline	Alt 1F Incineration	Alt 2F Nutrient extraction	Alt 3F Source-separation
Group 1	0	-1	0	0
Group 2	0	1	2	2
Average	0	0	1	1

Next, the stakeholders were asked to weight the different criteria. The stakeholders discussed in groups but weighted the criteria individually. The weights assigned by the different stakeholders is presented in Table 13 together with the average weight for each criterion.

Table 13. Weights assigned to each criterion by stakeholders at the second workshop for the Fyriså case study.

Criteria	Weights assigned by the individual stakeholders							Average
Global warming potential	10	20	10	8	7.5	10	7.5	10.4
Eutrophication potential	5	10	0	4	7.5	8	5	5.6
Nutrient recovery	15	20	15	8	15	7	7.5	12.5
Total costs	10	10	20	20	20	20	20	17.1
Acceptance	20	10	20	40	30	25	20	23.6
Risk of exposure to pollutants	10	5	10	10	10	10	20	10.7
Technical robustness	15	15	10	5	5	15	10	10.7
Technical flexibility	15	10	15	5	5	5	10	9.3

There is a considerable difference in the score for *Acceptance* between the two groups. Aspects that were discussed as being important for acceptance included, but was not limited to, benefits of having several types of recycled fertilizer products, the importance of returning the organic matter to agriculture and certification systems for the different products. For the weighting exercise also, stakeholder opinions varied. The average weights show that *Eutrophication potential* and *Technical flexibility* are relatively less important. Stakeholders commented that emissions of eutrophying substances are well regulated, and therefore handled by other means and therefore given less weight in this assessment. The robustness of technologies was considered more important than the flexibility, possibly due to uncertainties connected to climate change.

4.3.7 Sustainability scores for all systems

The criteria were given a score based on the systems performance. A score of -2 to +2 was given, where 0 represented similar performance as the baseline system and 2 was the highest score (Table 14). *Nutrient recovery* is based on the sum of recovered nitrogen and phosphorus from Table 8. The criteria *global warming potential*, *eutrophication potential*, *nutrient recovery* and *total costs* were scored based on the following:

Over 40 % worse than baseline: score -2
Up to 40 % worse than baseline: score -1
Within 20 % of baseline: score 0
Up to 40 % better than baseline: score 1
Over 40 % better than baseline: score 2

Table 14. Scoring for each criterion for each system alternative and total sustainability score for the Fyriså case study.

	Weight (%)	Alt 0F Baseline	Alt 1F Incineration	Alt 2F Nutrient extraction	Alt 3F Source-separation
Global warming potential	10.4	0	0	1	0
Eutrophication potential	5.6	0	0	2	1
Nutrient recovery	12.5	0	2	2	2
Total costs	17.1	0	0	0	0
Acceptance	23.6	0	0	1	1
Risk of exposure to pollutants	10.7	0	2	0	1
Technical robustness	10.7	0	0	-2	1
Technical flexibility	9.3	0	1	1	1
Total score		**0**	**55.7**	**58.1**	**84.9**

The sustainability scores for all alternatives are quite similar when the average weights are used along with the average score for *acceptance*. Most importantly, the overall score is positive for all alternatives, meaning that they all perform better than the baseline alternative. But when the *acceptance* score from group 1 is used (Table 12), the score changes to 0, 32.1, 34.6 and 61.4 for Alt 0F Baseline, Alt 1F Incineration, Alt 2F Nutrient extraction and Alt 3F Source-separation, respectively. When the *acceptance* score from group 2 is used the score changes to 0, 79.3, 81.7 and 108.5 for Alt 0F Baseline, Alt 1F Incineration, Alt 2F Nutrient extraction and Alt 3F Source-separation, respectively. The magnitude of the scores change, but the systems remain in the same internal order.

The overall score for each system using the average score for *acceptance* and the individual stakeholders' weights (Table 14) is shown in Figure 12, with the error bars showing the range of scores. This figure shows that depending on the weighting, all systems could potentially obtain the same score.

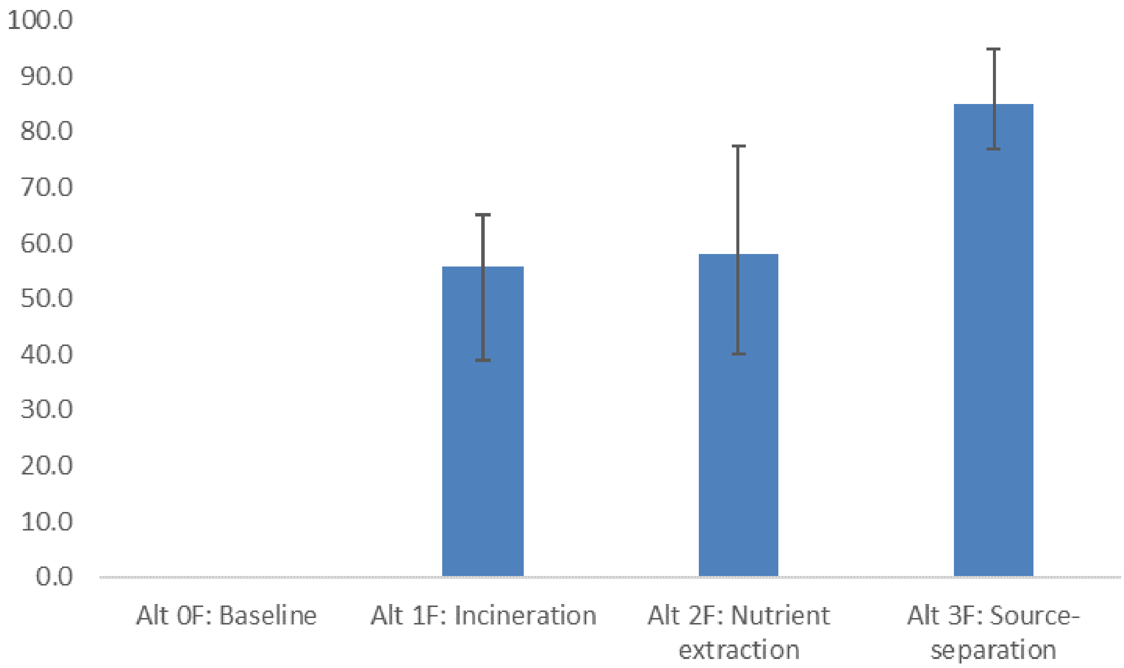


Figure 12. Total sustainability score for each system alternative in the Fyriså case study. The error bars show the scores based on stakeholder individual weighting of criteria.

4.4 Discussion of results

4.4.1 Assessment of criteria

The *global warming potential* for all alternatives were within 40% of the emissions in the baseline system. The highest offset of emissions originating from production of mineral fertilizer comes from Alt 2F Nutrient extraction, due to the high nutrient recovery in that system. When looking at the total GHG emissions from operations, Alt 2F Nutrient extraction has the highest. However, due to the high offset of mineral fertilizer, the system still has the lowest net emissions. The other systems have net emissions that are within +/- 20% of the baseline net emission, meaning that the difference is not large enough to merit a higher or lower score for any of them. One important thing to note regarding emissions originating from production of chemicals is that newer technologies have a disadvantage in terms of optimization of processes and efficiency compared to the conventional treatment systems. The conventional wastewater treatment has been studied and optimized for decades, while the more innovative technologies have not. This means their resource consumption might not be optimized, and there is reason to believe it could be reduced. The innovative systems perform well compared to the conventional system in this study, but as noted, for the most resource-intensive system (Alt 2F Nutrient extraction) it is mainly due to the offset of other resources. Finally, the system boundaries can have large effects on the calculated emissions. For example, these systems do not include emissions from construction or infrastructure, soil production or landfilling of waste incineration ash. Furthermore, the systems are not modelled in large detail, which introduces uncertainties in the calculations.

Regarding *eutrophication potential*, the major source of PO_4^{3-} equivalents comes from discharge of N and P through the treated wastewater. The baseline system and Alt 1F Incineration perform similarly.

Alt 1F Incineration has no emissions from storage of sludge and slightly less NOx emissions but has a higher discharge to water due to a higher degree of dewatering of sludge, which is needed before incineration. Alt 2F Nutrient extraction has almost half the direct eutrophication potential than the baseline. This is due to conventional treatment of the effluent water from the UASB reactor at Kungsängsverket, where the same removal efficiencies as in baseline are used. This could be considered unnecessary if it is assumed that the baseline system fulfils discharge limits, leading to unmotivated costs for this high removal. Especially for nitrogen, one reasonable adjustment to this system would be to include only chemical precipitation of phosphorus and not biological nitrogen removal before discharge of wastewater. The high nutrient removal is a benefit to the Alt 2F Nutrient extraction considering both eutrophication but also technical flexibility (see 5.3.4), but at the same time the system has the highest greenhouse gas emissions from operation. This shows that higher removal efficiencies are beneficial in some respects, but not in others. For Alt 1F Incineration, the emissions from direct discharge of wastewater are slightly higher than the baseline due to higher internal load of nutrients at the Kungsängsverket treatment plant, but at the same time there are no sludge storage emissions. In practice, there would be some storage-related emissions because there would at least be some short-term storage emissions throughout the system. However, this is true for all systems and therefore might not affect the assessment.

There is no recovery of nitrogen in Alt 1F Incineration. For Alt 2F Nutrient extraction, the nutrient recovery is high because nutrient extraction technologies are implemented at the largest treatment plant. The reason for choosing the largest treatment plant is that it has the greatest impact for resource recovery, since Kungsängsverket in Alt 2F Nutrient extraction treats 92% of the wastewater in the area, with the addition of septic sludge from on-site systems and digestion of sludge from several smaller treatment plants. In Alt 3F Source-separation, the same technologies are applied only to source-separated blackwater. The blackwater contains most of the nutrients in domestic wastewater but compared to Alt 2F Nutrient extraction, smaller amounts of N and P can be extracted in Alt 3F Source-separation. However, there is some additional P recovery from incineration ash in Alt 3F Source-separation. In general, all recovery systems have higher nutrient recovery than the baseline. One important assumption made in the assessment is that recovered N and P are considered equally valuable. It is possible that policymakers would value recovery of P higher. For example, P could be counted twice compared to N which could change the scoring of this criterion.

For calculations of costs the largest uncertainty lies in the estimated costs for the UASB-reactor and nutrient extraction technologies in Alt 2F Nutrient extraction and 3F Source Separation. The assumption of an interest rate of 3% for the annual investment cost calculation could also affect the results, as well as the assumption of maintenance costs being 3 % of the total investment cost.

In general, the qualitative criteria are more difficult to assess objectively. Since there are no quantities to compare, some subjectivity could be included. There are also certain indicators or aspects that are used for the assessment and choosing additional or other indicators could of course change the score for the qualitative criterion in question.

Overall, increasing the detail in the systems could lower uncertainties and make assessment of quantitative criteria more accurate. What would be interesting is to include a deeper assessment of *eutrophication potential*, including modelling of nutrient leaching from soil after different types of fertilizers have been applied. This would require a much more sophisticated model than was used here.

4.4.2 Scoring and weighting

As was noted by the stakeholders at the second workshop, the scoring of *acceptance* could be done in various ways. The score can be very different depending on what perspective you have and what aspects are taken into consideration. However, as presented in Chapter 4.3.6, the different scores given to the *acceptance* criterion by the different stakeholders using average weights for criteria did not change the ranking of the system alternatives.

Some interesting notes from the workshop around acceptance concerned sludge use. Organic matter in sludge can be one of the main reasons for using sludge on farmland for some farmers. But there is a big problem connected to the selling of crops fertilized with sludge as Swedish flour mills often refuse to buy them thus reducing the acceptance among farmers. There is also the concern that sludge might contain something that will be discovered as a health or environmental threat. However, this is also true for mineral fertilizers or animal manure but the acceptance of those tend to be higher. Somehow sludge is judged more harshly, possibly since it is human excreta based and this has an inherently lower acceptance. Another aspect of resource recovery is that during climate change, the water holding capacity of soils and carbon sequestration could have increased importance. Applying organic matter to soils could improve their water holding capacity and serve as carbon sequestration. When incinerating sludge, the organic matter is lost meaning that the potential benefits of returning organic matter are lost.

For the weighting of criteria, the idea was to have stakeholders assign weights based on their personal opinions and prioritization, so the variation in weighting was expected. It is interesting that systems Alt 1F Incineration and 2F Nutrient extraction had very similar scores when using average weights and scores for *acceptance*. Alt 3F Source-separation had the highest score, followed by Alt 2F Nutrient extraction. But, when looking at the range of total scores from using the individual stakeholder weighting, there are large overlaps in the total scores of the systems. The maximum score for Alt 2F Nutrient extraction is 77.5, while the lowest for Alt 3F Source-separation is 77.0. This indicates that weighting could be done in such a way that all systems obtain similar total scores. In most cases, though, the Alt 3F Source-separation obtains the highest sustainability score. It is worth noting that in none of the weightings used did any recovery system get a lower score than the baseline, meaning that they are all more sustainable alternatives.

The scoring for the quantitative criteria was based on intervals of 20%, as presented in chapter 4.3.7. If more narrow intervals were chosen, for example 10%, the relative scoring would change. The cost criterion for instance would be scored -1 for the Alt 3F Source-separation, which could impact the results. However, uncertainties in calculations are to be considered. Choosing a too narrow interval could also lead to uncertain results.

For Alt 3F Source-separation, stakeholders suggested that blackwater treatment could be decentralized instead of collected and transported to Kungsängsverket for treatment. The blackwater management and treatment could look like what was assessed for the Vantaanjoki catchment area in Alternative 3 (see chapter 3.1.3). The reason for not having it in the current system is the treatment technology system with biogas production and nutrient extraction of course yields more products the more substrate that is put in. This alternative (Alt 3F Source-separation) is however a sort of “transition scenario”, where source-separation is gradually introduced, and implementation of source-separation is meant to continue to increase. When the proportion of source-separated households is higher it might make more sense to have local treatment of blackwater, but in this alternative only 37% of the blackwater is separated. Urea-hygienization of blackwater (the ecotechnology assessed in the Vantaanjoki case) does not produce biogas, but it would be interesting to look at the energy balance for such a system in the area since there would possibly be lower energy uses in other parts of the system. The fertilizer product could also be more interesting, since the blackwater sludge in the current system has larger nutrient losses during the treatment than urea-hygienized sludge. The aspect of resilience could also be included, since stakeholders pointed out that centralization decreases resilience while decentralization increases it.

4.5 Conclusions

In summary, results show that the different stakeholder’s weights could result in a similar score for all recovery systems assessed. All the systems perform better than the baseline, as indicated by them all having higher sustainability score than the baseline system. Using average stakeholder weights for the criteria, the Alt 3F Source-separation system receives the highest sustainability score followed by the Alt 2F Nutrient-extraction system. For the quantitative criteria especially, the system boundaries and assumptions affect the outcome and changing these could potentially lead to a different outcome. The results should be viewed in context of this.

5 MULTI-CRITERIA ANALYSIS IN THE SŁUPIA CASE

In the Słupia catchment area, the sustainability of recovering nutrients and carbon from domestic wastewater was assessed. The same criteria were used as for the Fyrisån case, described in chapter 2.6.

5.1 System alternatives

5.1.1 Alt 0S Baseline

The baseline system represents the conventional wastewater management in the area (Figure 13). In the baseline system (Alt 0S Baseline), all treatment plants considered treated wastewater conventionally, with enhanced nitrogen removal at the largest plants. The size of the plants and treatment efficiencies used are based on data from the actual plants in the area. It was assumed that all sludge produced is transported to the largest treatment plant, Słupsk, where it is composted. Today, about 95% of the composted sludge is returned to agriculture. In the system alternative, it is assumed that 100% is returned to agriculture. The fertilizer product generated in the baseline system is composted sludge. In addition, biogas, generated at two treatment plants is used for heat and electricity production.

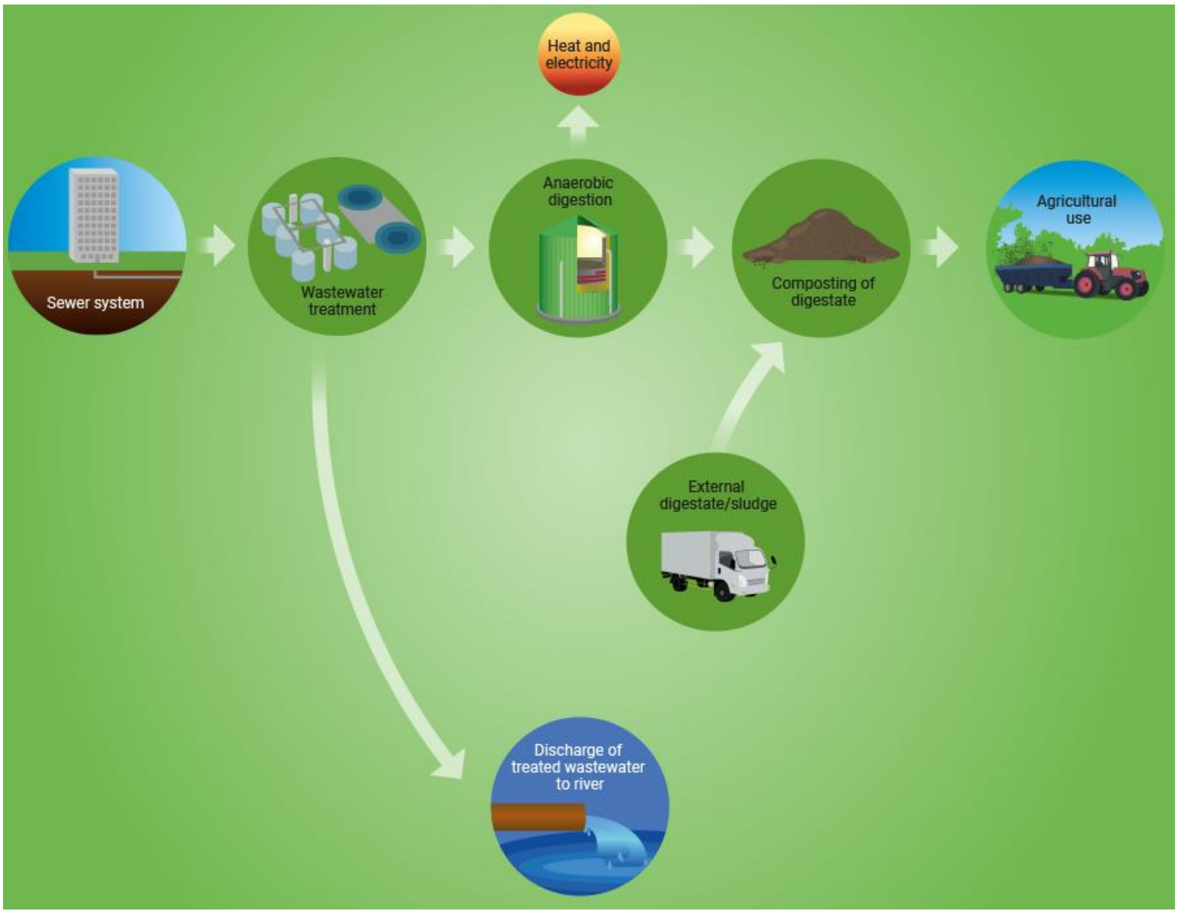


Figure 13. System illustration of the Alt 0S Baseline system in the Słupia case study. Note that it is the treatment at Słupsk treatment plant that is illustrated.

5.1.2 Alt 1S Reject water

In the first recovery system, Alt 1S Reject water, the wastewater is treated in the same way as in the baseline system with one exception. At the Słupsk WWTP, nitrogen is recovered through ammonia stripping from the reject water which is generated when sludge/digestate is dewatered after anaerobic digestion (Figure 14). In the baseline system, the reject water is directly circulated back to the incoming wastewater. Since the reject water is rich in nitrogen, returning it to the incoming wastewater increases the nitrogen load on the treatment and this in turn increases the energy consumption during the enhanced nitrogen removal. Removing some of the nitrogen in the reject water therefore leads to reduced energy consumption. Additionally, the amount of nitrogen which is converted to atmospheric nitrogen is reduced which leads to lower emissions of the greenhouse gas N_2O. Apart from the ammonia stripping, the system is identical to the baseline system. The fertilizer products generated in this system are composted sludge and ammonium sulphate. In addition, biogas, generated at two treatment plants, is used for heat and electricity production.

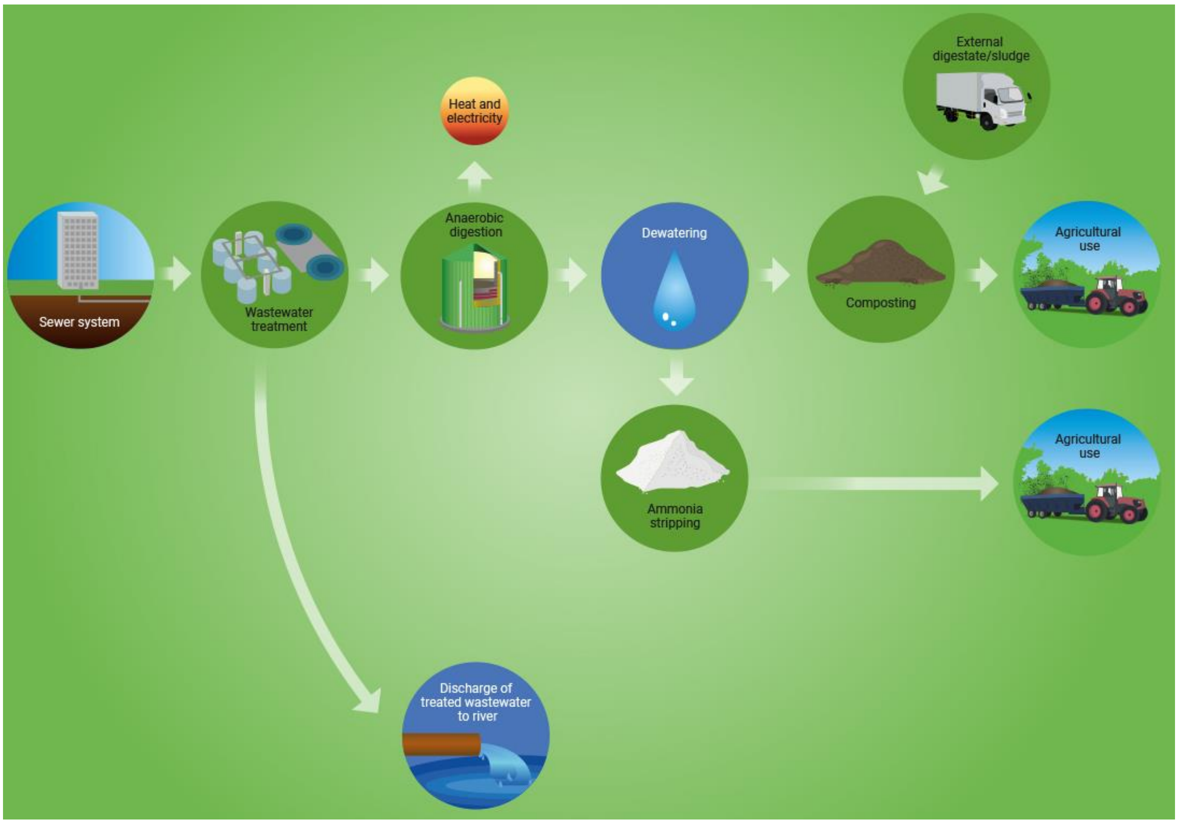


Figure 14. System illustration of the Alt 1S Reject water system in the Słupia case study. Note that it is the treatment at Słupsk treatment plant that is illustrated.

5.1.3 Alt 2S Nutrient extraction

The second alternative, Alt 2S Nutrient extraction, is essentially the same as was assessed for the Fyrisån catchment area (see 4.2) (Figure 15). Sludge is composted just as in the baseline system. However, the amount of sludge generated is lower since in this system the wastewater is treated anaerobically which produces less sludge than the conventional aerobic activated sludge process. The fertilizer products generated in this system are composted sludge, ammonium sulphate and struvite. In addition, biogas, generated at two treatment plants, is used for heat and electricity production.

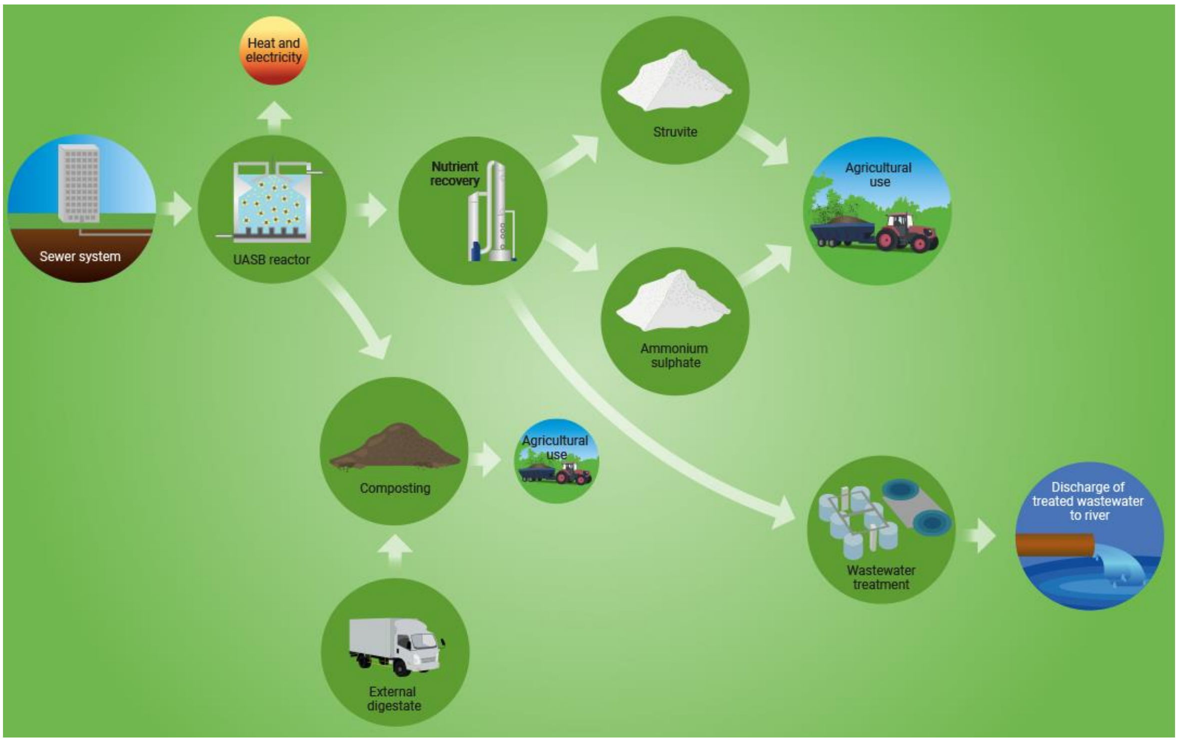


Figure 15. System illustration of the Alt 2S Nutrient extraction system in the Słupia case study. Note that it is the treatment at Słupsk treatment plant that is illustrated.

5.1.4 Alt 3S Source-separation

The third alternative Alt 3S Source-separation is also largely the same as described for Fyrisån catchment area (see 4.2) (Figure 16). Sludge incineration is not included here either, but the sludge produced from blackwater is stored separately as the quality is different from that of sludge from mixed wastewater, and therefore can constitute a different product if treated separately. In this system, a combination of Alt 1S Reject water and 2S Nutrient extraction is used where reject water from the conventionally treated greywater and mixed wastewater is fed to the ammonia stripper. In this way, benefits from both systems are generated. Just as in the Fyrisån case, blackwater is led to the treatment plant by pipe only for the largest plant, i.e. Słupsk WWTP. For all other plants, the source-separated blackwater is stored in closed tanks and transported to Słupsk WWTP for treatment. The fertilizer products generated in this system are composted sludge, ammonium sulphate, struvite and blackwater sludge. In addition, biogas, generated at two treatment plants, is used for heat and electricity production.

Figure 16. System illustration of the Alt 3S Source-separation system in the Słupia case study. Note that it is the treatment at Słupsk treatment plant that is illustrated.

5.2 System boundaries and assumptions

According to population change prognoses for two of the municipalities in the catchment area, Słupsk and Bytow, there will be no significant increases (Giełczewski, 2019). It was therefore assumed that the treatment plants would have the same number of people connected as today (Table 15).

Table 15. Treatment plants considered in the Słupia case study.

Treatment plant	Number of persons connected
Słupsk	115 414
Ustka	19 570
Przyborzyce	23 904
Sierakowice	19 647
Dębnica Kaszubska	14 880
Ugoszcz	3 660
Wierszyno	2 965
Borzytuchom	2 661
Parchowo	3 500

No on-site systems were considered in the Słupia catchment area. This was due to a lack of information on numbers, locations and current treatment. It was assumed the sludge produced at the WWTPs is transported to Słupsk WWTP for composting. All the finished composted product is returned to arable land.

The qualitative criteria *Risk of exposure to pollutants*, *Technical robustness and reliability* and *Technical flexibility* were assessed based on literature and expert knowledge. The criterion *Acceptance* is highly site-dependent and was partly assessed by the same method as the other qualitative criteria but mostly influenced by local stakeholders and experts at the second workshop.

Global warming potential was defined as CO_2 equivalents from emissions of CO_2, CH_4 and N_2O. The sources considered in CO_2 equivalents were CH_4 and N_2O emissions during treatment at the plants, and from transport and production of energy and chemicals. The recovery of energy leads to a lower net energy use by the system and therefore lower external input is needed. The use of recovered nutrients leads to an offset of CO_2 equivalents for production of an equal amount of mineral fertilizers and applying organic fertilizer on soil leads to carbon sequestration. The upgrading of biogas to biofuel leads to an offset of emissions, assuming that the biofuel replaces petroleum fuel. These offsets are subtracted from the emitted CO_2 equivalents, resulting in a net emission for the system. Emission factors for the different processes were mainly based on Tumlin *et al.* (2013). For the *Source-separation* system, the energy use of vacuum pumps in the sewer network where source-separation is introduced is included in the environmental criteria. Apart from this, the sewer network is identical in all systems and therefore its emissions are not accounted for in the comparison.

Nutrient recovery is defined as the amount of plant available nitrogen and phosphorus returned to agriculture and calculated from substances flows. *Eutrophication potential* is defined as PO_4^{3-} equivalents from emissions of total nitrogen, ammonia, total phosphorus and NOx. The sources considered are emissions of ammonia during the wastewater treatment and sludge storage, phosphorus and nitrogen discharged with treated effluent and NOx emissions from transports. The different emissions were converted to PO_4^{3-} equivalents (Heijungs *et al.*, 1992).

The *Total costs* were based on investment costs, operation and maintenance (O&M) and revenues from products. The investment costs considered were for conventional treatment plants (European Commission, 2010), sewer network (European Commission, 2010; Kärrman *et al.*, 2017), closed tanks for blackwater storage (Avloppsguiden, 2018), composting facility (calculated by same method as for the Vantaanjoki case study, see 3.2) and investments for UASB-reactor, ammonia stripping and struvite recovery reactors (Kärrman *et al.*, 2017). The annuity method was used to calculate the annual costs for investments based on an interest rate of 3%. Maintenance costs were calculated as 3% of total investment costs. Staffing costs were based on average salary of technician and estimated number of employees needed for operation (Balmér, 2018; Giełczewski, 2019). The price of heat and electricity was based on Polish data (Giełczewski, 2019) and price of chemicals was based on Nättorp & Remmen (2015) and Giełczewski (Giełczewski, 2019). Revenues for the fertilizer products were based on Nättorp & Remmen (2015), Biototal (2019) and Giełczewski (2019).

The treatment efficiencies were for conventional treatment based on information provided by the treatment plants in the area (Giełczewski, 2019). As data were not available for all treatment plants, assumptions were made that similar sized plants performed similarly. It was assumed that the treatment in the Baseline system complies with discharge limits and pathogen removal. For the UASB, struvite and ammonia stripping efficiencies were mainly based on Nättorp & Remmen (2015) and Kjerstadius *et al.* (2017).

The transport distances were estimated based on maps of the area. The average distance from the smaller treatment plants to Słupsk treatment plant, where the composting facility was located, was estimated to be between 21 and 58 km for the different plants. The transport distance for fertilizer products to a reuse site was assumed to be 13 km. Transport of chemicals to the treatment plants was not included in the systems.

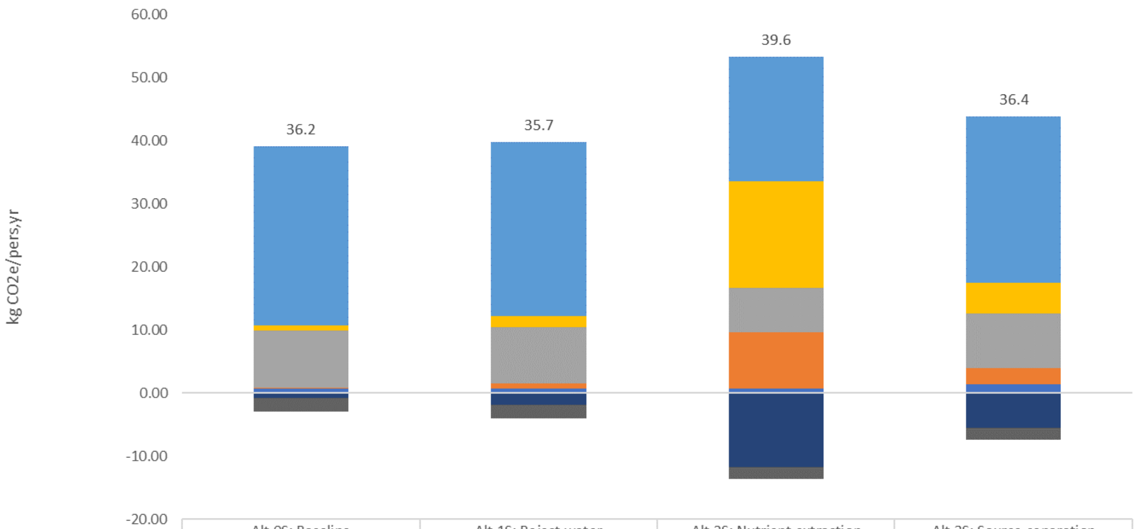
5.3 Results

5.3.1 Global warming potential, eutrophication potential and nutrient recovery

The results for *global warming potential*, *eutrophication potential* and *nutrient recovery* are shown in Table 16. The results are expressed as kg per person and year. The contribution of different sources to *global warming potential* and *eutrophication potential* is presented in Figure 17 and Table 17, respectively.

Table 16. Global warming potential, eutrophication potential and nutrient recovery for each system alternative in the Słupia case study.

	Global warming potential	**Eutrophication potential**	**Nutrient recovery**	
	kg CO_2 eq./pers/yr	**kg PO_4^{3-} eq./pers/yr**	**kg N/pers/yr**	**kg P/pers/yr**
Alt 0S Baseline	36.2	0.49	0.14	0.50
Alt 1S Reject water	35.7	0.48	0.41	0.50
Alt 2S Nutrient extraction	39.6	0.31	2.44	0.60
Alt 3S Source-separation	36.4	0.38	0.87	0.51



	Alt 0S: Baseline	Alt 1S: Reject water	Alt 2S: Nutrient extraction	Alt 3S: Source-separation
Sum	36.2	35.7	39.6	36.4
Carbon sequestration	-2.09	-2.09	-1.92	-1.89
Mineral fertilizer offset	-0.81	-1.87	-11.73	-5.55
Treatment	28.38	27.47	19.72	26.35
Heat	0.79	1.83	16.84	4.89
Electricity	9.04	8.88	7.08	8.56
Chemicals	0.18	0.84	8.92	2.64
Transport	0.68	0.69	0.70	1.35

Figure 17. Global warming potential for each system alternative divided into sources of emissions for the Słupia case study.

Table 17. Eutrophication potential expressed as total amount of PO_4^{3-} equivalents for each system alternative from different sources for the Słupia case study.

	Alt 0S: Baseline **tonnes PO_4^{3-} eqv./yr**	**Alt 1S: Reject water** **tonnes PO_4^{3-} eqv./yr**	**Alt 2S: Nutrient extraction** **tonnes PO_4^{3-} eqv./yr**	**Alt 3S: Source-separation** **tonnes PO_4^{3-} eqv./yr**
Composting	8.9	8.5	7.0	6.1
Directly to water	92.8	90.1	56.5	71.7
Transports (NOx)	0.043	0.043	0.048	0.17

The major source of greenhouse gases for all systems except Alt 2S Nutrient extraction is treatment emissions. The treatment emissions are CH_4 from digestion processes and N_2O from nitrogen removal. The treatment emissions in Alt 2S Nutrient extraction are lower due to there being more anaerobic treatment of the wastewater than in the other alternatives, reducing the N_2O emissions. The main source of CO_2 eq in Alt 2 Nutrient extraction is heat consumption, this is because the treatment technologies in this alternative require more heat than in the baseline system, even though they are used only at Słupsk treatment plant. On the other hand, the system has the lowest consumption of electricity. The consumption of chemicals is also considerably higher in Alt 2S Nutrient extraction than in the other systems, reflected by high CO_2-eq emissions from chemical production. Overall the Alt 2S

Nutrient extraction has the highest net emission of CO_2-eq. The Alt 1S Reject water has the lowest net emission, which is mainly from treatment emissions and electricity use. However, the alternatives 0S Baseline and 3S Source separation have almost the same net emissions as Alt 1S Reject water, also with main contributors being treatment emissions and electricity use.

The eutrophying emissions are mainly from treated wastewater which is discharged to the river. The composting emissions are proportional to the amounts of sludge composted, which is highest for baseline and lowest for Alt 3S Source-separation. There is more transport in Alt 3S Source-separation due to collection and transport of blackwater from the other treatment plants to the Słupsk treatment plant, which is reflected in higher emissions of NOx in Alt 3S Source-separation.

The Alt 1S Reject water has a higher recovery of nitrogen than the baseline system, because of ammonia stripping. Alt 2S Nutrient extraction has the highest nutrient recovery, followed by Alt 3S Source-separation.

All systems have similar *global warming potential*, although Alt 1S Reject water has the lowest and Alt 2S Nutrient extraction has the highest. Alt 1S Reject water has similar *eutrophication potential* as the baseline system. Alt 2S Nutrient extraction has the lowest *eutrophication potential* followed by Alt 3S Source-separation. Alt 2S Nutrient extraction has the highest total *nutrient recovery*, followed by Alt 3S Source-separation and Alt 1S Reject water

5.3.2 Total costs

The *total costs* are expressed as functional units per person per year, like the environmental criteria. The total costs for investments, operation and maintenance (O&M) and revenues from the fertilizer products are presented in Table 18.

Table 18. The costs for each system alternative for investments, operation and maintenance (O&M) and revenues for the Słupia case study.

	Alt 0S Baseline PLN/pers/yr	Alt 1S Reject water PLN/pers/yr	Alt 2S Nutrient extraction PLN/pers/yr	Alt 3S Source-separation PLN/pers/yr
Investments	196	197	215	266
O&M	161	169	191	214
Revenues	1.3	1.3	2.2	1.5
Total	356	365	403	479

There is an increasing cost for each alternative compared to the baseline system. The highest investment costs are found in Alt 3S Source-separation, which includes both new treatment technology at the Słupsk treatment plant, composting facility, additional pipe and pumps in the sewer network and conventional treatment plants. The sizes of these facilities are smaller than in the other alternatives, for example, the new treatment technology is only used for treating the blackwater whereas in Alt 2S Nutrient extraction, it is treating all wastewater at Słupsk treatment plant, but the sum of investment costs is still higher. Alt 1S Reject water has only the additional investment costs for the ammonia stripping reactor, and the accompanying O&M costs, making the costs only slightly higher than baseline. The Alt 2S Nutrient extraction has the highest revenues, due to having the highest nutrient recovery. This alternative also has the highest operational costs (i.e. highest energy and chemical consumption). Still the Alt 3S Source-separation has the highest total O&M costs, due to the costs for maintenance being calculated as a percentage of the total investment costs.

5.3.3 Risk of exposure to pollutants

In this assessment we focused on heavy metals, pharmaceuticals, microplastics and visible contaminants. Since the same amounts of all pollutants enter all systems, the assessment is based on the content of these pollutants in the different outputs from the systems and the amounts of each output. The outputs from the systems, where pollutants may be present, are:

Alt 0S Baseline: Composted sludge and effluent water
Alt 1S Reject water: Composted sludge, ammonium sulphate and effluent water
Alt 2S Nutrient extraction: Composted sludge, struvite, ammonium sulphate and effluent water
Alt 3S Source-separation: Composted sludge, struvite, ammonium sulphate, blackwater sludge and effluent water

Heavy metals can be incorporated into the struvite crystals as they form, by both nucleation and crystal growth processes. However, the levels per kg can be expected to be much lower for struvite than for conventional sludge (Rahman *et al.*, 2014). Some pharmaceuticals can adsorb to the struvite crystals (Harder *et al.*, 2019). Ammonium sulphate from ammonia stripping is assumed to contain none of the pollutants considered. The effluent i.e. treated wastewater, in all systems is assumed to contain similar amounts of all pollutants (visible contaminants are assumed to be absent in the effluent) due to same levels of treatment. The blackwater sludge is assumed to contain all considered pollutants, but in smaller amounts than conventional sludge because it does not contain greywater. Composted sludge is assumed to contain pollutants, and in the highest amounts compared to the other products. The amounts of each output/product in each system is presented in Table 19.

Table 19. Amounts of the different products in the system alternatives for the Słupia case study.

	Alt 0S Baseline	Alt 1S Reject water	Alt 2S Nutrient extraction	Alt 3S Source-separation
Composted sludge (tonnes dry matter/yr)	3 956	3 956	3 637	3 575
Ammonium sulphate (tonnes N/yr)		57.5	450	154
Struvite (tonnes P/yr)			65.5	11.0
Blackwater sludge (tonnes dry matter/yr)				150

Based on the assumptions above, together with the amounts of the products produced in each system, there is little difference in the risk of pollution by using the products in Table 19 as fertilizers . The latter two systems (Alt 2S Nutrient extraction and 3S Source separation) produce slightly less composted sludge than the first two, even if blackwater sludge is considered comparable to the composted sludge. Among the pollutants considered, heavy metals are probably a possible concern for struvite but much lower than in sludge. Therefore, the latter two systems can be considered posing a slightly smaller pollution risk.

5.3.4 Technical robustness

The indicators used for *technical robustness* were likelihood of operational stops and sensitivity to overflows, including the severity of consequences if either occurs. Since composting of sludge is included in all alternatives, it is not considered in this comparison.

Alt 0S Baseline: This includes conventional wastewater treatment and anaerobic digestion and therefore is considered the standard to which the other systems are compared to. Conventional wastewater treatment is a well-known treatment process and considered robust, as is conventional anaerobic digestion.

Alt 1S Reject water: This alternative has the addition of ammonia stripping from reject water, obtained when dewatering digested sludge. This is considered a well-known and robust technology, which exists already at full-scale operations. The risk of overflow is mostly influenced by the sewer system and maximum capacity of the wastewater treatment plants. This is similar to the baseline system.

Alt 2S Nutrient extraction: In this alternative, there are new treatment technologies at the Słupsk treatment plant which treats the majority of wastewater in the area. It is assumed that digestion in the UASB-reactor is done at lower temperatures (less than 30°C) to be energetically favourable, compared to conventional mesophilic digestion (37°C). Due to operation at lower temperatures, stable operation is more challenging to achieve than in conventional anaerobic digesters. This is due to the slow growth of anaerobic microorganisms, which is even slower at lower temperatures (Kjerstadius, 2017). However, stable operation can be achieved but the risk of operational problems is assumed to be higher than for the baseline. Additionally, due to the low COD concentration of the wastewater and low temperature, a considerable fraction of the CH_4 produced will be dissolved in the effluent. Because of this, the system alternative includes an extraction and oxidation of the dissolved methane. The consequence of this process not operating satisfactory is considered serious since CH_4 is a potent greenhouse gas. Alt 2S Nutrient extraction also includes ammonia stripping and struvite precipitation and recovery. Both technologies exist at full-scale operation and are assumed to be robust. The consequences of malfunction are minor, since the wastewater is further treated after the extraction of ammonia and struvite. In case of an operational stop, the *eutrophication potential* should not be significantly affected. One could assume that the UASB-reactor is less flexible to large increases in flow due to having the digester first and not following several basins. Otherwise, the risk of overflows is similar as in the baseline.

Alt 3S Source-separation: The sewer network for source-separation is considered robust (Kärrman *et al.*, 2017). This alternative is considered having the lowest risk for overflows, and least consequences. Separate collection of the blackwater, by pressurized sewer or by truck, means that there is less risk for overflows. Additionally, the environmental effect of overflow is reduced because the polluted blackwater is handled separately. This is especially true for the risk of spreading pathogens in the case of overflows, because these are mainly found in the blackwater. However, the fraction of wastewater which is source-separated is only 14%. The blackwater is treated with the same technologies as in Alt 2S Nutrient extraction, which in that alternative was considered less robust than the baseline.

However, in Alt 3S Source-separation, it is only the blackwater that is treated by these technologies. This is a considerably lower flow than in Alt 2S Nutrient extraction, and it has a higher COD concentration which should make stable operation of the UASB reactor less difficult and lead to less dissolved CH_4 in the effluent. Overall, the low proportion of source-separation makes the system comparable in robustness as the baseline system.

5.3.5 Technical flexibility

Technical flexibility was determined by two aspects: 1) the systems' capacity to handle changes in load due to increasing or decreasing population and 2) the possibility to change or add new technologies to meet new requirements on treatment, such as demand for resource recovery or stricter discharge limits.

Alt 0S Baseline: The baseline system is considered the standard.

Alt 1S Reject water: This alternative is comprised of the same wastewater treatment, only with the addition of ammonia stripping of reject water. This additional technology does not affect the flexibility in any large sense. It contributes to a more energy-efficient treatment but does not directly influence the ability to meet stricter discharge limits.

Alt 2S Nutrient recovery: This alternative offers more potential to modify treatment than the baseline alternative. For example, a membrane could be coupled to the UASB-reactor. However, since conventional treatment is used to polish the effluent the flexibility is not very high since this requires significant infrastructure. This could be rebuilt, just as in the baseline alternative, but it would be costly.

Alt 3S Source-separation: This alternative has the same treatment as the previous alternative, but only on a fraction of the wastewater. Conventional treatment of almost the same size is still required, since the blackwater that is separated is only a small volume compared to the greywater and mixed waste water in the system. Source-separation offers more alternatives to treatment and is considered an advantage over the other systems. Building separate greywater treatment offers many possibilities for water reclamation, for example. However, only 14% of the wastewater is source-separated, meaning that these benefits are not large enough on the system level to merit a higher score.

5.3.6 Second workshop in Słupia

At the second workshop held in the Słupia catchment area, the stakeholders were asked to discuss the scoring of the *Acceptance* criterion in three groups. The scores they assigned to this criterion for the different systems in each group are presented in Table 20 together with the average score. The average score has been rounded off to the closest integer.

Table 20. Acceptance scores assigned by the stakeholders at the second workshop in the Słupia case study.

	Alt 0S Baseline	Alt 1S Reject water	Alt 2S Nutrient extraction	Alt 3S Source-separation
Group 1	0	0	-1	-2
Group 2	0	0	0	-1
Group 3	0	1	1	-2
Average	0	0	0	-2

The stakeholders discussed the weighting of the criteria and scored them individually, except for one group that had an agreement for the weighting. The average weights assigned to each criterion in the different groups are presented in Table 21.

Table 21. Weights assigned to the criteria by stakeholders at the second workshop in the Słupia case study.

	Group 1	Group 2	Group 3	Average
Global warming potential	8.75	9	12	9.9
Eutrophication potential	12.5	15	8	11.8
Nutrient recovery	8.75	12	5	8.6
Total costs	18.75	21	15	18.3
Acceptance	17.5	10	10	12.5
Risk of exposure to pollutants	17.5	19	40	25.5
Technical robustness	8.75	7,5	5	7.1
Technical flexibility	7.5	6,5	5	6.3

All stakeholders agreed that the Alt 3S Source-separation would have the lowest acceptance. Some comments were about the blackwater sludge, which could receive low acceptance due to low processing and low awareness about its quality. Also, there were questions regarding the relevance of the Alt 3S Source-separation since the fraction of source-separation was low, thus leading to low amounts of produced struvite and ammonia sulphate. One group favoured the diversity of products from Alt 2S Nutrient extraction, while another foresaw issues with the products since they were not widely used by farmers today and not certified.

5.3.7 Sustainability scores for all systems

The criteria were given scores based on the systems performance. A score of -2 to +2 was given, where 0 represented similar performance as the baseline system and 2 was the highest score (Table 22). The criteria *global warming potential*, *eutrophication potential*, *nutrient recovery* and *total costs* were scored based on the following:

More than 40 % worse than baseline: score -2
Up to 40 % worse than baseline: score -1
Within 20 % of baseline: score 0
Up to 40 % better than baseline: score 1
More than 40 % better than baseline: score 2

Table 22. Scoring for each criterion for each system alternative and total sustainability score for the Słupia case study.

	Weight	Alt 0 Baseline	Alt 1 Reject water	Alt 2 Nutrient extraction	Alt 3S Source-separation
Global warming potential	9.9	0	0	0	0
Eutrophication potential	11.8	0	0	1	1
Nutrient recovery	8.6	0	1	2	2
Total costs	18.3	0	0	0	-1
Acceptance	12.5	0	0	0	-2
Risk of exposure to pollutants	25.5	0	0	1	1
Technical robustness	7.1	0	0	-2	0
Technical flexibility	6.3	0	0	1	0
Total score		**0**	**10.8**	**41.7**	**2.5**

The total sustainability score in Table 22 is calculated based on average weights and score for the *acceptance*. If using the *acceptance* score from group 1 (see Table 20) and average weights, the total score changes to 0, 10.8, 26.7 and 2.5 for Alt 0S Baseline, Alt 1S Reject water, Alt 2S Nutrient extraction and Alt 3S Source-separation, respectively. When using the *acceptance* scores from group 2 the corresponding scores become 0, 10.8, 41.7 and 17.5 and for the last group the scores become 0, 25.8, 56.7 and 2.5. In all cases, the Alt 2S Nutrient extraction receives the highest sustainability score. Only with the group 2 acceptance score does Alt 3S Source-separation perform better than Alt 1S Reject water, since Alt 3S Source-separation has score -1 instead of -2.

The total scores using the individual weights and the average score for *acceptance* as in Table 22 is shown in Figure 18. Note that one of the 10 “individual” weights which the error bars are based on is the average from one of the groups of five people. The error bars show the range of the total score.

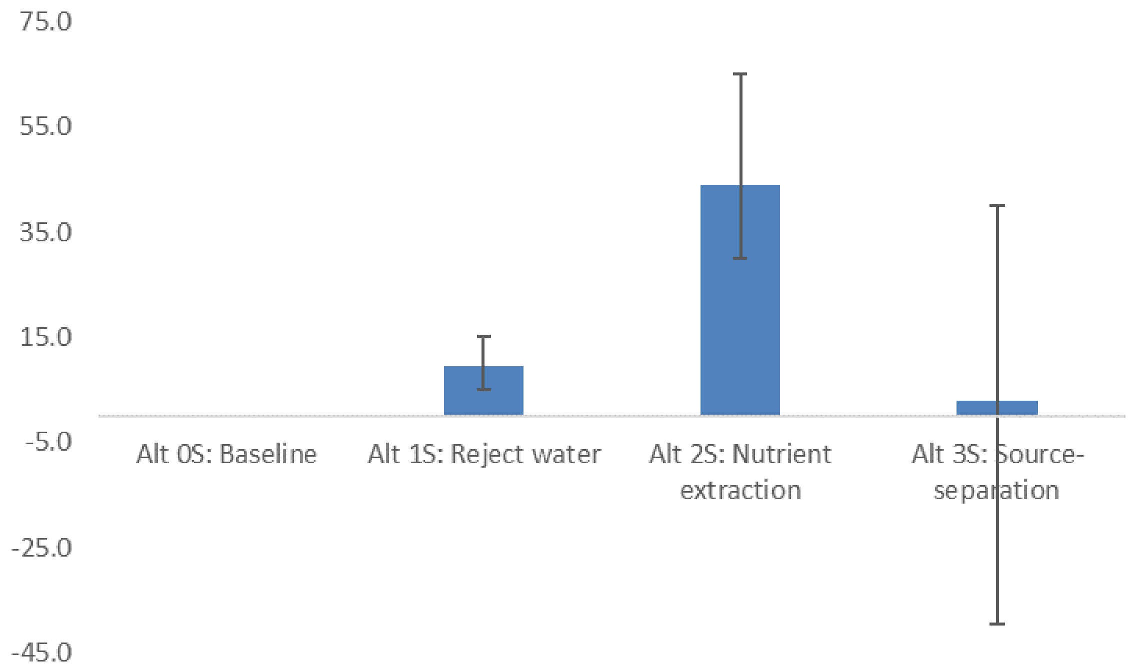


Figure 18. Total sustainability score for each system alternative in the Słupia case study*. The error bars show the range based on stakeholder individual weighting of criteria.*

One important thing to note in Figure 18 is that the sustainability score for Alt 3S Source-separation is negative based on the scoring from 3 different stakeholders. This means that depending on the weighting done at the workshop, Alt 3S Source-separation could perform worse than the baseline system. Based on all the weightings, Alt 2S Nutrient extraction performs better than Alt 1S Reject water. The range of scores for Alt 3S Source-separation partly overlaps with that of Alt 2S Nutrient extraction, indicating that certain weighting could possibly lead to the same score for both these systems.

5.4 Discussion of results

5.4.1 Assessment of criteria

The contribution of the different sources of greenhouse gas emissions are different in the alternatives, but the net emissions are similar. The highest net emission is from Alt 2S Nutrient extraction, even though it also has the largest emission offsets. Major contributors to emissions in this alternative are heat, production of chemicals and treatment. For the other systems the major sources of emissions are electricity and treatment, i.e. emissions of CH_4 from digestion processes and composting and N_2O emissions from nitrogen removal. The treatment emissions in Alt 2S Nutrient extraction are lower due to more of wastewater being treated anaerobically, which reduces N_2O emissions.

For eutrophication the Alt 1S Reject water performs similarly as the baseline, and the systems are quite similar. Alt 2S Nutrient extraction has much lower *eutrophication potential*, due to effluent being further treated before discharge. This system is essentially the same as in the Fyrisån case; see 4.4.1 for important notes in *eutrophication potential* for this alternative.

The same basic assumptions were made for the cost calculation and assessment of qualitative criteria for Słupia and Fyrisån; see 4.4.1.

One interesting note from the stakeholders at the second workshop was a question on the relevance of Alt 3S Source-separation. In this alternative, 14% of the wastewater is source-separated. The blackwater is treated by the same nutrient extraction technologies as in Alt 2S Nutrient extraction, but since the input of blackwater is so much smaller than the input of mixed wastewater in Alt 2S Nutrient extraction, the amount of nutrients recovered is much smaller. Additionally, the reject water from conventional treatment in Alt 3S Source-separation goes through ammonia stripping. The additional benefits of introducing source-separation are therefore relatively small, but the costs are about 30% higher. This indicates that a low fraction of source-separation is not a relevant choice for the Słupia catchment area in a system like Alt 3S Source-separation. It would be interesting to look at a longer implementation time, where a larger fraction of the wastewater generated is source-separated.

For the Alt 3S Source-separation, a similar adjustment to the system could be done as was discussed at the Fyrisån workshop, i.e. decentralization of blackwater treatment (see 4.4.3). This was, however, not raised as an issue at the Słupia stakeholder workshop. It would perhaps not make as much sense for the Słupia area since the acceptance of the blackwater sludge as a product was low and the proportion of source-separation was much lower in the Słupia area than in the Fyrisån area for Alt 3.

In general, increasing the detail in the systems could lower uncertainties and make the assessment of quantitative criteria more accurate. What would be interesting is to include a deeper assessment of *eutrophication potential*, including modelling of nutrient leaching from soil after different types of fertilizers have been applied. This would require a much more sophisticated model than was used here.

5.4.2 Scoring and weighting

As was noted by the stakeholders at the second workshop, the scoring of *acceptance* could be done in various ways. The score can be very different depending on what perspective and aspects are considered. As presented in 5.3.7, the *acceptance* score could affect the total score if using the average weights from the workshop. The scoring performed by one group led to better performance of Alt 3S Source-separation over Alt 1S Reject water. However, when looking at the large range of scores for the Alt 3S Source-separation in Figure 18, and the fact that the sustainability score is negative in some cases, the fact that Alt 3S Source-separation outperformed Alt 1S Reject water in one instance is perhaps not a significant result.

The scoring for the quantitative criteria is based on intervals of 20%, as presented in chapter 5.3.7. If choosing more narrow intervals, for example 10%, the scoring would change. For instance, the *eutrophication potential* in alt 2S Nutrient extraction is 38% lower than in baseline, just below the limit for a score 2 instead of a score 1. However, there is a consideration of uncertainties in calculations to be considered. Choosing a too narrow interval could also lead to uncertain results.

For the weighting of criteria, the idea was to have stakeholders assign weights based on their personal opinions and prioritization, so the variation in weighting was expected. Perhaps, the most important result regarding the sustainability score and weightings is that for some cases the total score was negative for Alt 3S Source-separation. For a decision-support context, this could have great significance. It is also clear that for all weightings the stakeholders made, Alt 2S Nutrient extraction outperforms Alt 1S Reject water.

5.5 Conclusions

The Alt 2S Nutrient extraction received the highest sustainability score followed by the Alt 1S Reject water system. Both performed better than the baseline system. The Alt 3S Source-separation received a higher sustainability score than the baseline system when the average stakeholder weights for the criteria was used. However, some of the stakeholder's weightings of the criteria resulted in the Alt 3S Source-separation system receiving a negative score, suggesting that the system could be less sustainable than the baseline system. In contrast, the same system in the Fyris case study received the overall highest score. It is important to note however that there are differences in the systems between the two vase studies and these could explain the differences in results. For the quantitative criteria especially, the system boundaries and assumptions affect the outcome and changing these could potentially lead to a different outcome. The results should be viewed in context of this.

6 DISCUSSION AND CONCLUSIONS

In both Fyris and Słupia the design of Alt 2 Nutrient extraction and Alt 3 Source-separation were comprised of essentially the same ecotechnologies. The differences were that sludge was stored in Fyris for Alt 2 Nutrient extraction and incinerated in Alt 3 Source separation while the sludge was composted in both systems in Słupia. The degree of source-separation also differed between the case-studies: 14% of wastewater was source-separated in Słupia while it was 37% in Fyris. These differences could explain why the system Alt 3 Source-separation got the highest overall score for Fyris while it got the lowest in Słupia. Additionally, the stakeholders scored *acceptance* of this system as -2 in Słupia while in Fyris stakeholders scored it 1. This shows that local context and stakeholder participation is an important part of sustainability assessments.

For the Fyriså case study, it is worth noting that in none of the stakeholder’s weightings used did any recovery system get a lower score than the baseline, meaning that they are all more sustainable alternatives. For the Słupia case study on the other hand, the Alt 3S Source-separation system got a sustainability score lower than the baseline system for some of the stakeholder’s weightings.

In the Vantaanjoki case study, anaerobic digestion of substrates got the highest sustainability score using average weights from the stakeholder workshop. However, the system alternative with pyrolysis of horse manure and grass and urea hygienization of blackwater got almost as high score. Both these alternatives got much higher scores than the alternative with composting, which was the baseline system. This indicates that both anaerobic digestion, and pyrolysis and urea-hygienization are more sustainable options for management of horse manure, waste-grass and blackwater.

It would be interesting to apply the Vantaanjoki case study to the Fyris and Słupia catchment areas, and the other way around. With a focus for resource recovery, it is natural to focus on the concentrated sources of carbon and nutrients, i.e. waste. However, if the focus were to be on general reduction of pollution and eutrophication, one might want to focus on the diffuse sources. Technologies and practices to manage such sources of pollution were not included in the systems studied in this project due to difficulties in designing system alternatives that were comparable even with different functions and inputs. Diffuse sources of eutrophication tend to originate from agriculture and constitute the major contribution to eutrophication. Therefore, it would be interesting to perform such a sustainability assessment.

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8 APPENDIX – REVIEW OF SUSTAINABILITY CRITERIA

Sustainability criteria is a wide definition, with equally wide areas of implementation. Sustainability criteria can be used in assessment or evaluation of sustainability (Hellström *et al.* 2000), such as a multi-criteria assessment (MCA) (Milutinovic *et al.*, 2014). Sustainability criteria have been used for various purposes, including management of wastewater and in agriculture. Sustainability criteria are often used as the base for MCA, also called multi-criteria decision analysis (MCDA). Sustainability criteria were searched for in the scientific literature. A list of criteria was compiled from several studies for wastewater (Table A1) and agriculture (Table A2) applications. From this list, criteria that were deemed appropriate for the scope of the case study sites were selected.

Table A1. Sustainability criteria used in scientific literature to assess sustainability of wastewater systems

Criteria	Reference examples
Environmental	
Water emissions	Hellström *et al.* (2000); Balkema *et al.* (2002); Diaper & Sharma (2007); Kalbar *et al.* (2012); Woltersdorf *et al.* (2018)
Air emissions	Hellström *et al.* (2000); Palme *et al.* (2005); Kalbar *et al.* (2012)
Impact on biodiversity and land fertility	Balkema *et al.* (2002)
Emissions to land	Hellström *et al.* (2000); Balkema *et al.* (2002); Palme *et al.* (2005); Diaper & Sharma (2007); Molinos-Senante *et al.* (2014); Woltersdorf *et al.* (2018)
Resource recovery	Balkema *et al.* (2002); Palme *et al.* (2005); Diaper & Sharma (2007); Molinos-Senante *et al.* (2014)
Use of energy/natural resources	Hellström *et al.* (2000); Balkema *et al.* (2002); Palme *et al.* (2005); Diaper & Sharma (2007); Molinos-Senante *et al.* (2014); Marques *et al.* (2015); Woltersdorf *et al.* (2018)
Land requirement	Balkema *et al.* (2002); Kalbar *et al.* (2012); Molinos-Senante *et al.* (2014)
Economic	
Total costs	Hellström *et al.* (2000); Balkema *et al.* (2002); Palme *et al.* (2005); Diaper & Sharma (2007); Kalbar *et al.* (2012)
Annual costs	Molinos-Senante *et al.* (2014); Woltersdorf *et al.* (2018)
Capital costs	Molinos-Senante *et al.* (2014); Marques *et al.* (2015); Woltersdorf *et al.* (2018)
Work demand	Hellström *et al.* (2000); Balkema *et al.* (2002); Diaper & Sharma (2007); Kalbar *et al.* (2012); Woltersdorf *et al.* (2018)
Social	
Acceptance	Hellström *et al.* (2000); Balkema *et al.* (2002); Palme *et al.* (2005); Diaper & Sharma (2007); Kalbar *et al.* (2012); Molinos-Senante *et al.* (2014); Marques *et al.* (2015); Woltersdorf *et al.* (2018)
Awareness and participation	Balkema *et al.* (2002); Kalbar *et al.* (2012); Marques *et al.* (2015)

Institutional requirements/capacity	Balkema *et al.* (2002); Marques *et al.* (2015); Woltersdorf *et al.* (2018)
Promoting sustainable behaviour	Kalbar *et al.* (2012)
Policy and legal issues	Marques *et al.* (2015); Woltersdorf *et al.* (2018)
Health	
Work environment	Hellström *et al.* (2000); Balkema *et al.* (2002); Palme *et al.* (2005)
Health risk	Hellström *et al.* (2000); Balkema *et al.* (2002); Palme *et al.* (2005); Diaper & Sharma (2007); Woltersdorf *et al.* (2018)
Technical	
Flexibility	Hellström *et al.* (2000); Balkema *et al.* (2002); Kalbar *et al.* (2012); Marques *et al.* (2015)
Reliability	Hellström *et al.* (2000); Balkema *et al.* (2002); Palme *et al.* (2005); Diaper & Sharma (2007); Kalbar *et al.* (2012); Molinos-Senante *et al.* (2014); Marques *et al.* (2015); Woltersdorf *et al.* (2018)
Robustness	Hellström *et al.* (2000); Balkema *et al.* (2002); Kalbar *et al.* (2012); Woltersdorf *et al.* (2018)
Lifetime	Balkema *et al.* (2002); Kalbar *et al.* (2012); Woltersdorf *et al.* (2018)
Compatibility with existing infrastructure	Diaper & Sharma (2007)

Table A2. Sustainability criteria used in scientific literature to assess sustainability of agricultural systems

Criteria	Reference
Environmental	
Fertiliser use	Carof *et al.* (2013); Latruffe *et al.* (2016)
Land use	Carof *et al.* (2013); FAO (2013); Latruffe *et al.* (2016)
Biodiversity	Carof *et al.* (2013); FAO (2013); Latruffe *et al.* (2016); Scharfy *et al.* (2017)
Resource use	Carof *et al.* (2013), Latruffe *et al.* (2016), FAO (2013)
Water use	Carof *et al.* (2013), Scharfy *et al.* (2017) / FAO (2013)
Air emissions	Latruffe *et al.* (2016), Scharfy *et al.* (2017), Carof *et al.* (2013), FAO (2013)
Soil effects	Latruffe *et al.* (2016), Scharfy *et al.* (2017), Carof *et al.* (2013)
Pesticides	Carof *et al.* (2013), Latruffe *et al.* (2016)
Water emissions	Scharfy *et al.* (2017), FAO (2013), Carof *et al.* (2013)
Animal welfare	FAO (2013)
Economic	
Productivity	Latruffe *et al.* (2016), Carof *et al.* (2013)
Subsidies	Carof *et al.* (2013), Latruffe *et al.* (2016)
Total costs	Carof *et al.* (2013), Scharfy *et al.* (2017)
Investment costs	Scharfy *et al.* (2017), FAO (2013)
Employment	Carof *et al.* (2013)
Product quality	FAO (2013)
Local economy	FAO (2013)

Amortization time	Scharfy *et al.* (2017)
Stability	FAO (2013), Latruffe *et al.* (2016)
Multifunctionality	Latruffe *et al.* (2016), Latruffe *et al.* (2016)
Quality of products	FAO (2013), Latruffe *et al.* (2016)
Social	
Livelihood	Latruffe *et al.* (2016), FAO (2013)
Acceptance	Latruffe *et al.* (2016), Scharfy *et al.* (2017)
Equity	Latruffe *et al.* (2016), FAO (2013)
Cultural and aesthetic values	Latruffe *et al.* (2016), FAO (2013)
Continuity	Scharfy *et al.* (2017), Latruffe *et al.* (2016)
Applicability	Scharfy *et al.* (2017)
Local economy	Latruffe *et al.* (2016)
Quality of products	Latruffe *et al.* (2016)
Uncertainties in crop cultivation	Carof *et al.* (2013)
Corporate ethics	FAO (2013)
Accountability	FAO (2013)
Participation	FAO (2013)
Rule of law	FAO (2013)
Holistic management	FAO (2013)
Health	
Health	Carof *et al.* (2013), FAO (2013)
Working conditions	Latruffe *et al.* (2016), FAO (2013), Scharfy *et al.* (2017)

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