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Improved life cycle assessment of wastewater and sludge management with resource recovery

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Abstract

Around the world every day, large amounts of wastewater are treated before release, to avoid impacts on humans and the environment. The treatment requires resources in the form of energy and chemicals, and it generates large amounts of sewage sludge, however, it can also serve as a source of energy, nutrients and carbon. These valuable resources can be recovered in many ways, including in the form of biogas, or through the use of sludge in agriculture or even, potentially, in form of biopolymer raw material.

Life cycle assessment (LCA) can be used to quantify the life cycle impact of wastewater and sludge management with resource recovery, on humans and the environment, in order to evaluate their environmental performance and avoid sub-optimisation. LCAs of such systems face different types of methodological problems. This thesis focusses on two such problems.

The first research topic concerns how to divide the environmental impact that results from a wastewater treatment process with the simultaneous production of a valuable by-product. Methodologies exist for handling such general situations, however, some properties inherent to wastewater and sludge management may result in complex allocation problems. This research identified the LCA of a system with wastewater treatment and simultaneous polyhydroxyalcanoate (PHA) production as particularly challenging, if PHA was considered as the main product. Three partly new allocation approaches were evaluated, and the choice of approach was found to influence the LCA results.

A second research topic concerns the potential importance of assessing the risks of the pathogens that exist in wastewater and sludge management systems, which is not currently done within the LCA framework. This research has found that these risks are potentially important compared to other impacts on human health, both for wastewater and sludge management systems where sludge is incinerated or used for agricultural purposes.

Keywords: LCA, wastewater treatment, sludge treatment, sludge handling, biosolids, resource utilisation, allocation, pathogen risks

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I would also like to thank Lic. Robin Harder, Dr. Fernando Morgan-Sagastume and Dr. Alan Werker, the co-authors of the papers on which this thesis relies, for fruitful discussions and support.

In my daily work, lunch and coffee breaks with the people at Chemical Environmental Science, and Forest Products and Chemical Engineering are highlights. I would especially like to thank many of my PhD student colleagues for daily discussions on everything from thesis writing to life in general.

Last but not least, I would like to thank family and friends for their interest in my studies and their supporting comments. I would especially like to thank Marie and Stefan Heimersson and Anders Wallmark for always being there for me.

Göteborg, February 2014

Sara Heimersson

List of Publications

This thesis is based on the research work presented in the following papers, which are referred to in the text by roman numerals. Manuscripts of the papers are appended at the end of the thesis.

I. Heimersson, S., Morgan-Sagastume, F., Peters, G. M., Werker, A. & Svanström, M. (2013) Methodological issues in life cycle assessment of mixed-culture polyhydroxyalkanoate production utilising waste as feedstock. Accepted for publication in New Biotechnology.

II. Heimersson, S., Harder, R., Peters, G.M. & Svanström, M. (2014) Including pathogen risks in life cycle assessment of wastewater management. Part 2: Quantitative comparison of pathogen risk to other impacts on human health. Submitted to The International Journal of Life Cycle Assessment.

Work related to the thesis has also been presented in the following publications.

A. Harder, R., Heimersson, S., Svanström, M. & Peters, G.M. (2014) Including pathogen risks in life cycle assessment of wastewater management. Part 1: Estimating the disease burden associated with pathogens. Submitted to The International Journal of Life Cycle Assessment.

B. Svanström, M., Bertanza, G., Bolzonella, D., Canato, M., Collivignarelli, C., Heimersson, S., Laera, G., Mininni, G., Peters, G., Tomei, M. C. (2013) Method for technical, economic and environmental assessment of advanced sludge processing routes. Accepted for publication in Water Science and Technology.

C. Sandin, G., Clancy, G., Heimersson, S., Peters, G., Svanström, M. & ten Hoeve, M. (2014) Making the most of LCA in technical inter-organisational R&D projects. Accepted for publication in Journal of Cleaner production.

D. Heimersson, S., Svanström, M & Peters, G. (2013) Life cycle assessment of sludge processing. Book chapter in Effective sewage sludge management: Minimization, recycling of materials, enhanced stabilisation, disposal after recovery, edited by Mininni, G., Rome, Italy: IRSA – Instituto di Ricerca sulle Acque.

E. Heimersson, S., Svanström, M. & Peters, G. (2013) Methodological issues in LCA of wastewater treatment combined with PHA biopolymer production. Paper at the conference Life Cycle Management 2013 in Göteborg, Sweden.

F. Heimersson, S., Svanström, M & Peters, G. (2012) Environmental performance of new wastewater and sludge treatment routes compared to conventional approaches. Paper at the European Waste Water Management Conference and Exhibition in Manchester, UK.

Contribution report

Paper I

The author wrote the article and did the modelling, with feedback from all co-authors.

Paper II

The author wrote the main part of the article and did the modelling for the results presented, with some numerical input from Lic. Robin Harder and feedback from all co-authors.

List of abbreviations

AP	acidification potential
COD	chemical oxygen demand
DALYs	disability-adjusted life years
EP	eutrophication potential
EU-15	the 15 member states that had joined EU 1^{st} of January 1995
EU-25	the 25 member states that had joined EU 1^{st} of May 2004
EU-27	the 27 member states that had joined EU 1^{st} of January 2007
GWP	global warming potential
HTP	human toxicity potential
IRP	ionising radiation potential
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
PHAs	polyhydroxyalcanoates
ODP	ozone depletion potential
POFP	photochemical oxidant formation potential
ROUTES	project ROUTES - Novel processing routes for effective sewage sludge management
SCWO	super-critical water oxidation
VFAs	volatile fatty acids
WO	wet oxidation
WWT	wastewater treatment

WWTP	wastewater treatment plant

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1 Introduction

We live in a world with planetary boundaries, but with a steadily increasing human population. In 2013, the world population reached 7.1 billion people, unevenly distributed over the globe (Population Reference Bureau, 2013). Each person uses between 35-90 litres of water per day (Metcalf & Eddy Inc et al., 2004), of which a large share ends up as wastewater as a result of direct (e.g. household) and indirect (e.g. industrial) water usage. Historically, in areas with a low population density, the direct release of wastewater is a minor problem. Urbanisation, in combination with a growing world population, has created the need to collect the increasing amount of wastewater and treat it, in order to avoid the risk of contagion and negative environmental impacts.

Collected wastewater contains a mixture of sand, gravel, organic material, nutrients, heavy metals, medications (including hormones) and pathogens, among other things. Wastewater treatment is, therefore, necessary, primarily in order to avoid problems such as eutrophication in the local environment. Today most urban wastewater is treated in one way or another. Wastewater treatment plants (WWTPs) function as societal kidneys: They receive wastewater mixed with everything that society wants to get rid of, and treat it in order to obtain water quality that is considered high enough to be released e.g. to the sea.

1.1 Research context

WWTPs have the potential to reduce most types of pollutants by 90% (LeBlanc et al., 2008), but require the investment of resources in the form of energy and chemicals. In addition, emissions to the air occur in the WWTPs, and large amounts of sewage sludge (in this thesis denoted sludge) are generated, containing most of the substances removed from the wastewater during treatment. More advanced treatment of the water effluent, consequently, leads to higher amounts of sludge being generated (Metcalf & Eddy Inc et al., 2004). In EU-27, about 10 million tonnes of dry solids (DS) of sewage sludge is generated annually (Milieu Ltd et al., 2010). The handling of these huge amounts of sludge generated in the world is a much debated issue. There are several possibilities for sludge disposal. Historically, sludge dumping in managed or unmanaged landfills or directly in the oceans has been seen as feasible options, and these alternatives are still used to varying extents. However, these alternatives are criticised, not only for their direct contribution to climate change (due to methane from the anaerobic degradation of organic material in landfills) and eutrophication (sludge dumping in the ocean is really in many cases just a matter of moving the problem away from the shores), but also because of the lost energy, nutrients and organic material in the sludge. The use of sludge in agriculture is one common option that recycles both nutrients and organic material. The United Nations Human Settlements Programme (2008) lists land reclamation, horticulture and landscaping, forestry, industrial processes (e.g. use in cement kilns), resource recovery (e.g. struvite) or energy recovery (e.g. anaerobic digestion that generates biogas, or incineration combined with energy recovery) as other potentially beneficial ways of using sludge.

Modern agriculture relies on the use of mineral nitrogen and phosphorus fertilisers to ensure high yields. Mineral phosphorus is a mined resource, and as such is limited, a fact that the BBC News recently highlighted (Knight and Bowler, 2013). Rockström et al. (2009) have suggested a framework based on nine "planetary boundaries", which define a "safe operating space for humanity with respect to the Earth system". Nitrogen and phosphorus cycles are described as one aspect of such a system in which natural flows are disturbed. Human interference with the nitrogen cycle has, according to Rockström et al., already largely exceeded this safe operating space, and human interference with the phosphorus cycle will also soon reach the same level. Recovery of the nutrients in sludge can be seen as one important way of closing environmental nutrient cycles. Nutrient recovery can be achieved either by directly recycling treated sludge to agricultural fields, and thus replacing some of our need for agricultural mineral fertilisers, or by extracting nutrients (mainly phosphorus) from the sludge and applying these nutrients directly on fields. Agricultural sludge use also fulfils the aspiration to recover organic material from the sludge, which could be especially relevant in areas with poor soils (e.g. with limited water retention capacity (Peters and Rowley, 2009)). Despite these potential advantages, agricultural sludge use is questioned, and in some countries even prohibited, mainly due to perceived potential risks related to its content of heavy metals, organic micropollutants (Bengtsson and Tillman, 2004), and pathogens (such as viruses and bacteria). Due to the large number of potential benefits and risks, there is a need for a holistic assessment of the overall impacts on humans and the environment from systems that involve wastewater treatment combined with agricultural sludge use. A holistic assessment is particularly vital in comparisons of wastewater treatment (WWT) scenarios with different sludge end-use situations. In addition, problems may be experienced when comparing the environmental performance of different wastewater management systems with different types of resource utilisation, i.e. it is not always clear if or how a studied system should be credited for the by-products that result from utilisation of the WWT resource.

My research focuses on the environmental assessment of wastewater and sludge management systems, including sludge end-use, using life cycle assessment (LCA). A special focus is on LCA methodological difficulties when it comes to assessing systems in which resource utilisation occurs. In an LCA, the studied system should preferably include the whole life cycle of the studied product or service, but in practice, methodological shortcomings, lack of data and time restrictions limit such assessments. The research presented in this thesis demonstrates that the coverage of relevant impacts on humans and the environment is lacking in LCAs of wastewater and sludge management systems. This research has been conducted by evaluating the potential impact of pathogen risk, and comparing it to other impacts on human health more commonly assessed in LCA, something which has not been assessed in previous LCA studies. The presented research also discusses methodological problems related to the assessment of wastewater and sludge management systems that generate one or more by-products in addition to the wastewater treatment service. The research shows how the overall environmental burden of a studied system can be divided between wastewater treatment and the product or service resulting from the utilisation of the WWT resource.

The research presented here has been performed as part of an EU project in which LCA has been used for assessing innovative sludge treatment scenarios as input for process development: the project ROUTES (Novel processing routes for effective sewage sludge management).

1.2 Guide for readers

This thesis is a consolidated thesis. As such it consists of two main parts: one thesis summary that presents the work that constitutes the basis for my licentiate degree, and a second part that consists of the articles on which the thesis is based (Paper I and Paper II). An additional six publications (Publications A-E), which present findings from my research are referred to as well. These include conference papers, journal papers and a book chapter (see List of Publications).

Chapter 2 describes the background of the research presented here: the reasons for performing the described research, the project that constitutes the context within which the research has been conducted, the method life cycle assessment (LCA) and a literature review of relevant previous research. Chapter 3 describes the overall aim of the performed research and defines two specific research questions that this thesis sets out to answer. The chapter also includes a description of the methodology used. Chapter 4 summarises the appended papers and discusses research findings and limitations in relation to the two research questions. Chapter 5 presents the conclusions from the research, and Chapter 6 discusses future research needs or opportunities, based on the findings in the thesis.

2 Background and Methods

This chapter puts the research presented here into a context: it describes general wastewater treatment, different possible forms of resource utilisation from wastewater or sludge, the project ROUTES within which this research has been conducted, and the LCA method, with a special focus on the assessment of wastewater and sludge management systems.

2.1 Wastewater treatment

The content of municipal wastewater reflects societal activities: whatever we put down the drain will be present in the wastewater that arrives at the WWTP. Human urine and excreta add organic material, nutrients like nitrogen, traces or decomposition products of medicines, hormones from contraceptives and microorganisms to wastewater. Other household activities, like laundering, add phosphates and other chemicals to wastewater. Where municipal wastewater and surface water are collected in a combined pipe system, road traffic provides yet other pollutants. The list could be made longer, but these examples illustrate the complex composition of wastewater.

The collected wastewater is treated to control the quality of the effluent water released to a recipient, mainly in terms of organic material and nutrients. The purpose of this is primarily to avoid eutrophication. Wastewater treatment can occur in a wide variety of ways. Generally, wastewater treatment consists of the treatment of incoming wastewater in the waterline, resulting in treated water that is released to a recipient, and sludge that is further treated in the sludge line, see Figure 1. In the waterline, sand and gravel are first removed from the wastewater, and then primary treatment and sedimentation remove smaller particles, resulting in a primary sludge. Secondary treatment (with or without nutrient removal), including sedimentation that separates the sludge from the water, generates a secondary sludge. In more advanced WWTPs, additional treatment steps may follow, or may be integrated with the other steps, before the wastewater is released to the environment. Sludges are further treated in the sludge line, either separately or mixed, e.g. in order to reduce the volume of sludge and to reduce the concentration of organic micropollutants and pathogens. The treatment typically consists of some kind of thickening, stabilisation processes and finally dewatering before transportation to the final sludge disposal or end-use, either on site or off site. Extensively treated sludge is sometimes called biosolids.

Kelessidis and Stasinakis (2012) have shown that the amount of sludge deposited in landfills decreased in Europe between 1990 and 2005. Sludge incineration almost doubled during the same time period, mainly in the EU-15 countries. Sludge reuse (mainly the agricultural utilisation of sludge and compost) has seen a slight increase. During the assessed period, legislation prohibiting ocean dumping of sludge went into force in the European Union (Kelessidis and Stasinakis, 2012). In 2008, 10% of all sludge in EU was landfilled, 30% was incinerated; 45% went to agricultural use and 15% was treated in other ways (Finnson, 2011).

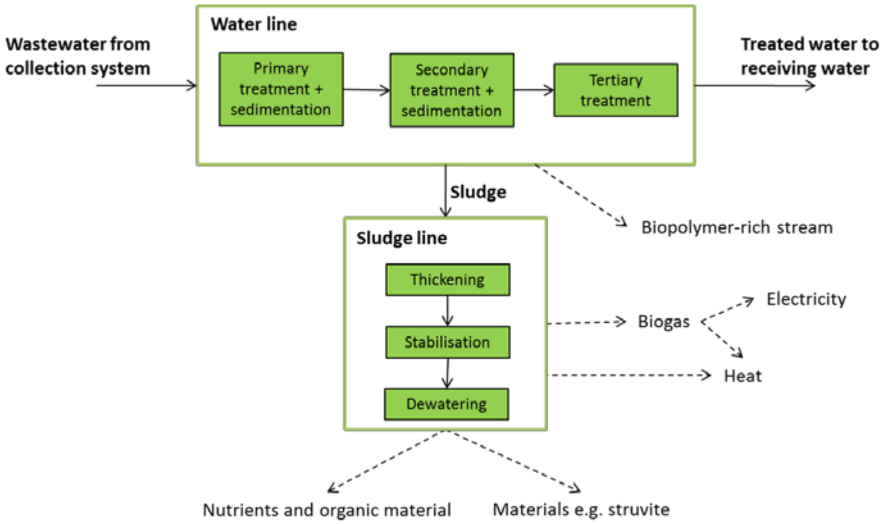

Figure 1. Schematic illustration of the basics of a common wastewater treatment plant, and examples of potential resource recovery.

2.2 Resource utilisation from wastewater treatment

The utilisation of resources from wastewater treatment includes possibilities for recovering resources from wastewater or from sludge during processing in the WWTP. The notion of resource utilisation includes recovering resources directly from the wastewater or sludge during treatment or from different end-uses of sludge that have left the WWTP. This can be in the form of energy, nutrients and organic matter, or materials. In addition to the list of potential ways of utilising resources from sludge provided in Section 1.1, Wang et al. (2008) provide a more detailed review of different alternative techniques for recovering resources from sludge, such as land application of biosolids to recover nutrients and organic material; anaerobic digestion; mono-incineration; co-combustion; supercritical water oxidation (SCWO) or pyrolysis for energy recovery; the reuse of incineration ash for construction materials or as a phosphorus resource. It is also possible to utilise the carbon resource directly from the wastewater during treatment, as is discussed for biopolymer production in this section.

2.2.1 Energy recovery

Biogas production through the anaerobic digestion of sludge is common in WWTPs. Biogas generally contains about 60% methane and 40% carbon dioxide (Wang et al., 2008), and can either be sold directly to be used as a fuel, or burnt on site, generating only heat or both electricity and heat. The energy can then be used internally at the plant or sold, depending on the local situation, e.g. the available infrastructure for delivering and trading electricity and heat. During anaerobic digestion, sludge becomes stabilised and its volume is reduced, which means there is less sludge to transport from the WWTP and dispose of, and a sludge that is easier and safer to handle.

The incineration of sludge is common in many European countries. Incineration either takes place on site or off site, as mono-incineration or co-incineration with e.g. municipal waste or coal. In some cases, additional fuel is needed for the incineration of sludge because of its high water content. Heat can potentially be recovered from the process. For a thorough review of different incineration techniques and their benefits and drawbacks, see Werther and Ogada (1999). It is possible to incinerate the residual sludge after anaerobic digestion, but the calorific value of this sludge is lower. In contrast, the dewaterability of sludge has improved (Werther and Ogada, 1999).

Other techniques for potential energy recovery also exist. The wet oxidation (WO) scenario assessed in ROUTES generates energy. Svanström et al. (2005) have described a supercritical water oxidation (SCWO) system in which the energy of the reactor effluent is used in a district heating system.

2.2.2 Nutrients and organic matter recovery

Nutrients, mainly nitrogen and phosphorus, in sludge can be utilised through the land application of treated sludge, either for agricultural or landscaping purposes (such as parks and golf courses). It is also possible to recover phosphorus by extracting phosphorus from wastewater to be used for agricultural purposes, e.g. precipitated as struvite, or from sludge, e.g. removed during or after treatment involving incineration or super-critical water oxidation (SCWO) (Linderholm et al., 2012, Svanström et al., 2004).

The recovery of organic matter is another potential benefit of the use of sludge for agricultural purposes, at least in areas with poor soils. Several literature sources, (Epstein, 1975, Ojeda et al., 2003, Wang et al., 2008), have concluded that sludge has the potential to improve the physical properties of soil, as it improves soil structure, decreases bulk density and increases soil porosity, and improves soil moisture retention and hydraulic conductivity.

Sewage sludge also contains heavy metals, drugs, organic micropollutants, microorganisms and other substances potentially harmful to humans and the environment. Owing to these risks, or the current uncertainty regarding the extent of these risks, the land application of treated sewage sludge for agricultural purposes is heavily debated in many countries, and has been so for many years.

In Sweden, sludge use for agricultural purposes is allowed, but restricted according to Ordinance SNFS 1994:2 ”Kungörelse med föreskrifter om skydd för miljön, särskilt marken, när avloppsslam används i jordbruket”. The ordinance regulates for which purposes sludge can be used (e.g. use on pasture land is prohibited), the sludge amounts that are permitted to be used per area for a certain time period, and the permitted load of heavy metals. Nevertheless, the agricultural use of sludge is heavily debated in Sweden. The Swedish EPA has been positive to the continued use of sludge in agriculture, but advises stronger legislation and lower limits of permitted contaminants in the sludge that is used for agricultural purposes (Naturvårdsverket, 2013). The Swedish Chemicals Agency has expressed concerns regarding cadmium flows to agricultural fields through sludge land application (Kemikalieinspektionen, 2011). In recent years, a number of newspaper articles have brought public attention to this topic by bringing forward concerns regarding the contamination of agricultural fields through sludge (Göteborgs-Posten, 2013, Alborg, 2013). Bengtsson and Tillman (2004) provide a description of the Swedish sludge debate up until 2004.

Agricultural sludge use differs between the countries in the European Union. As in Sweden, the subject is publicly debated. In some countries, a large share (around 50%) of the generated sludge is land-applied (e.g. Denmark, United Kingdom), while others do not land-apply sludge at all (e.g. the Netherlands and Greece). In a number of regions, agricultural sludge use is even prohibited, such as in the Netherlands and parts of Germany (Milieu Ltd et al., 2010).

In Australia sludge (biosolids) and the organic matter it contains are in high demand and most of the material (69%) is used in agriculture, forestry or land rehabilitation (www.biosolids.au/bs-autralia.php, accessed 2014-02-04).

2.2.3 Materials recovery

Materials for a number of different applications can be produced from wastewater and sludge, or are under development. Some examples of these are building and construction materials (Tay and Show, 1997), adsorbent materials (Otero et al., 2003), biopesticides (Vidyarthi et al., 2002) and materials to improve cement production (Husillos Rodríguez et al., 2013).

Another example of an application is utilising the volatile fatty acids (VFAs) in the organic material in the influent wastewater to produce a biopolymer-rich stream from which the polymer polyhydroxyalcanoate (PHA) can be recovered (Philip et al., 2007). The biopolymer-rich stream is generated in the waterline in a modified WWTP, followed by a PHA recovery step, either on site or off site. This process, which is novel and tested only on the pilot scale (Dias et al., 2006, Nikodinovic-Runic et al., 2013), is one of the technologies studied in ROUTES.

2.3 Project ROUTES

The research presented in this thesis has been conducted within the project ROUTES: Novel processing routes for effective sewage sludge management. The project is a part of the European Union's seventh framework programme under the theme Innovative system solutions for municipal sludge treatment and management. Within ROUTES, the development of process technologies for wastewater and sludge treatment is performed with two main objectives:

1) to improve sludge quality to enable agricultural use by producing a clean and stabilised sludge with specific attention to organic micro-pollutants, hygienic aspects and properties that can have an impact on soil, and
2) to minimise the volume of sludge to be disposed of by applying innovative technical solutions based on different approaches, either on the water or sludge treatment lines.

These main objectives are strived for by means of the development of process techniques implemented in WWTPs with four different aims, as illustrated in Figure 2. Depending on local conditions and raw wastewater quality, the preferred end use of sludge might vary. To be able to reach the main aims of the project, the studied process technologies are introduced to conceptual WWTPs that are anticipated to experience different types of problems. Reference scenarios are modelled, including the conceptual WWTPs, and compared to new scenarios in which the studied process technologies are implemented.

As part of ROUTES, the environmental, technical and economic feasibility of the investigated new scenarios are compared to reference scenarios. The methodology used for the techno-economic-environmental assessment is described in Publication B. The environmental assessment of the studied wastewater and sludge management scenarios has been performed using the LCA method. LCA results for the studied systems can be found in Publications D and F. Paper I and Paper II present LCA methodological issues identified during the work with the environmental assessment performed in the project.

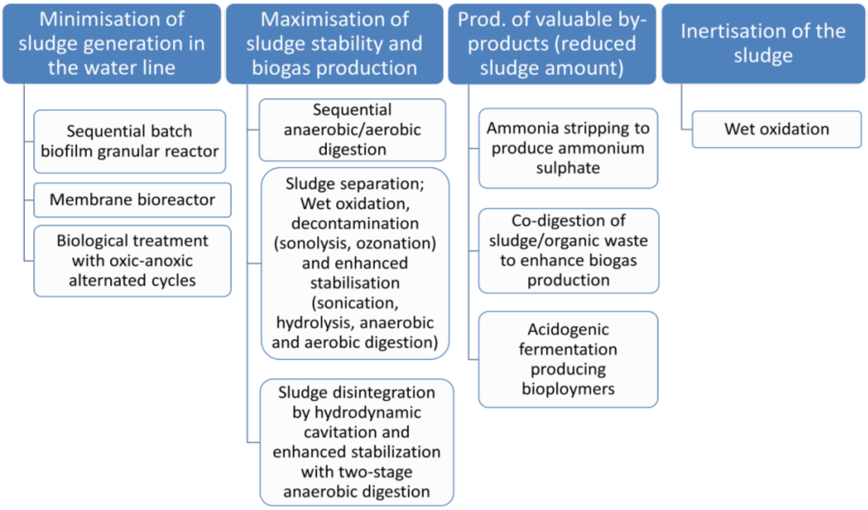

Figure 2. Four goals for sludge processing in ROUTES and the approaches/technologies studied to achieve those goals.

Both the possibilities of and difficulties with LCA work of this type, in large inter-organisational projects, are discussed in Publication C. The publication highlights the importance of a well-motivated role description for LCA in the planning of a project. The LCA work in ROUTES was carried out partly to guide the development of process technologies within the project, and partly to evaluate the achievements of the developed processes within the project from an environmental systems perspective. A third goal was to contribute to LCA knowledge.

ROUTES is a three-year project which started in 2011. Research partners from universities, research institutes and companies around Europe are involved in the work.

2.4 Life cycle assessment methodology

LCA is a useful method for the assessment of different environmental impacts (including impacts on human health) of the life cycle of a product or a service. The method is internationally accepted, and since the 1990s commonly applied (Baumann and Tillman, 2004, Peters, 2009). The methodology is standardised in ISO14040:2006 and ISO14044:2006. Further guidance on LCAs in a European context can be found in the International Reference Life Cycle Data System (ILCD) Handbook (European Commission Joint Research Centre, 2010).

In an LCA, the environmental impact connected to the life cycle of a product or a service is determined. Usually, LCA is carried out as an iterative process, following a certain procedure, as can be seen in Figure 3. The assessment is made based on an inventory of the physical flows into and out of a system, and calculated based on a functional unit, such as the treatment of 10 ML wastewater or treatment of 1,000 ton DS sewage sludge. The use of resources in and the emissions from the studied system are then translated into contributions to a number of environmental impact categories, such as global warming potential (GWP), eutrophication potential (EP) and human toxicity (HTP), to enable a holistic assessment of the environmental performance of a product or a service. A comparative assessment can be made to compare two products or services with the same function.

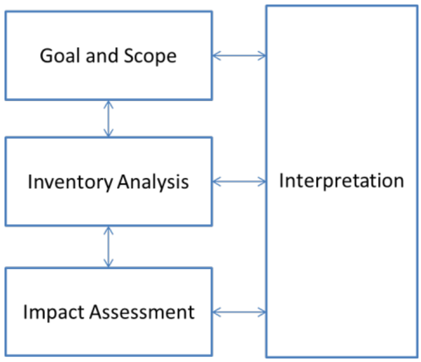

Figure 3. The four steps of a life cycle assessment.

Goal and scope definition. The aim of an LCA, the functional unit, the system studied, its geographic and time boundaries, and the limitations of the study are described in the first step of an LCA. This is called the goal and scope definition. This step also specifies which environmental impacts that the assessment intends to cover. The aim of the study is highly important, as it determines many choices that will be made throughout the assessment. The results of the LCA are, thus, dependent on the aim, and therefore, mainly answer the specific questions stated in the goal definition.

One of these important choices in an LCA is the handling of multifunctional systems. If a system generates several products (or services), there is a need to decide how large a share of the impact from the production process that each of the by-products are to be responsible for. A similar situation occurs if an input consumable to a system is produced in a multipurpose process, then the full impact caused by the production process should not necessarily burden the specific consumable. Problems like these are referred to as allocation issues. If possible, the production process is to be subdivided, and each flow connected to one specific product (European Commission Joint Research Centre, 2010), but this is usually only possible to a certain extent, either because some processes generate two or more products, or because of lack of disaggregated data on the studied system. The studied product can be seen to be responsible for the entire common production process, but many researchers would argue that this is not always fair, and it is common to either try to give the studied system a benefit for the by-product function (referred to as substitution or system expansion), or to divide (allocate) the impact between co-products. ISO 14044:2006 recommends avoiding allocation, as far as possible, and instead apply substitution. In general, when substitution is applied in LCA, a conventional product, or service, that fulfils the same function as the by-product or service of the system, is selected (thus, not necessarily the same type of product or service). The studied system is then given a benefit for the production of this replaced product or service that is avoided (and sometimes the use of the product or service, depending on the system boundaries).

If substitution is not a reasonable option, it means that allocation must be used, and thus cannot be avoided. The impact can be allocated between the products based on, e.g. mass, energy content or price. This would mean that the heaviest, most energy-rich or most valuable product is connected to a larger environmental burden. Pioneering work on allocation issues in LCA has been performed e.g. by Tillman et al. (1994).

Life cycle inventory. The second step of an LCA is the life cycle inventory (LCI) in which relevant physical flows into and out of the studied system are mapped. This may include resources into the system, and emissions from the system. The production of inputs to the system, such as electricity and consumables, are normally included in the inventory.

Life cycle impact assessment. In an life cycle impact assessment (LCIA), the flows identified in the LCI are characterised based on which environmental impacts they contribute to. By using characterisation factors, the different environmental impacts resulting from the studied system per functional unit can be quantified. Different characterisation methods commonly provide general fate-exposure models by which characterisation factors are generated that express how much each emission contributes to a certain impact. The total impacts per impact category can be calculated by summarising the contributions from the studied system to each impact category (see e.g. Goedkoop et al. (2013)).

Life cycle impacts can either be expressed with midpoint or end-point indicators. A midpoint method, according to the ILCD Handbook (European Commission Joint Research Centre, 2011), is "…a characterisation method that provides indicators for comparison of environmental interventions at a level of cause-effect chain between emissions/resource consumption and the endpoint level" (e.g. climate change expressed as kg CO_2 equivalents). An endpoint method, according to the same source, is "…a characterisation method/model that provides indicators at the level of Areas of Protection (natural environment's ecosystems, human health, resource availability) or at a level close to the Areas of Protection level" (e.g. climate change translated into its effect on human health, expressed as human years lost due to the climate change). Impacts are more commonly assessed using midpoint indicators. Translating impacts to endpoints introduces further uncertainties into the assessment.

Impact results at the endpoint level can be further aggregated into one single indicator, but such weighting is highly value-based and introduces large uncertainties into the assessment. The results can also be normalised, which implies that the results are related to the total environmental impact in a region so that the contribution (and thereby the significance) of the impact connected to the specific studied product or service can be determined (Baumann and Tillman, 2004).

Interpretation. The interpretation of LCIA results is important. It gives the audience of the LCA guidance in how to interpret the results based on how the problem is formulated and how the assessment has been performed, as stated in the Goal and Scope, and the choice of inventory data. This step often includes an uncertainty analysis of critical parameters.

2.5 Life cycle assessment of wastewater and sludge management systems

Beginning in the second half of the 1990s, a large number of studies have reported on LCAs of WWT or sludge treatment. Several extensive reviews have been published focusing on wastewater and sludge management systems (Corominas et al., 2013), sludge treatment systems (Yoshida et al., 2013) or with specific focus on wastewater treatment technologies (Larsen et al., 2007). The reviews partly cover the same material.

The boundaries of systems studied in published LCAs on wastewater and sludge treatment vary, as discussed by Lundin et al. (2000) and Corominas et al. (2013). Either the boundaries can include both wastewater and sludge treatment as well as sludge final use or disposal, as in Figure 4, or they can include one or several of these. The production and the collection of wastewater are commonly disregarded, but have been included in some studies (see e.g. Tillman et al. (1998), Remy and Jekel (2008) and Lundie et al. (2004)). The production and maintenance of capital goods, such as buildings and machinery, is also disregarded in a majority of the published studies on wastewater and sludge management systems. When these are included they are commonly found to be of less importance (Corominas et al., 2013, Peters and Rowley, 2009). The background system covers the production of energy and material inputs (e.g. chemicals) to varying extents.

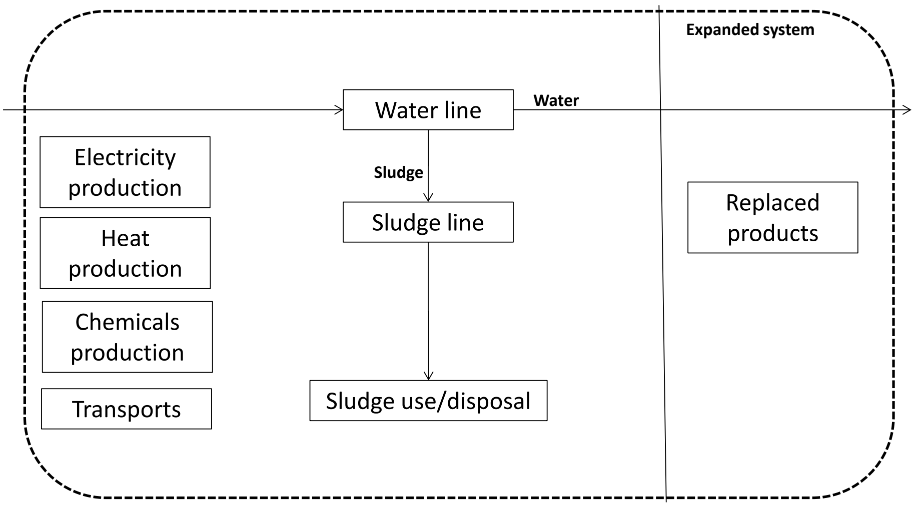

Figure 4. General wastewater and sludge treatment system. The process box “replaced products” shows that substitution is a common way of solving allocation issues in wastewater and sludge LCAs.

2.5.1 Allocation approaches applied in LCAs on wastewater management systems

A common allocation issue in LCAs on wastewater and sludge management systems is the allocation of impacts between a WWT service and a resource from the WWTP that is utilised, such as biogas. An allocation problem would also occur if an input to the studied system, e.g. a specific chemical, is produced in a multiproduct process. The first type of problem is the one that has attracted the most attention in LCA literature on wastewater and sludge management systems. Resource utilisation in wastewater and sludge management systems implies that a by-product or service is generated in the WWTP, which means that such systems almost always are multifunctional systems. Many studies can, therefore, be found in LCA literature that apply one or several of the allocation approaches described in Section 2.4 above.

In wastewater and sludge management LCAs, particular interest has historically been on allocation issues in multifunctional systems with WWT followed by agricultural sludge use. One of the earliest studies that credited the nutrient by-product function in such systems was Tillman et al. (1998), followed by Lundin et al. (2000). Both studies applied substitution (system expansion) by giving the studied system credit for the avoided use of mineral fertiliser, depending on the nitrogen and phosphorus levels in the sludge. Today, such substitution is the predominant way of handling multifunctionality in systems that provide agricultural utilisation of sludge, in addition to WWT, see, amongst others, Lundin et al. (2004), Johansson et al. (2008), Peters and Rowley (2009), Foley et al. (2010) and Hospido et al. (2010).

Another common by-product in WWTPs is biogas. In LCAs, the biogas is often assumed to be incinerated and to generate heat, or power and heat which are primarily used within the WWTP (Yoshida et al., 2013). Excess amounts are assumed to replace grid electricity and conventional heat production, depending on the availability of an infrastructure that enables such replacement. For example, biogas is replaced in this way in Publication D, and in a large number of the studies reviewed by Yoshida et al. (2013). It would also be possible to assume that this biogas will be used to replace natural gas as a fuel, which e.g. is the case at the WWTP in Gothenburg, Sweden (http://gryaab.se/default.asp?ulid=22&lid=3&show=1, assessed 2014-02-17).

2.5.2 Life cycle impact categories commonly assessed in wastewater management systems

Some examples of life cycle impact categories commonly assessed in LCAs on wastewater and sludge management can be seen in Figure 5 below. The most commonly assessed life cycle impact category in LCAs on wastewater and sludge management is global warming potential (GWP) (Corominas et al., 2013, Yoshida et al., 2013). GWP considers impacts from emissions of greenhouse gases on climate change, and is entirely based on emissions to air which are reasonably easy to include in life cycle inventories, and for which an internationally agreed-upon midpoint characterisation method exists (IPCC, 2007). Eutrophication potential (EP) and acidification potential (AP) are also very commonly assessed in around two-thirds of the studies reviewed by Corominas et al. (2013). Ozone depletion potential (ODP) and abiotic resource depletion (AD) were assessed in less than half of the studies reviewed by Corominas et al. (2013). Human toxicity potential (HTP) and ecotoxicity potential are slightly less often included in LCAs (Corominas et al., 2013, Yoshida et al., 2013, Peters and Lundie, 2001), and the specific characterisation methods used varies (Renou et al., 2008), owing to a lower degree of consensus on methodology in the scientific community. Inventory data on heavy metals and organic micropollutants are also lacking in many cases, as well as characterisation factors for many possibly relevant substances.

The environmental impacts to be assessed are ideally selected to reflect the interests of a variety of stakeholders who are responsible for, or affected by, the specific system under study. In practice, the choice of impact categories that can be assessed is often limited owing to the scarcity of methodologies and limited available data.

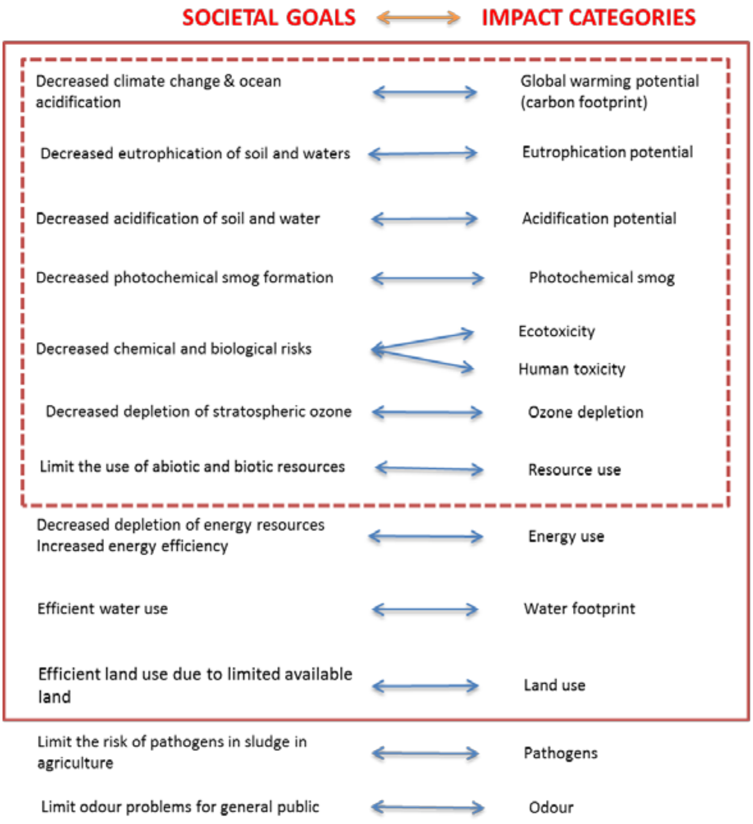

Figure 5. Societal goals and life cycle impact categories used to assess these. Impact categories sometimes assessed in LCAs are within the thick line. Commonly assessed in wastewater and sludge LCAs, according to reviews by Corominas et al. (2013) and Yoshida et al. (2013), are within the dashed line.

2.5.3 Identified methodological issues in life cycle assessment of wastewater and sludge systems

Despite that LCA methodology has been applied to evaluate the environmental performance of different wastewater and sludge management systems since the 1990s, and has a well described methodology, there is still a need for further development to address methodological difficulties related to systems that include the utilisation of recovered resources from wastewater and sludge.

Although a best practice has evolved in literature for many allocation issues in LCAs on wastewater and sludge management systems (e.g. how to account for the beneficial utilisation of nutrients when sludge is used for agricultural purposes, as discussed in Section 2.5.1), the assessment of systems with simultaneous WWT and recovered resource utilisation still faces challenges. The use of sludge on agricultural fields can potentially improve the organic matrix, and thereby the water-retention capacity of the soil, a by-product function that is not commonly accounted for in LCAs to this date. Peters and Rowley (2009) demonstrated the benefit of the increase in moisture retention of soil onto which sludge is applied within an LCA framework. Another issue is how to handle multifunctionality in systems in which WWT is considered to be a by-product, as could be the case in the mixed-culture production of PHA in WWTPs (discussed in Section 2.2.3), if PHA production is the studied function. The problem is largely a matter of finding a basis on which a replaced service can be calculated, or a basis on which an allocation can be founded.

Another methodological issue regards the life cycle impact categories assessed in wastewater and sludge management LCAs. The impact categories listed in Section 2.5.2 are very important and often give sufficient coverage of the environmental impacts of the LCAs of different systems. However, for some LCAs on wastewater and sludge management systems, further impact categories would be needed to cover the main concerns of stakeholders. As part of ROUTES, the importance to industry representatives of different impacts on humans and the environment was evaluated through a questionnaire at the ROUTES end-user conference on 25th of October 2012 in Rome, Italy. The study was performed in order to be used for the selection of impact categories in the LCAs performed within the project. The participants at the conference were asked to grade the importance of different impact categories from "not important" to "very important" to their organisation, on a six-grade scale. 24 of approximately 60 participants responded to the survey, and the result is shown in Figure 6. As can be seen in the figure, a majority of the respondents assessed pathogen risks and odour as important or very important, which is especially interesting as neither of these are currently assessed within the LCA framework. Impacts on humans and the environment from odours is a relatively unexplored area. Pioneer work within the field is ongoing, e.g. LCAs on pig manure in the Danish project Cleanwaste (Greg Peters, personal communication 2014-01-08). Pathogen risks can be assumed to be of specific interest in LCAs of systems that include the agricultural use of sludge. Pathogen risks are commonly quantified using quantitative microbial risk assessment (QMRA), but have, so far, not been assessed in LCAs. Generally, local and site-specific impacts are more challenging to assess using LCA, than those that provide effects on the global or regional level. As an LCA should ideally cover the impacts of major concern to its stakeholders, and as pathogen risk is a concern for stakeholders worried about human exposure through sewage sludge, it would be valuable to include pathogen risk in an LCA framework.

Figure 6 also reveals the potential build-up of the soil organic matrix when sludge is utilised in agriculture as important to many wastewater industry stakeholders. The carbon balance in the soil can, thus, be a relevant area for further improvement of LCA methodology.

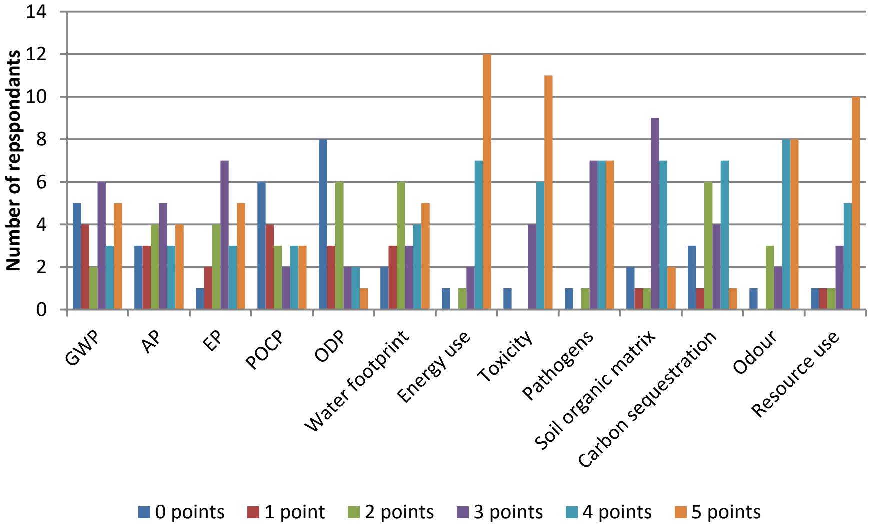

Figure 6. Response to stakeholder questionnaire evaluating the importance of different life cycle impacts in LCAs of wastewater and sludge management systems, according to industry and academia representatives that participated in the ROUTES end-user conference 2012-10-25 in Rome, Italy. The participants were asked to assess the importance of the different impacts for their organisation, from 0 points (not important) to 5 points (very important).

3 Aims and Approach

This thesis discusses some LCA methodological challenges investigated while performing LCAs on the technologies studied in the project ROUTES. The main findings are presented in Paper I and Paper II (see List of Publications) and are further discussed in this thesis summary.

3.1 Overall aim of research

The overall aim of my research is to improve LCA methodology and practice so that the methodology can provide useful guidance on environmental life cycle impacts, particularly as regards the management of wastewater and sludge for systems that utilise resources recovered from wastewater and sludge. The research presented in this thesis focuses on two research questions.

3.2 Research questions

Research question 1. Which allocation approaches are relevant and useful in resource recovery in wastewater and sludge management?

In Paper I, an LCA case study was performed for a system that utilises the carbon in wastewater to produce a biopolymer-rich stream from which PHA can be recovered. Special focus is on solving the allocation issue for the multi-purpose process when PHA is produced alongside the treatment of wastewater. This allocation is particularly problematic when a novel technology is studied, creating uncertainty about the usage and the price of the biopolymer product

Research question 2. Is it possible, is it important, and is it relevant, to include pathogen risks in LCAs of wastewater and sludge management?

LCIA methodology has, so far, mainly been able to consider potential life cycle environmental impacts in a generalised way and in a global context. Some recent or current efforts focus on LCIA methodology that can handle case-specific and site-specific impacts. Only recently has a framework for the inclusion of the toxicity impacts of chemicals gained acceptance (Rosenbaum et al., 2008). The reason for this can be assumed to be that toxicity is highly dependent on exposure assumptions and sensitivity of humans and the environment, which needed to be covered in an appropriate way in LCA. Another reason could be the fact that toxicity can be assessed by quantitative risk assessment, why the inclusion of toxicity impacts in LCA has not been considered as urgent as for other impacts. No LCA methodology has so far been applied for the assessment of life cycle pathogen risk to humans or the environment. The research presented in Paper II evaluates the importance of the inclusion of pathogen risk in an LCA, by comparing the pathogen risk assessed using QMRA methodology adjusted to have system boundaries consistent with LCA methodology (see Publication A), to other impacts on human health. The assessment was made for two WWTP model systems in which sludge was either used on agricultural fields or incinerated.

3.3 Overall methodological approach

The research presented in this thesis uses LCA theory and practice within the field of wastewater and sludge management in earlier scientific literature and specific case studies designed for the purpose of exploring the use of new methodological ideas. The specific areas of research focused on have been guided by needs identified during work within the project ROUTES.

Although the two appended papers both present research on potential improvement of LCA methodology, they have different areas of focus. While Paper I mainly focuses on allocation problems perceived in the goal and scope definition phase of LCA, Paper II deals with the scarcity of methodologies shortcomings for the characterisation of impacts in the LCIA step, see Figure 3.

4 Summary of Appended Papers and Discussion of Research Findings

As described earlier, this thesis is built on research presented in Paper I and Paper II. These papers contribute, in different ways, to improved LCA practice in assessments of wastewater and sludge management systems. This chapter summarises the findings in the appended papers, and discusses how the research contributes to answering the research questions defined in Chapter 3. It also contains a further discussion of the investigated subjects.

4.1 Summary of Paper I

Paper 1 reports on a situation in which existing allocation approaches were not useful for solving issues of multi-functionality in the LCA of wastewater and sludge handling systems, and gives practical guidance on this matter. The paper reports on investigated methodological challenges faced when conducting an LCA on a novel mixed-culture fermentation technology that utilises carbon in wastewater to produce a biopolymer, with a simultaneous wastewater treatment function. The technology is currently only implemented at pilot-scale. A model system of a WWTP was studied in which a biopolymer-rich stream was generated, from which the biopolymer PHA could be recovered. The purpose of the study was to provide input to ROUTES, in which LCA results were needed for a similar system in order to guide in the development of process technology. PHA was considered as the main function of the studied system, and the WWT as a by-function.

One methodological issue discussed was the question of whether or not wastewater inflow could be regarded as a free feedstock that should not be allocated any environmental impacts from earlier stages. Another issue discussed was how to allocate environmental impacts between the generation of PHA and the wastewater treatment function.

The suggestions concerning the second issue were the main contribution to the development of LCA methodology. During wastewater treatment, the carbon content in wastewater is reduced, as part of the treatment function in the studied system. The carbon is used for the production of a biopolymer-rich stream. This means that the two functions of the production system are closely interconnected, or in fact are the same process: the “reduction of carbon content”. It can also be said that the allocation concerns the partitioning between a service and a product, a relatively unusual case in LCA. One possibility demonstrated in the article was to use substitution to account for the replaced wastewater treatment in the system. This avoided the need for allocation, but the question of how this replacement was to be made (on which basis) remained. Finding a common physical unit for the wastewater treatment service and the biopolymer product to base the substitution or allocation on did not seem possible. An economic basis for the substitution or allocation was rejected, as the LCA concerned a novel technology for which the costs for an integrated full-scale plant are unknown: An allocation based on economic parameters was assumed to introduce large uncertainties into the assessment due to the uncertain price of the specific PHA. This was because neither the properties of potential products, nor the characteristics of large-scale application were clear.

The study concluded that there was limited guidance about LCA methodology in the literature for the type of system studied. A new basis was suggested, which substituted the replaced WWT, based on the reduction of carbon content in the wastewater achieved by the generation of PHA (chemical oxygen demand (COD) was used as a proxy owing to data limitations). The substitution was done in two different ways, both calculating the replaced WWT service based on the COD reduction that occurred. In the studied system, a reduction of the carbon content in the wastewater occurs in two steps: for the build-up of the microorganisms and for the generation of the PHA in the cells in the biomass. One option would be to assume that the build-up of biomass would occur in the WWTP, regardless if PHA was to be produced or not, and that the generation of PHA in the cells during fermentation occurs for the sole purpose of the PHA production function of the system. In such a case, the system would be credited for avoiding conventional wastewater treatment that corresponded to the reduction in COD during biomass build-up. Another option would be to consider the entire reduction in COD was for the sole purpose of wastewater treatment. In such a case, the studied system would be credited for avoiding WWT service that corresponded to the reduction in COD caused by microorganism build-up and biopolymer generation. As an alternative, new approach, the same carbon (COD) basis was used for allocating the impact between the two functions of the system, in this case based on the share of the total carbon reduction in the studied system that occurred because it was incorporated in the PHA (see Equation 1 in Paper I). The study revealed the great importance of the choice of allocation approach for the overall GWP impact of the model system, and found the new methodological approach useful. The result proved to be dependent on the assumptions made about the modelling of electricity in the background system.

4.2 Selection of allocation approach in LCAs assessing resource utilisation from wastewater and sludge

The first research question addressed which allocation approaches are relevant and useful in LCAs on systems with resource recovery from wastewater and sludge. This question was addressed in relation to the mixed-culture technology for simultaneous WWT and the generation of the biopolymer PHA, studied in ROUTES.

4.2.1 One system: two different possible foci

The focus in an LCA of this type can be either on the WWT service or (any of) the (by-)product(s), which is reflected in the choice of functional unit. Paper I and Publication E both discuss allocation approaches for a system in which simultaneous WWT and PHA production occurs, but with different foci. In Publication E, WWT is considered to be the main service and PHA a by-product. Such a situation would occur, e.g. in an LCA that compared two WWT scenarios with different types of resource utilisation. In Paper 1, PHA is considered the main product and WWT a by-service. LCAs comparing the PHA generated from wastewater in a WWTP with another type of polymer would face the challenge described in Paper I.

In line with standards, the studied system should be subdivided as far as possible (European Commission Joint Research Centre, 2010) to avoid allocation. However, the need to divide the impacts from the simultaneous WWT service and the PHA product remains for both types of LCAs identified above. In both studies (Paper I and Publication E), physical causation was found too hard to apply as a basis for allocation, as none of the more common physical denominators was found appropriate. An allocation made on an economic basis was also rejected, because of uncertainties about the price of PHA since full-scale technology is not available, as discussed in Section 4.1. A third option, to avoid allocation by crediting the system for the by-product or service by substitution (system expansion) was considered. The challenges related to substitution differed in Paper I and Publication E, depending on which product was considered to be the by-product. In Publication E, the challenge was related to finding a polymer that could be considered appropriate for replacement with PHA, because of the novelty of the mixed-culture production process and the uncertainties of the properties of the specific PHA. In Paper I, the main challenge was related to finding a basis for the substitution, i.e. a basis for calculating the replaced wastewater treatment service. The latter issue proved to be the more challenging one.

4.2.2 Finding an allocation basis

Two ways of avoiding allocation by replacing the WWT service and one possible allocation approach were tested in the study in Paper I. For all of these options the replacement of COD reduction in the wastewater due to the generation of PHA (as a proxy for the carbon reduction that occurred) was used as basis. As is often the case in life cycle inventories, data availability partly determines the options at hand when choices are to be made. In the search for an appropriate basis for the substitution of the wastewater treatment service in Paper 1, data availability proved to be equally important. The carbon resource in the wastewater was found to be the only possible physiochemical allocation basis, and fortunately COD data was available and could be used as a proxy for carbon content.

In order to properly evaluate possible allocation approaches, it proved to be important to gain an extensive understanding of the studied process and its conventional alternative process. The study presented in Paper I was performed within ROUTES (described in Section 2.3). Performing the research within ROUTES enabled thorough discussions with experts on mixed-culture PHA production processes, which facilitated the understanding of an appropriate allocation basis. Access to expertise within the field was important for the outcomes in Paper I.

4.2.3 Relevance for systems with other resource utilisation

Paper I focuses on simultaneous WWT and PHA production, but similar problems could also occur when other products or services generated in, or by, the WWTP are studied. A comparison of biogas produced in a WWTP to biogas generated from the anaerobic digestion of biological municipal waste, means that a system that only produces biogas is compared to a system that in addition to the biogas also provides the service of stabilising sludge. Such a system was studied by Uusitalo et al. (2014), but they disregarded the replaced sludge stabilisation function, and considered the sludge as a “free” waste treatment function, with no impacts on the system, neither positive nor negative.

Paper I assesses a relatively simple case in which an industrial WWT is assumed to consist of carbon reduction. In an advanced WWTP, the nutrients (nitrogen and phosphorus) would also be removed, which would complicate the modelling of the replaced wastewater treatment service even further, as the replaced nutrient removal would need to be considered.

Paper II presents a study of a system that provides a WWT service and generates sludge that is used in agriculture for its nutrient content. The system was credited for replacing the use of mineral fertilisers, based on the nitrogen and phosphorus content of the sludge. The use of sludge in agriculture could also have an effect on soil quality, but this was disregarded in the study due to lack of knowledge on the nature and extent of this possible effect. Ideally, a substitution of the possible beneficial effects on ecosystem services of improved soil quality, such as its water retention capacity, could have been accounted for as well, possibly based on the carbon content in the land-applied sludge. The interest that different stakeholders have in this matter, as illustrated in Figure 6, further identifies an important area for improvement in LCAs of wastewater and sludge management systems.

4.3 Summary of Paper II

Stakeholder concerns regarding sludge land application are generally related to health and environmental impacts from, e.g. emissions of heavy metals or pathogenic microorganisms. Despite this, human toxicity and pathogen risks are not routinely assessed in the LCAs of such systems, owing to limited data, and in the case of pathogen risk, owing to the absence of an available methodology. A study was, therefore, performed in which quantitative microbial risk assessment (QMRA) methodology was adjusted to have a functional unit and system boundaries consistent with LCA methodology (Publication A). The potential impact on human health of a generic WWTP followed by either land application of sludge for agricultural purposes or incineration were assessed (Paper II). Publication A reports on the LCA adjusted QMRA methodology, and Paper II reports on the application of a full LCA in which pathogen risks were compared to other impacts on human health in order to provide an understanding of the orders of magnitude.

The LCA calculated the total impact from the model systems on the burden of disease (in disability-adjusted life years, DALYs) for the endpoint of human health. This calculation included impacts from the midpoints GWP, ODP, ionising radiation potential (IRP), particulate matter formation (PMFP), photochemical oxidant formation (POFP), HTP and pathogen risk. ReCiPe characterisation methods (Goedkoop et al., 2013) were used for GWP, IRP, ODP, PMFP and POFP. For human toxicity re-calculated USEtox results were used, and for pathogen risk the results presented in Publication A were used together with additional results calculated for the incineration system.

The results showed that pathogen risks can contribute significantly to the overall impact on human health in both model systems: the extent to which pathogen risk contributes is largely dependent on modelling conditions, such as the assumed concentration of pathogens in the influent wastewater, and the choice of life cycle impact assessment method for human toxicity. For agricultural sludge use, the overall results showed to be sensitive to the characterisation method chosen for human toxicity (mainly dependent on heavy metal emissions to agricultural soil).

4.4 Assessing risks of pathogens in LCA

Research question 2 raises the issue of whether or not it is possible, important and relevant to include pathogen risks in LCAs of wastewater and sludge management, using the current LCA framework. These three issues are discussed in this section.

4.4.1 Is it possible to include pathogen risks in an LCA?

In Publication A, an attempt was made to assess pathogen risks with an approach based on LCA-adjusted QMRA methodology. Attempts to include pathogen risks in an LCA have, so far, been very limited in published literature, not only for sludge management systems, but for LCAs in general. This is why the study presented in Publication A and Paper II can be seen as an important contribution to the field.

When performing an LCA, it is important to be aware of the limitations of the method. This is especially important when results from immature emission characterisation methods are evaluated. In Paper II, the performed assessment of pathogen risks was not considered specific enough for a comparison of different model systems, or for a precise assessment of the differences between the agricultural application of sludges with different qualities. If an LCA is made for the purpose of guiding the development of process techniques for sludge quality improvement, the methodology could be used, but data availability would be too low to compare the pathogen risks of the different treatment processes. Methodological shortcomings were not the primary reason for why the method cannot be used for such comparisons, as the method applied in Publication A could have been adjusted. The main reason for not comparing different systems was instead a lack of case-specific input data. The assessment of pathogen risks proved to be dependent on pathogen concentrations (see Paper I and Publication A), which, combined with the fact that an explicit goal in the assessment was to include as many relevant pathogens as possible, highlights the need for case-specific data on several pathogens. A fact that further complicated the assessment was that, in order to take pathogens into account, not only was pathogen concentration needed, but also a factor for calculating the burden of disease as a result of the exposure to the specific pathogen was needed. An LCA can only give an answer to a question if the main important aspects of the question can be assumed to be captured in the LCA with the available characterisation methods and inventory data.

The method for including pathogen risks in an LCA, described in Publication A, is limited to agricultural sludge systems, but the same methodology could also be used in developing methods for assessing other types of systems. This was done for a closely related sludge incineration system in Paper II. Expected human exposure routes differ depending on the sludge handling method. Agricultural sludge use is likely to have many more relevant exposure pathways than sludge incineration, as human exposure might occur during and after land-application, while pathogens, in principle, are fully eliminated during incineration.

4.4.2 Is it important to assess pathogen risks?

Paper II showed that it is important to include pathogen risks in assessments of wastewater and sludge management systems, regardless of sludge management approach chosen, because pathogen risk has the potential to make an important contribution to the overall impact on human health. The assessment in Paper II was made at the endpoint level, for several categories that have an impact on human health. Endpoint indicators introduce larger uncertainties into the assessment than if a midpoint approach had been chosen, but, on the other hand, these indicators enable a structured comparison of the importance of different impacts for a system, and are, therefore, preferable for the purpose of the study in Paper II.

4.4.3 The relevance of LCA as a tool for assessing pathogen risks

Research question 1 asks whether or not it is relevant to assess pathogen risks on human health using LCA, for systems studying the utilisation of sewage sludge in agriculture. In other words, it asks whether or not LCA is an appropriate tool for such assessments.

Impact on humans and the environment of wastewater management systems with agricultural sludge utilisation has been assessed several times in LCA literature (see e.g. Lundin et al. (2004), Johansson et al. (2008) and Hospido et al. (2010)). Despite the LCA methodological shortcomings identified, these studies have proven to be useful for revealing the benefits and drawbacks of different systems. LCA can thus be a useful tool for the assessment of such systems.

Pathogen risk can either be assessed in a separate QMRA that is presented alongside an LCA, or it can be included within the LCA framework, as shown in Paper II and Publication A. Which of the two approaches that is preferable may depend on the specific situation. The consideration of two sets of results in parallel, possibly with different bases for comparison and inconsistent system boundaries, forces decision-makers to engage in the interpretation of results, and possibly weigh different indicators against each other. This either happens tacitly or in a more structured multi criteria decision analysis (MCDA) framework, with its own requirements for subjective weighting factors (Rowley et al., 2012). Separate LCA and QMRA results can, therefore, allow a more detailed overall assessment, but to fully utilise the potential, they require access to the decision-makers (and sometimes other stakeholders), for instance, in an MCDA workshop, as decision-maker participation is necessary. In cases when the decision-maker is not accessible, e.g. if a branch-organisation initiates an LCA that targets consumers' decisions in purchasing, then including pathogen risks in the LCA would be preferable, as this would provide a more structured comparison and avoid subjective weighting by the individual customer.

LCAs should reflect the interests, the needs or responsibilities of the intended audience of the study. The aim of the assessment is preferably defined in consultation with the commissioner of the study, and the LCIA categories assessed should be selected based on stakeholder interests and responsibilities. A relevant question arises: Can LCA "help" in answering the question of whether or not sludge should be applied to land? Paper II showed that pathogen risks might be an important contributor to the overall impacts from a WWTP system with agricultural sludge handling. As the risks proved to be sensitive to pathogen concentrations in the wastewater inlet, the pathogen risks might, in some cases, have a much lower impact. Would it be important to include an impact category, although it may not be a major contributor to the overall environmental impact, just because stakeholders are concerned? For many stakeholders, local impacts related to sludge use are the main concerns, and global overall environmental impact may be considered less important.

In Sweden, a very active lobby group exists with the primary goal of stopping the use of agricultural sludge, see nätverket Ren åker ren mat (http://www.renakerrenmat.se/, assessed 2014-01-19). The wastewater industry works on reducing the risks of agricultural sludge use (and increasing public acceptance) by introducing a system for certifying sludge that is to be used for agricultural purposes, based on avoiding emissions of harmful substances to the wastewater at source, upstream the WWTP (http://www.svensktvatten.se/Vattentjanster/Avlopp-och-Miljo/REVAQ/, accessed 2014-02-17). Could an LCA that evaluates the global overall preference of agricultural sludge systems compared to other sludge disposal alternatives make any difference in a debate that, so far, has come to focus on local risks? An LCA puts a life cycle perspective on assessments, and assesses a large number of impacts. Such an assessment broadens the perspectives in the debate because it introduces a holistic way of viewing the issue. If the LCA, that is a method with the ambitious aim of assessing all environmental impacts of importance to stakeholders, cannot capture all the impacts of major concern to the stakeholders, the LCA results are at risk of being less useful and even overlooked by stakeholders. Including local risks, like toxicity and pathogen risks in an ambitious and careful way in LCAs is, therefore, a prerequisite for the tool to be useful in the agricultural sludge debate. This could expand the debate to focus on other possible impacts in addition to the risks to the local environment.

Several authors have identified the need for public acceptance of using sludge in agriculture. Bengtsson and Tillman (2004) summarised the Swedish debate on the matter in 2004, and have argued that facts alone cannot solve the issue, but that a discussion on values and beliefs is needed as a complement. Wang et al. (2008) have concluded that biosolids can be applied on land only if land application is socially accepted (and the sludge meets quality standards). An LCA might show whether or not agricultural sludge application is preferable from a global environmental point of view compared to other sludge disposal alternatives. An LCA is a useful tool in that it provides the possibility to relate the local impacts of great concern to stakeholders to other potential impacts. If used as part of the input for decision-makers, it could be an important contribution to the societal debate on agricultural sludge use.

4.5 Contribution to the research field

The overall aim of this research has been to improve LCA methodology and practice in order to provide useful guidance on environmental life cycle impacts, particularly as regards wastewater and sludge management, for systems in which resources in wastewater and sludge are utilised.

This research provides guidance for LCA practitioners on how to approach complex allocation issues in studies of wastewater and sludge management systems, with a specific focus on how a WWT service is credited in a system in which the WWT is a by-function.

The research also guides the LCA practitioner that is to make an LCA on a WWT system in which sludge is land-applied in his or her choice of impact categories by showing the importance of assessing pathogen risks in an LCA. The research provides arguments for why it is relevant to include pathogen risk in LCA, and gives examples of situations when it is extra useful to be able to assess pathogen risks within the LCA framework. It also shows a useful methodology for the inclusion of pathogen risks in LCA.

Both of these issues were identified as especially challenging in assessments of wastewater and sludge management systems in Section 2.5.3, thus this research has the potential to improve future assessments within the area.

5 Conclusions

The research presented in this thesis contributes to the overall aim of my research which is to improve LCA methodology and practice so that LCA can be used to provide useful guidance on environmental life cycle impacts in the area of wastewater and sludge management. The impacts in focus here are related to wastewater and sludge management with resources recovery. Paper I contributes to the development of LCA methodology for the goal and scope definition phase of an LCA, while Paper II provides new insights into the LCIA phase. More specifically, the research contributes to answering the research questions in the following way:

Research question 1. What allocation approaches are relevant and useful in resource recovery in wastewater and sludge management?

The study presented in Paper I evaluated LCA methodological issues related to a multi-functional system. The system used wastewater as feedstock for simultaneous wastewater treatment and for the production of the biopolymer PHA. The nature of the studied system made classic allocation approaches less useful, owing to uncertainties about the future price. The study suggested a new allocation approach that can be seen as more relevant, and showed a dependence of the overall GWP result on the allocation approach chosen.

Research question 2. Is it possible, is it important and is it relevant, to include pathogen risks in LCA of wastewater and sludge management in the current LCA framework?

The study presented in Paper II found that, although of great importance to stakeholders, the coverage of some case- and site-specific environmental impacts are often very poor in LCAs of systems that include the use of sludge in agriculture. No LCA study that assesses the risks of pathogens was found in the scientific literature. The reason for this is likely to be the shortcomings of characterisation modelling, and the lack of inventory data. Paper II shows that for model systems that involve wastewater management with either agricultural sludge use or sludge incineration, pathogen risks potentially contribute substantially to the total impacts on human health. The inclusion of pathogen risks in an LCA is relevant, especially for decision-makers, in order to provide them with pathogen risk results that are comparable with other life cycle impacts. Such inclusion will provide a basis for decision making that is generated with the same functional unit and system boundaries for all reported impacts, which makes it practical to evaluate without the need for introducing subjective weighting factors.

6 Recommendations for Future Research

Resource utilisation from wastewater and sludge is an area with many technical possibilities, and is the subject of much on-going research (e.g. in the project ROUTES, in which the research presented in this thesis has been carried out). In addition to resource utilisation through sludge (e.g. biogas, nutrients), the utilisation of carbon directly from the wastewater is under development, as is discussed in this thesis for mixed-culture biopolymer production. The options for resource utilisation are likely to multiply in the future. This means that LCAs of wastewater and sludge management systems are likely to face new challenges.

In the meanwhile, there are several LCA methodological issues to be solved. In Section 2.5.3 a number of improvement areas were identified. Impacts on humans and the environment from odours is one relatively unexplored area. Odour problems are discussed as a potential problem in the neighbourhood of WWTPs or during transport, storage or the end-use of sludge, but have never been assessed in an LCA, according to the available literature. The inclusion of carbon sequestration and moisture retention in soils into LCIs is another issue that is debated in the LCA community, and which can have an effect on wastewater and sludge studies (Peters and Rowley, 2009).

In addition to the issues directly related to methodology, there is also the problem of the lack of data in many situations, which complicates toxicity assessments. This thesis shows the potential importance of assessing pathogen risks in an LCA. However, in order to conduct a more specific assessment that enables comparisons between different wastewater and sludge management systems, there is a need for more, reliable, data on pathogen concentrations that cover more pathogens present in sludge in the specific systems under study.

The public and scientific debate regarding agricultural sludge use is intense. Science, including environmental systems analysis, can play a greater role as the provider of robust information for decision-makers. This calls for better ways of assessing not only the drawbacks of spreading sludge, as done in Paper II, but also the benefits of such a practice. One of the benefits is the potentially valuable impact of agricultural sludge on the organic matrix of soil, which is important especially in regions with poor soils.

7 References

ALBORG, K. 2013. Åkrarna gödslas med p-piller. *Aftonbladet*, 2013-11-19.

BAUMANN, H. & TILLMAN, A.-M. 2004. *The Hitch Hiker's Guide to LCA - An orientation tin life cycle assessment methodology and application,* Lund, Sweden, Studentlitteratur.

BENGTSSON, M. & TILLMAN, A. M. 2004. Actors and interpretations in an environmental controversy: The Swedish debate on sewage sludge use in agriculture. *Resources, Conservation and Recycling,* 42**,** 65-82.

COROMINAS, L., FOLEY, J., GUEST, J. S., HOSPIDO, A., LARSEN, H. F., MORERA, S. & SHAW, A. 2013. Life cycle assessment applied to wastewater treatment: State of the art. *Water Research,* 47**,** 5480-5492.

DIAS, J. M. L., LEMOS, P. C., SERAFIM, L. S., OLIVEIRA, C., EIROA, M., ALBUQUERQUE, M. G. E., RAMOS, A. M., OLIVEIRA, R. & REIS, M. A. M. 2006. Recent advances in polyhydroxyalkanoate production by mixed aerobic cultures: From the substrate to the final product. *Macromolecular Bioscience,* 6**,** 885-906.

EPSTEIN, E. 1975. Effect of sewage sludge on some soil physical properties. *Journal of Environmental Quality,* 4**,** 139-142.

EUROPEAN COMMISSION JOINT RESEARCH CENTRE 2010. ILCD Handbook - International Reference Life Cycle Data System. First ed.: European Union.

EUROPEAN COMMISSION JOINT RESEARCH CENTRE 2011. ILCD Handbook - International Reference Life Cycle Data System - Recommmendation for Life Cycle Impact Assessment in the Euroean context. First ed.: European Union.

FINNSON, A. 2011. Slamanvändning och slamdebatt – ett europeiskt perspektiv. *In:* JOHANSSON, B. (ed.) *Återvinna fosfor – hur bråttom är det?* Stockholm, Sweden: Formas.

FOLEY, J., DE HAAS, D., HARTLEY, K. & LANT, P. 2010. Comprehensive life cycle inventories of alternative wastewater treatment systems. *Water Research,* 44**,** 1654-1666.

GOEDKOOP, M., HEIJUNGS, R., HUIJBREGTS, M. A., DE SCHRYVER, A., STRUIJS, J. & VAN ZELM, R. 2013. ReCiPe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midoint and the endpoint level, Report 1: Characterisation. Ruimte en Milieu, Ministerie von Volkhuisvesting, Ruimtelijke Ordening en Milieubeheer.

GÖTEBORGS-POSTEN. 2013. Sätt stopp för slamspridning. *Göteborgs-Posten*, 2013-11-04.

HOSPIDO, A., CARBALLA, M., MOREIRA, M., OMIL, F., LEMA, J. M. & FEIJOO, G. 2010. Environmental assessment of anaerobically digested sludge reuse in agriculture: Potential impacts of emerging micropollutants. *Water Research,* 44**,** 3225-3233.

HUSILLOS RODRÍGUEZ, N., MARTÍNEZ-RAMÍREZ, S., BLANCO-VARELA, M. T., DONATELLO, S., GUILLEM, M., PUIG, J., FOS, C., LARROTCHA, E. & FLORES, J. 2013. The effect of using thermally

dried sewage sludge as an alternative fuel on Portland cement clinker production. *Journal of Cleaner Production,* 52**,** 94-102.
IPCC 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. . Geneva, Switzerland: IPCC.
JOHANSSON, K., PERZON, M., FRÖLING, M., MOSSAKOWSKA, A. & SVANSTRÖM, M. 2008. Sewage sludge handling with phosphorus utilization - life cycle assessment of four alternatives. *Journal of Cleaner Production,* 16**,** 135-151.
KELESSIDIS, A. & STASINAKIS, A. S. 2012. Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries. *Waste Management,* 32**,** 1186-1195.
KEMIKALIEINSPEKTIONEN 2011. Kadmiumhalten måste minska – för folkhälsans skull. En riskbedömning av kadmium med mineralgödsel i fokus. Rapport från ett regeringsuppdrag. Swedish Chemicals Agency.
KNIGHT, L. & BOWLER, T. 2013. The world's insatiable hunger for phosphorus. *BBC News Business*.
LARSEN, H. F., HAUSCHILD, M., WENZEL, H. & ALMEMARK, M. 2007. NEPTUNE - New sustainable concepts and processes for optimization and upgrading municipal wastewater and sludge treatment, Work Package 4 - Assessment of environmental sustainability and best practice. Deliverable 4.1 - Homogeneous LCA methodology agreed by NEPTUNE and INNOWATECH.
LEBLANC, R. J., MATTHEWS, P. & RICHARD, R. P. E. 2008. Global atlas of excreta, wastewater, sludge and biosolids management: moving toward the sustainable and welcome uses of a global resource.: United Nations Human Settlements Programme (UN-HABITAT).
LINDERHOLM, K., TILLMAN, A. M. & MATTSSON, J. E. 2012. Life cycle assessment of phosphorus alternatives for Swedish agriculture. *Resources, Conservation and Recycling,* 66**,** 27-39.
LUNDIE, S., PETERS, G. M. & BEAVIS, P. C. 2004. Life cycle assessment for sustainable metropolitan water systems planning. *Environmental Science and Technology,* 38**,** 3465-3473.
LUNDIN, M., BENGTSSON, M. & MOLANDER, S. 2000. Life cycle assessment of wastewater systems: Influence of system boundaries and scale on calculated environmental loads. *Environmental Science and Technology,* 34**,** 180-186.
LUNDIN, M., OLOFSSON, M., PETTERSSON, G. J. & ZETTERLUND, H. 2004. Environmental and economic assessment of sewage sludge handling options. *Resources, Conservation and Recycling,* 41**,** 255-278.
METCALF & EDDY INC, TCHOBANOGLOUS, G., BURTON, F. L. & STENSEL, H. D. 2004. *Wastewater engineering, treatment and resure,* New York, McGraw-Hill.

MILIEU LTD, WRC & RPA 2010. Environmental, economic and social impacts of the use of sewage sludge on land. Final report, Part III: Project Interim Reports.: European Commission, DG Environment.
NATURVÅRDSVERKET 2013. Hållbar återföring av fosfor - Naturvårdsverkets redovisning av ett uppdrag från regeringen. Swedish Environmental Procetion Agency.
NIKODINOVIC-RUNIC, J., GUZIK, M., KENNY, S. T., BABU, R., WERKER, A. & O'CONNOR, K. E. 2013. Carbon-rich wastes as feedstocks for biodegradable polymer (polyhydroxyalkanoate) production using bacteria.
OJEDA, G., ALCANIZ, J. M. & ORTIZ, O. 2003. Runoff and losses by erosion in soils amended with sewage sludge. *Land Degradation and Development,* 14**,** 563-573.
OTERO, M., ROZADA, F., CALVO, L. F., GARCíA, A. I. & MORÁN, A. 2003. Kinetic and equilibrium modelling of the methylene blue removal from solution by adsorbent materials produced from sewage sludges. *Biochemical Engineering Journal,* 15**,** 59-68.
PETERS, G. M. 2009. Popularize or publish? Growth in Australia. *International Journal of Life Cycle Assessment,* 14**,** 503-507.
PETERS, G. M. & LUNDIE, S. 2001. Life-cycle assessment of biosolids processing options. *Journal of Industrial Ecology,* 5**,** 103-121.
PETERS, G. M. & ROWLEY, H. V. 2009. Environmental comparison of biosolids management systems using life cycle assessment. *Environmental Science and Technology,* 43**,** 2674-2679.
PHILIP, S., KESHAVARZ, T. & ROY, I. 2007. Polyhydroxyalkanoates: Biodegradable polymers with a range of applications. *Journal of Chemical Technology and Biotechnology,* 82**,** 233-247.
POPULATION REFERENCE BUREAU 2013. 2013 World population datasheet. Washington DC, USA.
REMY, C. & JEKEL, M. 2008. Sustainable wastewater management: Life Cycle Assessment of conventional and source-separating urban sanitation systems.
RENOU, S., THOMAS, J. S., AOUSTIN, E. & PONS, M. N. 2008. Influence of impact assessment methods in wastewater treatment LCA. *Journal of Cleaner Production,* 16**,** 1098-1105.
ROCKSTRÖM, J., STEFFEN, W., NOONE, K., PERSSON, Å., CHAPIN, F. S., LAMBIN, E. F., LENTON, T. M., SCHEFFER, M., FOLKE, C., SCHELLNHUBER, H. J., NYKVIST, B., DE WIT, C. A., HUGHES, T., VAN DER LEEUW, S., RODHE, H., SÖRLIN, S., SNYDER, P. K., COSTANZA, R., SVEDIN, U., FALKENMARK, M., KARLBERG, L., CORELL, R. W., FABRY, V. J., HANSEN, J., WALKER, B., LIVERMAN, D., RICHARDSON, K., CRUTZEN, P. & FOLEY, J. A. 2009. A safe operating space for humanity. *Nature,* 461**,** 472-475.
ROSENBAUM, R. K., BACHMANN, T. M., GOLD, L. S., HUIJBREGTS, M. A. J., JOLLIET, O., JURASKE, R., KOEHLER, A., LARSEN, H. F., MACLEOD, M., MARGNI, M., MCKONE, T. E., PAYET, J.,

SCHUHMACHER, M., VAN DE MEENT, D. & HAUSCHILD, M. Z. 2008. USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *International Journal of Life Cycle Assessment,* 13**,** 532-546.

ROWLEY, H. V., PETERS, G. M., LUNDIE, S. & MOORE, S. J. 2012. Aggregating sustainability indicators: Beyond the weighted sum. *Journal of Environmental Management,* 111**,** 24-33.

SVANSTRÖM, M., FRÖLING, M., OLOFSSON, M. & LUNDIN, M. 2005. Environmental assessment of supercritical water oxidation and other sewage sludge handling options. *Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, ISWA.,* 23**,** 356-366.

SVANSTRÖM, M., JOHANSSON, K. & STENDAHL, K. Supercritical water oxidation of sewage sludge in combination with phosphate recovery. Leading-edge conference on Drinking Water and Wastewater Treatment Technologies, June 1-4 2004 Prague, Czech Republic.

TAY, J.-H. & SHOW, K.-Y. 1997. Resource recovery of sludge as a building and construction material — A future trend in sludge management. *Water Science and Technology,* 36**,** 259-266.

TILLMAN, A.-M., EKVALL, T., BAUMANN, H. & RYDBERG, T. 1994. Choice of system boundaries in life cycle assessment. *Journal of Cleaner Production,* 2**,** 21-29.

TILLMAN, A. M., SVINGBY, M. & LUNDSTRÖM, H. 1998. Life cycle assessment of municipal waste water systems. *International Journal of Life Cycle Assessment,* 3**,** 145-157.

UUSITALO, V., HAVUKAINEN, J., MANNINEN, K., HÖHN, J., LEHTONEN, E., RASI, S., SOUKKA, R. & HORTTANAINEN, M. 2014. Carbon footprint of selected biomass to biogas production chains and GHG reduction potential in transportation use. *Renewable Energy,* 66**,** 90-98.

WANG, H., BROWN, S. L., MAGESAN, G. N., SLADE, A. H., QUINTERN, M., CLINTON, P. W. & PAYN, T. W. 2008. Technological options for the management of biosolids. *Environmental Science and Pollution Research,* 15**,** 308-317.

WERTHER, J. & OGADA, T. 1999. Sewage sludge combustion. *Progress in Energy and Combustion Science,* 25**,** 55-116.

VIDYARTHI, A. S., TYAGI, R. D., VALERO, J. R. & SURAMPALLI, R. Y. 2002. Studies on the production of B. thuringiensis based biopesticides using wastewater sludge as a raw material. *Water Research,* 36**,** 4850-4860.

YOSHIDA, H., CHRISTENSEN, T. H. & SCHEUTZ, C. 2013. Life cycle assessment of sewage sludge management: A review. *Waste Management and Research,* 31**,** 1083-1101.