THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Improved methods and practices in life cycle assessment of wastewater and sludge management

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Cover:
Anaerobic digestion facilities at the wastewater treatment plant Ryaverket in Gothenburg.

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In loving memory of my greatest supporter,
Stefan Heimersson
(1954-2015)

Improved methods and practices in life cycle assessment of wastewater and sludge management

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Abstract

Large amounts of municipal and industrial wastewater are treated each year in order to prevent negative consequences to human health and the environment. The treatment processes, directly or indirectly, give rise to environmental impact, but also offer several possibilities to recover resources.

The research presented in this thesis is aimed at improving the relevance of Life Cycle Assessments (LCAs) for the evaluation of the environmental performance of wastewater and sludge management systems, e.g., for process development purposes, or to provide guidance in decision-making on sludge management alternatives.

A review of previous studies within the area show that the data inventory practice differs, in terms of which emission and recoverable flows are included and how these flows are quantified, which may have a large influence on results. The review is intended to serve as guidance for future life cycle inventory practice.

One area of focus of this research has been systems in which sludge is used in agriculture, partly as this is an issue that attracts stakeholder concern. It was shown that pathogen risk, which historically has not been assessed within the LCA framework, may constitute an important contribution to the overall impact on the endpoint human health. Another important contributor was human toxicity potential. The uncertainties when assessing human toxicity was, however, shown to be high for this type of systems when using currently available assessment methodology, mainly due to uncertainties in the characterisation of heavy metals. Applying a characterisation method adjusted to be more specific for exposure through sludge applied in agriculture did not influence results much. The way resource utilisation from sludge as organic fertiliser is accounted for in LCA studies was also evaluated, and a novel approach to account for the potential benefits of the provision of organic matter to arable land (in addition to the benefits of nutrient provision) was suggested and evaluated. Another focus area has been how to allocate impacts between the different functions provided in a system with simultaneous wastewater treatment and generation of PHA. A novel basis for comparison of the functions was suggested and evaluated, and was shown to be useful.

Keywords: Life cycle assessment, wastewater treatment, sewage sludge, biosolids, environmental impact, decision basis

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I would like to thank the co-authors of the papers on which this thesis relies, Prof. Christel Cederberg, Dr. Robin Harder, Dr. Giuseppe Laera, Dr. Fernando Morgan-Sagastume, Dr. Alan Werker, David I'Ons and Dr. Lena Blom, for fruitful discussions and support.

My daily work, lunch, and coffee breaks with the people at Chemical Environmental Science, and Forest Products and Chemical Engineering have been highlights of my time as PhD student. I would especially like to thank many of my PhD student colleagues for valuable daily discussions.

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Sara Heimersson
Gothenburg, March 2016

List of publications

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

I. Heimersson, S., Morgan-Sagastume, F., Peters, G. M., Werker, A. & Svanström, M. (2014) Methodological issues in life cycle assessment of mixed-culture polyhydroxyalkanoate production utilising waste as feedstock. New Biotechnology, 31, (4), 383-393.

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. Environmental Science & Technology, 48, (16), 9446-9453.

III. Heimersson, S., Svanström, M.; Laera, G.; Peters, G. (2015) Life cycle inventory practices for major nitrogen, phosphorus and carbon flows in wastewater and sludge management systems. Accepted for publication in The International Journal of Life Cycle Assessment.

IV. Heimersson, S., Svanström, M., Cederberg, C. & Peters, G. (2015) Improved life cycle modelling of benefits from resource utilisation from sewage sludge. Submitted to the journal Resources, Conservation and Recycling.

V. Heimersson, S., Harder, R., Peters, G.M., Blom, L., I'Ons, D. & Svanström, M. (2015) State-of-the-art LCA on sewage sludge management for local decision-making in Gothenburg – is it enough? Manuscript.

Work related to the thesis has also been presented in the following publications, referred to in the text by capital letters.

A. 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.

B. 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 Gothenburg, Sweden.

C. 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. Water Science and Technology, 69, (12), 2407-2416.

D. 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. Environmental Science & Technology, 48, (16), 9438-9445.

E. 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. Journal of Cleaner Production, 70, 723-731.

F. Bertanza, G., Canato, M., Heimersson, S., Laera, G., Salvetti, R., Slavik, E. & Svanström, M. (2014) Techno-economic and environmental assessment of sewage sludge wet oxidation. Environmental Science and Pollution Research 2014, 22, (10), 7327-7338.

G. Svanström, M., Laera, G. & Heimersson, S. (2015) Problem or resource - why it is important for the environment to keep track of nitrogen, phosphorus and carbon in wastewater and sludge management. Journal of Civil and Environmental Engineering, 5:200. doi:10.4172/2165-784X.1000200.

H. Tomei, M.C., Bertanza, B., Canato, M., Heimersson, S., Laera, G. & Svanström, M. (2015) Techno-Economic and Environmental Assessment of Upgrading Alternatives for Sludge Stabilization in Municipal Wastewater Treatment. Accepted for publication in Journal of Cleaner Production.

I. Gianico A, Bertanza G, Braguglia CM, Canato M, Laera G, Heimersson S, Svanström M, Mininni G (2015) Upgrading a wastewater treatment plant with thermophilic digestion of thermally pre-treated secondary sludge: techno-economic and environmental assessment, J Clean Prod 102:353-361. DOI: 10.1016/j.jclepro.2015.04.051

J. Kobayashi Y, Peters G, Ashbolt N, Heimersson S, Svanström M, Khan S (2015) Global and local health burden trade-off through the hybridisation of Quantitative Microbial Risk Assessment and Life Cycle Assessment to aid water management, Water Res 79:26-38. DOI: 10.1016/j.watres.2015.03.015

Contribution report

Paper I

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

Paper II

The author performed the LCA, with some numerical input from Dr. Robin Harder, and wrote the main part of the article, with feedback from all co-authors.

Paper III

The author performed the review and wrote the article, with support from Magdalena Svanström and feedback from the other co-authors.

Paper IV

The author performed the LCA and wrote the article, with support on agricultural issues from Prof. Christel Cederberg and feedback from the other co-authors.

Paper V

The author performed the LCA, with assistance on the toxicity results from Dr. Robin Harder. The author wrote the article with feedback from all other 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 1st of January 1995
EU-25	the 25 member states that had joined EU 1st of May 2004
EU-27	the 27 member states that had joined EU 1st 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
LiCRA	project LiCRA – A new perspective on sludge management – cross disciplinary enhancement of hybrid life cycle risk 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
SOC	soil organic carbon
VFAs	volatile fatty acids
WO	wet oxidation
WWT	wastewater treatment
WWTP	wastewater treatment plant

Table of contents

1 Introduction

Every day, between 35-90 litres of water (Metcalf & Eddy Inc et al. 2004) are used per person, either directly, e.g. for household purposes, or indirectly, e.g. for industrial purposes. A large share of this ends up as wastewater. Historically, the direct release of wastewater has been a minor problem in areas with a low population density. Urbanisation, in combination with a growing world population (from 2.5 billion people in 1955 to 6.5 billion people in 2005 (Population Reference Bureau)), has created the need to collect an increasing amount of wastewater and treat it. 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 to avoid problems for human health and the environment, such as eutrophication in the local environment. Today, most urban wastewater is treated in one way or another before discharge. Municipal wastewater treatment plants (WWTPs) function as societal kidneys: They receive municipal wastewater, including human urine and excreta and greywater from households, and sometimes also wastewater from industries, and treat it in order to obtain water quality that is considered high enough for it to be released, e.g., to the sea. The treatment generates sewage sludge (in this thesis denoted sludge), which needs to be disposed of. Historically, this perspective of wastewater as waste has been predominant, but, in recent years, there has been a shift away from the view of wastewater and sludge as wastes and towards seeing them as a resource of valuable carbon (C), nitrogen (N) and phosphorus (P). C can, for instance, be recovered during sludge treatment (anaerobic digestion) in the form of biogas: an energy carrier which can be used as a fuel or as a source for materials production, e.g., in bio-refineries, and thereby contribute to a bio-based society. Recent research also utilises C in wastewater to generate a biopolymer during wastewater treatment (Morgan-Sagastume et al. 2010), which after recovery from sludge could replace conventional fossil-based polymers. P and N are nutrients vital for agricultural productivity which can be recovered from sludge by different means, e.g., through direct use of hygienised sludge on arable land, and thereby contribute to a circular flow of nutrients in society. In moving towards a more circular and bio-based society, it can be expected that the focus on resource recovery from wastewater and sludge will increase.

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 sludge are generated, containing most of the substances removed from the wastewater during treatment. More advanced treatment of the water effluent can, consequently, lead to higher amounts of sludge being generated (Metcalf & Eddy Inc et al. 2004). In the EU-27, about 10 million tonnes of dry solids (DS) of sewage sludge are generated annually (Milieu Ltd et al. 2010). The handling of the 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, and these alternatives are still used in some locations. However, such alternatives are criticised, not only for their direct contribution to climate change, e.g., due to methane from the anaerobic degradation of organic material in landfills, and eutrophication (sludge dumping in the ocean is, 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 resources. The use of sludge in agriculture is one common sludge handling route that recycles both nutrients and organic material. The United Nations Human Settlements Programme (2008) lists land reclamation, horticulture and landscaping, forestry, industrial processes, materials 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 N and P fertilisers to ensure high yields. Mineral phosphorus is a mined resource, and as such it is limited (Neset & Cordell 2012). Rockström et al. (2009) have suggested a framework based on nine "planetary boundaries", which defines a "safe operating space for humanity with respect to the Earth system", which is further developed by Steffen et al. (2015). N and P cycles are described as one aspect of the Earth system in which natural flows are disturbed. Human interference with the N and P cycles has, according to Steffen et al. (2015) already largely exceeded this safe operating space. Recovery of the nutrients in sludge can be seen as one important way of closing environmental nutrient cycles, if leakages can be minimised. 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 P) from sludge and applying these nutrients on fields. Use of treated sludge in agriculture also fulfils the aspiration to recover organic material from the sludge, which could be particularly important in areas with poor soils, e.g., with limited water retention capacity (Peters & Rowley 2009) or low levels of soil organic carbon (SOC) (Brady et al. 2012). Despite these potential advantages, the use of sludge on arable land is questioned, and in some countries even prohibited, mainly due to the risks related to its content of heavy metals, organic micropollutants, and pathogens (Bengtsson & Tillman 2004). 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, e.g., agricultural sludge use. Life Cycle Assessment (LCA) is an environmental systems analysis method used to assess the environmental consequences connected to the use of a studied product or service, including impacts from its full life cycle. LCA is often used as a partial decision basis in different types of decision contexts. In the context of wastewater and sludge management, this could, for example, be as input to strategic decisions by the wastewater industry or policymakers on sludge handling strategies, as input during wastewater and sludge treatment process development, or when deciding on the preferred ways of providing nutrients to arable land. A holistic assessment is particularly vital in comparisons of wastewater treatment (WWT) scenarios with different sludge end-use situations aimed at providing input to strategic decisions on how to manage sludge, e.g., as such systems are expected to give rise to slightly different impacts.

The research presented in this thesis has been performed within three different projects all of which have focused on the environmental assessment of wastewater and sludge management systems using LCA. 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 the system boundaries of such assessments. The research presented in this thesis demonstrates some shortcomings in LCA methodology and practice when assessing wastewater and sludge management systems, and suggests solutions to some of the identified problems. The research has focused on three areas; 1) Life Cycle Inventories (LCIs) of wastewater and sludge treatment systems, 2) assessment of direct human health impacts related to constituents of sludge spread on arable land, and 3) assessing possibilities in resource recovery.

1.2 Projects in which the research was performed

The research presented in this thesis was performed within three different projects. In each of the projects, LCA was intended to guide decision-making; either guiding European process developers and policy-makers on wastewater and sludge treatment process development and future policy-making, or guiding decision-making in the Swedish wastewater industry or the local municipality of Gothenburg on sludge management strategies.

1.2.1 ROUTES project

The project ROUTES "Novel processing routes for effective sewage sludge management" was part of the European Union's Seventh Framework Programme under the theme Innovative system solutions for municipal sludge treatment and management (see www.eu-routes.eu). ROUTES was a three-year project (2011-2014). 18 partners from universities, research institutes, and companies around Europe were involved in the work, see further description in Braguglia et al. (2012).

Within ROUTES, the development of process technologies for wastewater and sludge treatment was 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 were strived for by means of the development of process technology for implementation in WWTPs either to minimise the sludge generation in the waterline, to maximise sludge stability and biogas production, to produce valuable by-products, or to make the sludge non-reactive. Depending on local conditions and raw wastewater quality, the considered end-use of sludge varied. To be able to evaluate if the processes developed reached the goals, the studied process technologies were introduced to conceptual WWTPs that were anticipated to experience different types of problems. Reference scenarios were modelled and compared to new scenarios in which the studied process technologies had been implemented.

The environmental feasibility of the suggested upgrades was studied using LCA as part of a larger integrated assessment in which also the technical and economic feasibilities of the upgrades were evaluated in pursuit of a holistic assessment. The methodology used for the techno-economic-environmental assessment is described in Publication C. LCA results for some of the systems studied in the project can be found in Publication A. Results of the integrated assessment can be found in Publications F, H and I. Papers I-II present LCA methodological issues identified and partly solved during the work with the environmental assessment performed in the project. The original purpose of both studies was to provide input to the ROUTES project. However, due to confidentiality issues, model systems relying on literature data was instead used to illustrate the findings in the papers.

The integrated techno-economic-environmental assessment was performed as a tiered process; a first preliminary assessment was performed after half of the project time in order to provide feedback to the process developers and in order to indicate if any of the studied routes was not feasible to develop further. A second assessment was carried out at the end of the project, partly to guide the future development of the process technologies, and partly to evaluate the achievements of the developed processes within the project. The results were also intended to provide guidance in future policy-making. Both after the first and second assessment rounds, results were presented to the large project group and at a project-specific end-user conference.

Both the possibilities and difficulties associated with LCA work performed in large inter-organisational research and development projects are discussed in Publication E, in which ROUTES is one of the projects evaluated. The publication highlights the importance of a well-motivated and clear role description for LCA in the planning of a project.

1.2.2 LiCRA project

The project LiCRA - a new perspective on sludge management – cross-disciplinary enhancement of hybrid life cycle risk assessment, financed by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS), was initiated in 2013 in order to improve assessment of human health risks connected to sludge utilisation on arable land, in particular regarding human toxicity. In comparison to the ROUTES project, LiCRA was much smaller; research was mainly performed by the Chemical Environmental Science research group at Chalmers, but representatives from the local WWTP in Gothenburg, Ryaverket (owned by the municipal company Gryaab AB) and from Gothenburg City were actively involved stakeholders in the project. As part of the project method, development aimed at improving the assessment of human health impact from sludge used on arable land was performed, with a focus on human toxicity (Harder et al. 2015b), and, to a smaller extent, pathogen risk (Publication D). In a full LCA, a system in which hygienised sludge was applied to arable land was then compared to a system in which sludge was incinerated, partly to test the importance of human toxicity impacts from sludge on arable land relative to impacts on human health from the remaining system, and partly to compare this route to another sludge handling route. The usefulness of the LCA for the specific decision-making context (to provide a decision basis for WWTP managers on future sludge strategy for the Gothenburg region) was also evaluated (described in Paper V).

Papers III-V, and Publication D, were written as part of the LiCRA project, with partial input from the project described hereafter.

1.2.3 The project ‘LCA on sludge handling with phosphorus utilization’

In parallel to the LiCRA research project, a smaller project was performed, financed by The Swedish Water & Wastewater Association, and a number of Swedish WWT companies: Gryaab AB, The Käppala Association, Stockholm Vatten AB, Sydvästra Stockholmsregionens va-verksaktiebolag (Syvab), Uppsala Vatten och Avfall AB and VASYD. This project was performed during 2015-2016 in order to inform the Swedish wastewater industry of the environmental performance of different alternative strategies for managing sludge. The need for new strategies was stressed by the fact that new legislation on sludge management was expected (Naturvårdsverket 2013), with more stringent requirements, e.g., on hygienisation of sludge before application on arable land. A new milestone target of 40% P and 10% N recovery to arable land in year 2018 is also suggested for the Swedish Environmental Objectives (Naturvårdsverket 2013). The main goal of the project was, thus, to compare different scenarios for sludge treatment followed by nutrient recycling to arable land with respect to the environmental life cycle performance of each scenario. The work was mainly performed by the research group Chemical Environmental Science, with support on strategic decisions and part of the data inventory from a reference group consisting of representatives from the different WWTPs listed above. The work in this project provided valuable input to Paper V, especially on inventory data, and insights into methodological issues when assessing sludge treatment systems in a local decision-making context.

1.3 Guide for readers

This thesis consists of two main parts: one thesis summary that presents the work that constitutes the basis for my doctoral degree, and a second part that consists of the articles on which the thesis is based (Papers I-V). An additional ten publications (Publications A-J) are referred to as well. These include conference and journal papers and a book chapter (see List of Publications).

Chapter 2 describes the background to the research presented here: the reasons for performing the described research, the method LCA and a literature review of relevant previous research, illustrating shortcomings in present LCA methodology and practice, and highlighting the need for the research presented in this thesis. Chapter 3 describes the overall aim of the performed research, and defines five specific research questions, within three different research areas, that this thesis sets out to answer. The chapter also includes a description of the methodology used. Chapter 4 summarises the appended papers and Chapter 5 discusses research findings and limitations in relation to the research questions, and the usefulness of LCA for assessing wastewater and sludge treatment systems. Chapter 6 discusses future research needs or opportunities, based on the findings in the thesis, and Chapter 7 presents the conclusions from the research.

2 Background and Methods

This chapter establishes a background for the performed research; it describes general wastewater treatment, different possible forms of resource utilisation from wastewater or sludge, and the LCA method, with a special focus on the assessment of wastewater and sludge management systems. The last section of the chapter identifies shortages in present LCA methods and practices when assessing 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 N and P, traces or decomposition products of medicines, hormones from contraceptives, and microorganisms to wastewater. Other household activities like laundering add phosphates and other chemicals. Where municipal wastewater and surface water are collected in a combined pipe system, road traffic provides yet other pollutants, along with industrial activities that might also be connected to the sewer system. These examples illustrate the complex composition of wastewater. For instance, the wastewater influent to the wastewater treatment plat Ryaverket, assessed in the LCA in Paper V, contained, e.g, in 2014 in average 61 mg/L of total organic carbon (TOC), 3.31 mg/L of total nitrogen and 3.31 mg/l of total phosphorus. In addition, it also contained 0.081 mg/L of zinc (Zn), 0.054 mg/L of copper (Cu), 0.0035 mg/L of nickel (Ni), 0.0029 mg/L of lead (Pb), 0.0027mg/L of chromium (Cr), 0.0001 mg/L of cadmium (Cd) and 0.00008 mg/L of mercury (Hg) (Mattsson 2015).

The collected wastewater is treated to achieve sufficient quality of the effluent water that is subsequently released to a recipient. Treatment has mainly focused on removing organic material and nutrients. The purpose of this collection and treatment is primarily to avoid microbial risk, and, in recent decades, also to avoid eutrophication. Wastewater treatment can be conducted in a wide variety of ways, in the waterline, whereafter the treated water is released to an aquatic recipient. The generated sludge 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 advanced N removal and P precipitation) often follows after this, including sedimentation that separates secondary sludge from the treated water. In more advanced WWTPs, additional wastewater treatment steps may follow, or may be integrated with the other steps. The different sludges are then further treated in the sludge line, either separately or mixed, for instance in order to reduce the volume of sludge and to reduce the concentration of organic micropollutants and pathogens. Sludge treatment typically consists of thickening and 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 new 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. Legislation prohibiting ocean dumping of sludge also went into force in the European Union. In 2008, 10% of all sludge in the EU was landfilled, 30% was incinerated, 45% went to agricultural use and 15% was treated in other ways (Finnson 2011).

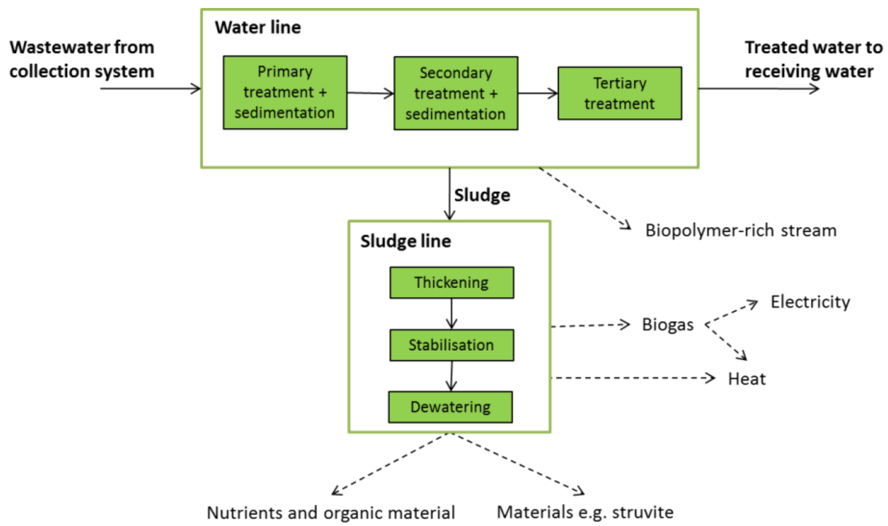

Figure 1. Schematic illustration of the basics of a common wastewater treatment plant, and examples of potential resource recovery.

2.2 Resource recovery in wastewater and sludge management

The notion of resource utilisation in this context includes recovering resources directly from the wastewater or sludge during treatment or from different end-uses of sludge that has 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; and the reuse of incineration ash for construction materials or as a phosphorus resource. It is also possible to utilise the C resource directly from the wastewater during treatment, as is discussed for biopolymer production in this section, or to utilise the nutrients, such as through struvite recovery.

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 upgraded (to increase the share of methane) and sold, e.g., as a vehicle fuel or for industrial purposes, or burnt on site, generating only heat or both electricity and heat. This energy can then be used internally at the plant or sold, depending on the local situation, for instance the available infrastructure for delivering and trading electricity and heat. This choice may seem unimportant when the environmental impact is to be studied from a holistic perspective, but this choice may greatly affect the results of an LCA, as will be discussed later in this thesis. During anaerobic digestion, sludge is stabilised and its volume is reduced, which means that the sludge is easier and safer to handle, and that there is less sludge to transport from the WWTP and dispose of.

Incineration of sludge is common in many European countries. Incineration either takes place on site or off site, as mono-incineration or co-incineration, for instance, with municipal waste or coal. In some cases, additional fuel is needed for the incineration of sludge because of its high water content. Heat and electricity 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 reduced by digestion. On the other hand, the dewaterability of the sludge is improved (Werther & Ogada 1999).

Other techniques for energy recovery also exist. Other examples are the wet oxidation technique assessed in Publication F, and the supercritical water oxidation (SCWO) system assessed by Svanström et al. (2005). In the latter case, the energy present as heat in the reactor effluent was recovered and used in a district heating system.

2.2.2 Nutrients and organic matter recovery

The main nutrients in sludge (N and P) 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 P by extracting it from wastewater or sludge, e.g., precipitated as struvite, or recover it from incineration ash or SCWO residues (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 researchers (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, increases soil porosity, and improves soil moisture retention and hydraulic conductivity. Hedlund (2012) has shown that an increase in SOC level leads to a higher uptake of the N mineral fertiliser by crops (for soils with low SOC levels).

Sewage sludge also contains heavy metals, medicines, organic micropollutants, pathogens, 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 (Bengtsson & Tillman 2004).

In Sweden, sludge use for agricultural purposes is allowed, but restricted according to the national ordinance SNFS 1994:2. 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 during a certain time period, and the permitted load of heavy metals. The Swedish national environmental objectives promote the recycling of nutrients, see for instance Swedish EPA (2013) on the development of new milestones for the Swedish environmental objectives. 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 to lower the limits for contaminants in the sludge that is used for agricultural purposes (Swedish EPA 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, see, e.g., Alborg (2013) and Göteborgs-Posten (2013). Bengtsson and Tillman (2004) provide a description of the Swedish sludge debate up until 2004.

Agricultural sludge use differs between countries in the European Union. As in Sweden, the subject is sometimes publicly debated. In some countries, a large share (around 50%) of the generated sludge is land-applied, such as in Denmark and the United Kingdom, while others do not land-apply sludge at all, such as 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 and the organic matter it contains are in high demand and most of the sludge (69%) is used in agriculture, for landscaping, or for land reclamation purposes (Australian & New Zealand Biosolids Partnership 2013).

2.2.3 Materials recovery

Materials for a number of different applications can be produced from wastewater and sludge, or technologies are in the process of being developed. Some examples of these are building and construction materials (Tay & Show 1997), adsorbent materials (Otero et al. 2003), bio-pesticides (Vidyarthi et al. 2002), and materials to improve cement production (Husillos Rodríguez et al. 2013).

Another example utilises the C in the organic material in 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, and is followed by a PHA recovery step, either on site or off site. This process, which is novel and has been tested so far only on the pilot scale (Dias et al. 2006; Nikodinovic-Runic et al. 2013), is one of the technologies studied in the ROUTES project described in Section 1.2.1.

2.3 Life Cycle Assessment (LCA) methodology

LCA is a 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 popular internationally, and since the 1990s commonly applied (Baumann & Tillman 2004; Peters 2009). The methodology is standardized in ISO 14040:2006 and 14044:2006. Further guidance on LCAs in a European context can be found in the International Reference Life Cycle Data System (ILCD) Handbook (EC-JRC 2010).

An LCA is normally performed in order to inform decision-makers about the environmental consequences of studied systems. Decisions on future sludge strategies can, for example, be influenced by many different types of actors; policy-makers interested in promoting sludge handling that supports national or regional environmental objectives; wastewater industry associations that guide the wastewater industry in a specific country to comply with existing legislative requirements and to work proactively towards meeting future expected requirements; or local WWTP steering committees that adjust their sludge handling strategies in order to comply with expected new legislative requirements under the local conditions of a specific site and within a constrained economic budget, just to mention some possible actors. These actors are likely also affected by the expectations of other stakeholders, such as the general public. Different types of stakeholders ask different types of questions, resulting in a system being studied from different perspectives. In this thesis, such situations are referred to as different decision contexts. One of the largest benefits of LCA is the fact that each LCA is (or at least should be) adjusted to the questions asked in a specific study. Since the goal of the study is determined by the decision context in which it is performed, each LCA is (or should be) tailored to the specific decision context where it is to be used.

In an LCA, the environmental impact connected to the life cycle of a product or a service is determined. The general procedure for performing LCAs is described in Figure 2. 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 the treatment of 1,000 metric tonnes of sewage sludge. The use of resources in and the emissions generated by 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 potential (HTP), to enable a holistic assessment of the environmental performance of a product or a service.

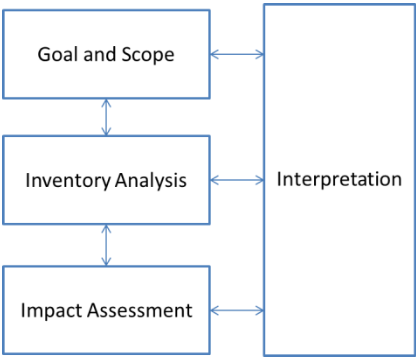

Figure 2. The four steps of a Life Cycle Assessment.

Goal and scope definition. The aim of an LCA, the functional unit, the system studied, its geographic and time boundaries, and the delimitations 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 goal 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.

A comparative assessment can be made to compare two products or services with the same function. A distinction can be made between attributional and consequential LCAs. An attributional LCA aims at describing the environmental impacts of a system while a consequential LCA focuses on the consequences of action, i.e., changes in systems (Ekvall & Weidema 2004).

One of the 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 (according to the ILCD Handbook (EC-JRC 2010)), the production process is to be subdivided, and each energy or substance flow is to be connected to one specific product. However, this is usually only possible to a certain extent; either because some unit processes actually generate two or more products, or because there is a lack of disaggregated data on the studied system. The studied product can be considered to be responsible for the entire common production process, as is sometimes done for wastes (see, e.g., Doca (2009)), but it is common to either try to give the studied system a benefit for any functions provided in addition to the main studied function (an approach referred to as substitution or system expansion), or to divide (allocate) the impact between the different co-functions. ISO 14044:2006 recommends that analysts avoid allocation, as far as possible, and instead apply substitution. In general, when substitution is applied in an LCA, a conventional product or service that fulfils the same function as the by-product or service of the system, is selected. The studied system is then given a credit for the production (and sometimes also the use, depending on the system boundaries) of this replaced product or service that is, in fact, avoided.

If substitution is not a reasonable option, that means that allocation (sometimes referred to as partitioning) must be applied. The impact can be allocated between the products based on, e.g. physical causations, mass, energy content or price. This means that the heaviest, most energy-rich or most valuable product is generally connected to a larger environmental burden. Pioneering work on allocation in LCA has been performed, e.g., by Tillman et al. (1994).

Some authors (see, e.g., Baumann and Tillman (2004) and Thomassen et al. (2008)) argue, in contrast to the recommendations in the ISO 14044:2006, that, substitution should in general be applied for consequential studies while an allocation approach should be used for attributional studies.

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 resource use in the system, and emissions from the system, in line with the system definition and impact categories that were described in the goal and scope definition. The production of inputs to the system, such as electricity and consumables, are normally included in the inventory. It is common to distinguish between the foreground system, i.e., the part of the system that the commissioner can directly influence, and the background system, such as the production of consumables. The choices of data, e.g., if average or marginal data should be used for the inventory, may depend on whether an attributional or a consequential study is performed. It is also common to have higher demands on the specificity of the data for the foreground than the background system. Inclusion of impacts from the background system requires quantification of, e.g., energy and consumables in the foreground system.

Life Cycle Impact Assessment. In the Life Cycle Impact Assessment (LCIA), the flows identified in the LCI are characterised based on the environmental impacts they contribute to. By using characterisation factors, the different environmental impacts resulting from the studied system, per functional unit, can be quantified. Characterisation methods commonly provide general fate-exposure-effect models by which characterisation factors are generated that express how much each emission contributes to a certain impact. The total impact per impact category can be calculated by summarising the contributions from the studied system to each impact category, see for instance Goedkoop et al. (2013). For most impact categories, several characterisation methods exist. For human toxicity and freshwater toxicity impacts, a consensus model, called USEtox, has recently been developed (Rosenbaum et al. 2008), by the development teams behind several older methods. The ILCD handbook (EC-JRC 2011) provides recommendations on which characterisation methods to use for each impact category.

LCIs can either be expressed using midpoint or endpoint indicators. A midpoint method, according to the ILCD Handbook (EC-JRC, 2011, p. xiii), 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", for instance 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", for instance climate impact translated into its effect on human health, expressed as human years lost or years living with disability (DALY) due to the climate change. Impacts are more commonly assessed using midpoint indicators. Translating impacts to endpoints introduces further uncertainties and subjectivities into the assessment but can be useful, e.g., if an aggregation of different impact categories is desirable.

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 for instance could be 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 & Tillman 2004).

Interpretation. LCA is an iterative process. Interpretation is an important part of each of the steps described above and often leads to modification of the assessment. In addition, the interpretation of LCIA results gives the audience of the LCA guidance on how to interpret the results based on how the problem has been formulated and how the assessment has been performed, as stated in the goal and scope definition, and the choice of inventory data. This step often includes one or more sensitivity analyses of critical factors.

2.4 LCA of wastewater and sludge management systems

Beginning in the second half of the 1990s, a large number of studies have reported on LCAs of wastewater 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 on wastewater treatment technologies (Larsen et al. 2007). The reviews partly cover the same material.

2.4.1 Goal and scope identification

An LCA only answers the specific question that it is set up to address, i.e., the goal of the study. LCAs made for at least two principally different decision contexts have previously been published; either wastewater and sludge management is the studied function (the majority of relevant published studies, see e.g. Johansson et al. (2008) and Hospido et al. (2012)) or nutrient recovery is the focus of the study, see, e.g., Linderholm et al. (2012). The choice of focus affects, amongst others, the handling of multifunctionality in the systems. Ekvall et al. (2007) state that LCAs that calculate the environmental burden per tonne of waste, can be used for comparisons of different operations for dealing with the waste, but not for analyses of changes in the quantity of waste.

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 3, or they can include only one of these. The generation and the collection of wastewater are commonly disregarded, but the production of the pipe system has 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 than other parts (Corominas et al. 2013; Peters & Rowley 2009). The background system covers the production of energy and material inputs, e.g., chemicals, to varying extents.

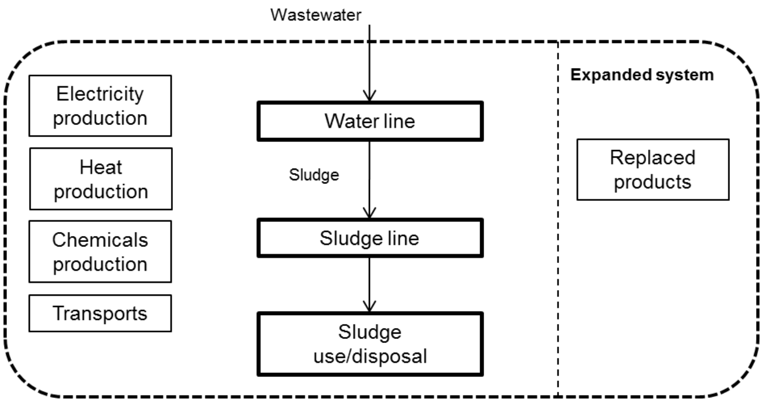

Figure 3. General wastewater and sludge treatment system. The process box "Replaced products" indicates that substitution is a common way of solving allocation issues in wastewater and sludge LCAs. Boxes within bold borders are often considered to be part of the foreground system.

2.4.2 Life Cycle Impact categories commonly assessed in wastewater and sludge management systems

The most commonly assessed life cycle impact category is global warming potential (GWP) (Corominas et al. 2013; Yoshida et al. 2013). Eutrophication potential (EP) and acidification potential (AP) are also 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 reviewed studies. Human toxicity potential (HTP) and ecotoxicity potential are less often included in LCAs (Corominas et al. 2013; Peters & Lundie 2001; Yoshida et al. 2013), and the specific characterisation methods used vary (Renou et al. 2008), owing to a lower degree of consensus on methodology in the scientific community. Inventory data on e.g. heavy metals and organic micropollutants in sludge are also lacking in many cases, as well as characterisation factors for many possibly relevant substances. Energy use, water use, and land use are impacts occasionally assessed.

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. This will be further discussed below. In practice, the choice of impact categories that can be assessed, and the relevance of assessing these, is often limited due to the scarcity of accepted methodologies, and inventory and characterisation data.

2.4.3 Allocation approaches applied in LCAs of wastewater and sludge management systems

A common allocation issue in LCAs of wastewater and sludge management systems is the allocation of impacts between a WWT service and another function that the system performs, for example when biogas is generated and is used outside of the system. An allocation problem would also occur if an input to the studied system, for instance 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, which is increasingly common, implies that a by-product or -service is generated in the WWTP, which means that such systems are often 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, such as Hospido et al. (2004), Johansson et al. (2008) and Peters and Rowley (2009).

In wastewater and sludge management LCAs, particular interest has historically been placed on multifunctionality issues in relation to 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, based on the N and P levels in the sludge. Today, such substitution is the predominant way of handling multifunctionality in systems that involve agricultural utilisation of sludge, in addition to WWT (see, e.g., Lundin et al. (2004), Johansson et al. (2008), Peters and Rowley (2009) and Hospido et al. (2010)). Benefits other than N and P from sludge used in agriculture have not been included in previous LCAs, with a few exceptions: Schaubroeck et al. (2015) accounted for the use of peat and straw that was replaced due to the organic material content in the sludge applied on arable land, Peters and Rowley (2009) accounted for the increased water retention capacity in Australian soil as a result of agricultural sludge use and, e.g., Foley et al. (2010a) quantified C sequestration as a result of land-applied sludge.

Another common by-product in WWTPs is biogas. In LCAs, the biogas is often assumed to be combusted and thereby to generate heat, or both electricity and heat, 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 A, 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 vehicle fuel, which is the actual case at the WWTP in Gothenburg, Sweden, assessed in Paper V. A few studies have assumed that biogas is used as a vehicle fuel, replacing either natural gas or diesel (Cao & Pawłowski 2013; Foley et al. 2010b; Mills et al. 2014; Pasqualino et al. 2009).

2.4.4 Identified methodological issues in LCAs of wastewater and sludge management systems

Despite the fact 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 and practical difficulties related to systems that include the utilisation of recovered resources from wastewater and sludge.

One interesting methodological issue regards the life cycle impact categories assessed in wastewater and sludge management LCAs, both as regards which impacts that are assessed, and the relevance of the methodology and the LCIA results. The choice of life cycle impact categories should be guided by their relevance for a specific study, i.e. both an estimation of which impact categories that are likely to be influenced by the studied system, and how important the societal concerns that each impact category addresses are to stakeholders. As part of ROUTES, the importance to wastewater industry representatives and academics, active in wastewater treatment process development, of different impacts on human health and the environment was evaluated through a questionnaire at the ROUTES end-user conference on the 25th of October 2012 in Rome, Italy. This survey 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 environmental and health concerns 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 4. Although the group of participants does not cover all types of relevant stakeholders, these are some of the main primary stakeholders in many decision contexts relevant for wastewater and sludge treatment LCAs. The impact categories listed as most commonly assessed in LCAs on wastewater and sludge treatment systems in Section 2.4.2 sometimes give sufficient coverage of the environmental impacts of the LCAs of different systems. However, for some LCAs, such as when sludge is used for agricultural purposes, further impact categories would be needed in order to cover the main concerns of stakeholders. As can be seen in Figure 4, there was a great interest amongst the responding stakeholders for assessing pathogen risk and odour. Comparing this to the information in Section 2.5.3, it can be concluded that neither of these are usually assessed within an LCA framework. Impacts on human health and the environment from odours is a relatively unexplored area. Pioneering work within the field was done by Heijungs et al. (1992), and more recently for LCAs of pig manure management in the Danish project Cleanwaste (Peters et al. 2014). 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 no characterisation method for assessment within the LCA framework exists. Larsen et al. (2009) discussed possibilities for such an assessment, but these thoughts were not further explored. Generally, local and site-specific impacts are more challenging to assess using LCA than those that generate effects on the global or regional level, because the potentially very large variations in exposure and in sensitivity of exposed environments or organisms. 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 should be of value to include pathogen risk in an LCA framework, or at least to shed light on its potential importance compared to other risks.

One of the impacts of major concern to stakeholders is human toxicity, due to the heavy metals and organic micropollutants present in sludge. Human toxicity potential (HTP) has been assessed in several studies, although the results have been found to vary depending on characterisation method (Renou et al. 2008) for a system in which sludge was land applied. Since then, a new framework, USEtox, for the inclusion of the human toxicity and freshwater ecotoxicity impacts of chemicals has gained acceptance (Rosenbaum et al. 2008). Marine and terrestrial ecotoxicity are impact categories that can be assessed using earlier methods, e.g. Goedkoop et al. (2013), but for which no consensus model yet exists. Toxicity assessments in LCA have developed relatively slowly, probably because toxicity is highly dependent on exposure assumptions and the sensitivity of humans and the environment, which need to be covered in an appropriate way in LCA. Another reason could be the fact that toxicity can be assessed by Quantitative Risk Assessment (QRA), and for this reason, the inclusion of toxicity impacts in LCA has perhaps not been considered as urgent as for other impacts. The relevance of HTP assessments for wastewater and sludge systems, using the USEtox methodology, needs to be evaluated.

Although a common practice has evolved for many allocation issues in LCAs of wastewater and sludge management systems (for instance on how to account for the utilisation of nutrients when sludge is used for agricultural purposes, as discussed in Section 2.4.3), there are still challenges to be solved, both as regards the quantification of resources and replaced products in different types of studies, and as a response to the identification of some situations where available common practice is not applicable. A multifunctionality issue experienced in connection to the ROUTES project was how to handle multifunctionality in systems in which WWT is considered to be a by-service, 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 was largely a matter of finding a basis on which a replaced service could be calculated, or a basis on which an allocation could be founded.

Another issue connected to the LCA practice, when accounting for recovered resources, is how to account for benefits other than N and P when sludge is land-applied. The use of sludge on agricultural fields can potentially increase the SOC content, and, thereby, the water-retention capacity of the soil, and the utilisation of the applied N (Hedlund 2012). Figure 4 also reveals that the potential build-up of the soil organic matrix, when sludge is utilised in agriculture, is important to many wastewater industry stakeholders. However, for the purpose of the LiCRA project, previous approaches (Peters & Rowley 2009; Schaubroeck et al. 2015) were not found suitable for accounting for benefits other than N and P from sludge use on arable land, as no irrigation can be assumed to be replaced in the studied region (south-west Sweden), and organic amendments are not commonly used to improve soil quality on farms with no access to manure in the region.

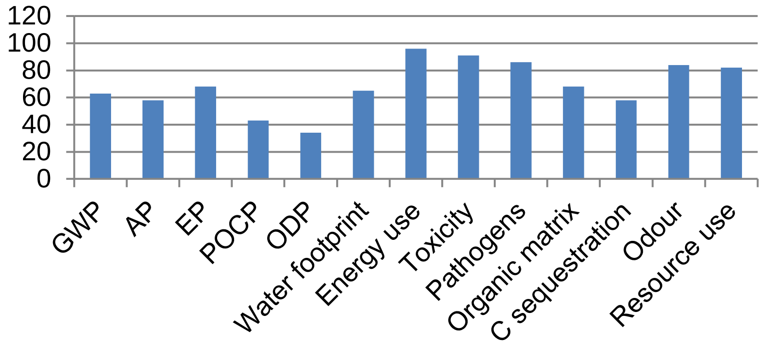

Figure 4. Response to stakeholder questionnaire evaluating the importance of different life cycle impacts in LCAs of wastewater and sludge management systems, according to industry and academia representatives that participated in the ROUTES end-user conference 2012-10-25 in Rome, Italy. The participants were asked to grade the importance of the different impacts for their organisation, from 0 points (not important) to 5 points (very important). Overall points for each impact category by all participants are reported in the figure.

3 Aims and Approach

This thesis discusses LCA methodological challenges encountered during the work on three different projects described in Section 1.2, when assessing wastewater and sludge management systems, and how these challenges have been addressed. The main findings are presented in Papers I-V (see List of publications) and are further discussed in this thesis summary.

3.1 Aim of the research

The overall aim of this research is to improve LCA methodology and practice so that LCA can provide more useful guidance on environmental life cycle impacts resulting from the management of wastewater and sludge, in particular for larger urban treatment systems with a focus on resource recovery.

An LCA can only answer the specific questions that it is set up to address. But a precondition for fully utilising the potential of the LCA to answer these questions is to frame the LCA in an appropriate way in relation to the questions. As the ILCD Handbook (EC-JRC 2010) and the guideline documents in the ISO14040 series are very general, guidance is needed on how to apply them to situations specific to wastewater and sludge management systems. This research aims to investigate how to proceed in certain specific situations where guidance is lacking. Three specific research areas (A-C) were identified based on the discussion in Section 2.4.4, and each of these are defined in the current section. For each of these areas, one or two specific research questions are formulated. Figure 5 summarises how the different research questions and appended papers relate to the different research areas. In addition, this thesis summary explores the potential for LCAs of wastewater and sludge management systems to answer the questions set up for the studies, i.e. discusses which conclusions that can be drawn for a specific LCA, and which perspectives the LCA does not address.

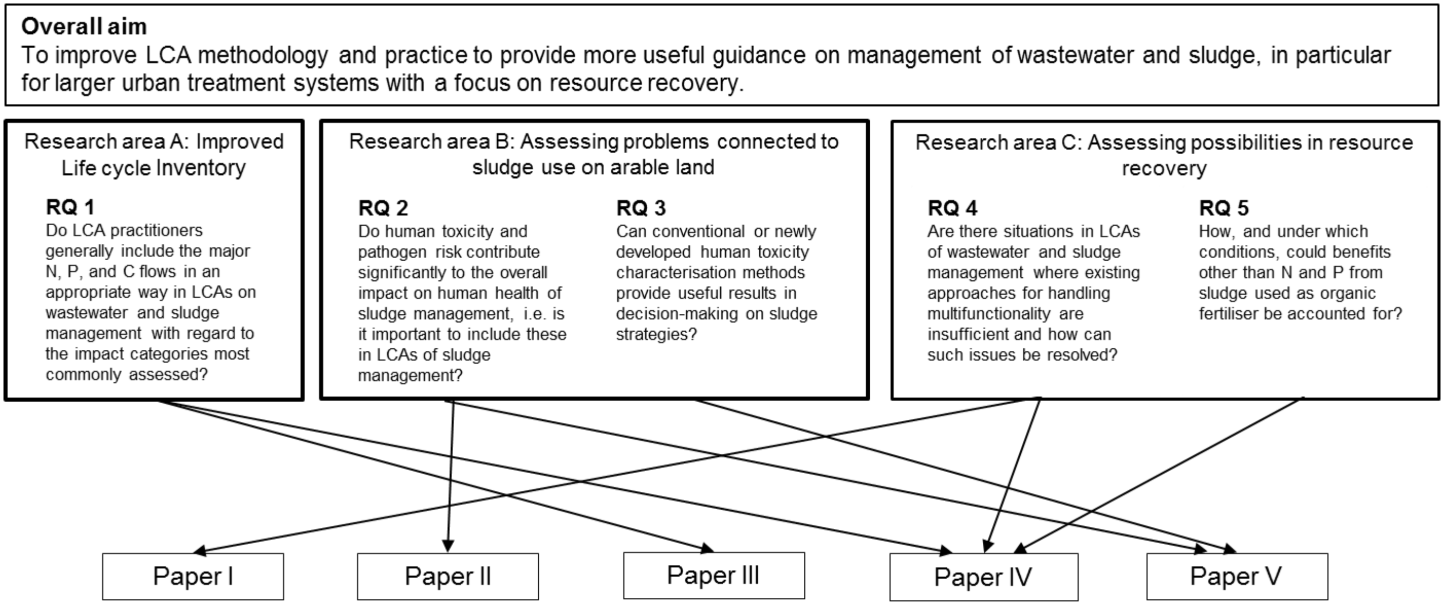

Figure 5. Schematic picture displaying the overall aim and the research questions (RQs) that were identified in connection to this aim. How each of the appended papers connect to the different RQs is also displayed.

3.1.1 Research area A: Improved Life Cycle Inventories

An LCA must be able to accurately map all resource and emission flows, for the entire studied system, that may significantly contribute to the impact categories the study sets out to assess. Otherwise, results may be skewed and misleading. The fact that resource recovery from wastewater and sludge is increasingly pursued highlights the need for accurate mapping of flows involved in this resource recovery. Resources are recovered from wastewater and sludge mainly due to their content of N, P, and C. At the same time, many of the potential environmental impacts directly related to constituents of the sludge are also related to these elements. This means that the fate of such flows during wastewater and sludge treatment decides how large a share of the N, P, and C will end up as a flow that can be recovered as a beneficial by-product of the studied system (hereafter denoted recoverable flows), and how large a share will end up as an emission that potentially contributes to environmental impacts.

Research question 1: Do LCA practitioners generally include the major N, P, and C flows in an appropriate way in LCAs on wastewater and sludge management with regard to the impact categories most commonly assessed?

In particular, Paper III addresses research question 1 by reviewing LCI practice during the past decade for N, P, and C flows, in order to investigate which flows are included for wastewater and sludge treatment systems, and how these are quantified, including variations in this practice. This mapping made it possible to evaluate these practices to identify good examples and development needs. Improved inventories of the potential benefits of N, P, and C in sludge used for agricultural purposes was, in Paper III, identified as an area where practices need to be improved. As a response to this, Paper IV investigates whether the existing knowledge of such benefits can enable improved quantification of benefits.

3.1.2 Research area B: Assessing problems connected to sludge use on arable land

For LCAs of wastewater and sludge treatment systems to be useful as part of a decision-making process, the decision-maker needs to understand the perspectives that LCA can bring to a specific decision context, and which perspectives it cannot address. LCIA methodology has, so far, mainly focused on assessing life cycle environmental impacts in a generic way that better corresponds to actual impacts for global environmental impacts. The more the actual impact relies on, for instance, the specific fate and effect of an emission, the more the guidance provided by the generic approach of a traditional LCA can be questioned. Some efforts focus on the development of LCIA methodology that can handle case-specific and site-specific impacts to a higher extent than common in LCA, see e.g., Harder et al. (2015b), Gallego et al. (2010) and Finnveden and Nilsson (2005).

For sludge spreading on arable land, two areas of great concern to stakeholders are human toxicity and risks related to exposure to pathogens, which are impacts related to the metals, organic contaminants, and pathogens in the sludge. These are examples of impacts that have a more site- and case-specific character. Several characterisation methods exist today for the inclusion of toxicity impacts of metals and organic compounds, but large discrepancies have been shown when applying these on sludge treatment systems (Paper II, Renou et al. (2008)). For pathogens, no LCA had, prior to Publication D and Paper II, assessed life cycle impacts on human health or the environment. Two research questions were identified for research area B.

Research question 2: Do human toxicity and pathogen risk contribute significantly to the overall impact on human health of sludge management, i.e. is it important to include these in LCAs of sludge management?

The research presented in Paper II evaluates the importance of the inclusion of human toxicity and pathogen risk in human health impact assessment in the LCA of wastewater and sludge management systems. A new method developed in this research context for pathogen risk assessment, described in Publication D, was used.

Paper V (and to some extent also Paper II) addresses the limitations in currently available toxicity assessment methodology of importance to wastewater and sludge treatment systems. The assessment was made for two model WWTP systems in which stabilised sludge was either used on agricultural fields or incinerated.

Research question 3: Can conventional or newly developed human toxicity characterisation methods provide useful results in decision-making on sludge strategies?

The risks of using sludge as organic fertiliser on arable land is of concern to many stakeholders, and HTP is, from that perspective, one of the more relevant impact categories to assess in LCAs of wastewater and sludge treatment. Paper V presents an LCA case study of two sludge handling systems, one in which sludge is hygienised by pasteurisation and, subsequently, spread on arable land, and one in which the sludge is incinerated and P is recovered from the ashes and used as a fertilizer on arable land. The paper contains an evaluation of the importance to overall results of using the scientific consensus method USEtox

(Rosenbaum et al. 2008) and the newly developed method SLAtox (Harder et al., 2015), for assessing HTP. SLAtox was developed to be specific for a sludge context. Paper V discusses whether HTP results in LCA is relevant for decisions on sludge handling strategy in the specific decision context in Paper V. This concerns not only whether the LCIA is specific enough to assess sludge spreading on arable land, but also if the LCA method, in itself, is suitable for determining whether or not sludge should be land applied.

3.1.3 Research area C: Assessing possibilities in resource recovery

As stated above, the main aim of this research is to improve LCAs of wastewater and sludge treatment in which resource recovery occurs. Research questions 4 and 5 deal with two types of challenges related to resource recovery; how to handle multifunctionality issues and how to quantify benefits.

Research question 4: Are there situations in LCAs of wastewater and sludge management where existing approaches for handling multifunctionality are insufficient and how can such issues be resolved?

This thesis focuses mainly on LCAs performed for the wastewater industry, but also discusses other possible decision contexts. The choice of decision context affects, for example, the choice of the function which is seen as the central studied function in a system and, thus, the handling of multifunctionality issues. Paper I and Paper IV address research question 4 by highlighting two specific types of systems in attributional LCAs identified during the work in the three described research projects as extra challenging when assessing possibilities in resource recovery: i) a system that utilises the C in wastewater to produce a biopolymer-rich stream, by mixed-culture fermentation technology, from which PHA can be recovered, i.e., achieves simultaneous WWT and the generation of the biopolymer PHA, and ii) a system of sludge treatment generating biogas, and digested sludge that is used for agricultural purposes.

Paper I suggests a new allocation approach to solve the multifunctionality issue in the first type of system and evaluates its usefulness.

Paper IV evaluates different possible ways of handling multifunctionality for the second type of system, and questions the choice of replacement ratio for the replacement of mineral fertiliser by sludge in previous studies.

Research question 5: How, and under which conditions, could benefits other than N and P from sludge used as organic fertiliser be accounted for?

Other benefits, in addition to the nutrient recovery, are sometimes brought forward by farmers (KSLA 2012), for instance, the provision of organic matter to soils. Paper IV suggests how benefits other than N and P recovery can be considered when sludge is land applied, in situations where available approaches are found insufficient, and illustrates its practical application.

3.2 Overall methodological approach

The research presented in this thesis explores and adds to LCA theory and practice within the field of wastewater and sludge management by reviewing practice within different LCAs in earlier scientific literature (Paper III presents an extensive review) and evaluating the use of new methodological ideas by applying them to case studies (Papers I-II and IV-V). The specific areas of research have been guided by needs identified during work within three different projects, described in section 1.2.

The five appended papers all present research on LCA methodology, but they have different focus areas. While Papers I and IV mainly focus on allocation problems found in the goal and scope definition phase of LCA, Paper III focuses primarily on the current practice in LCIs, and Paper II deals with the characterisation of impacts in LCIA. Paper V discusses, in a broad sense, the interpretation and usefulness of LCA results in a specific decision context.

4 Summary of Appended Papers

As described earlier, this thesis is built on research presented in Papers I-V. These papers contribute, in different ways, to improved LCA theory and practice in assessments of wastewater and sludge management systems. This chapter summarises the findings in the appended papers.

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 C in wastewater to produce a biopolymer-rich stream, from which, the biopolymer PHA can be recovered, during wastewater treatment. PHA was, in this case, considered the main function of the studied system, and the WWT a by-function.

One methodological issue discussed was the question of whether or not the wastewater inflow could be regarded as a free feedstock that should not be allocated any environmental impacts from earlier process 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 contributions to the development of LCA methodology. During wastewater treatment, the C content in wastewater is reduced; the C reduction is thus part of the treatment function in the studied system. The C 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 happen in the same process and are both related to the C removal. It should also be mentioned that the allocation concerns the partitioning between a service and a product, which is challenging in terms of finding a basis for comparison. One possibility demonstrated in the paper was to use substitution to account for the wastewater treatment function that the process performs in addition to the generation of a biopolymer-rich stream. This avoided the need for allocation, but the question of on which basis that this substitution was to be made remained. Finding a common physical unit for the wastewater treatment service and the biopolymer production to base the substitution or allocation on proved to be difficult. 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. Further, an allocation based on economic parameters was deemed to introduce too large uncertainties into the assessment due to the uncertain price of the specific PHA that has not yet been introduced to the market; neither the properties of potential products, nor the characteristics of large-scale application were yet clear.

The study concluded that there was limited guidance in the literature on how these challenges could or should be dealt with for the type of system studied. In the studied system, a reduction of the C 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. A new substitution basis was suggested, which relied on the reduction of C content in the wastewater achieved by the generation of PHA (chemical oxygen demand (COD) was used as a proxy because of data limitations). The substitution was done in two different ways, both of which accounted for the replaced WWT service based on the COD reduction that occurred. One option was to assume that the build-up of biomass would occur in the WWTP regardless whether PHA was to be produced or not, and that the generation of PHA in the cells during fermentation would occur 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 corresponds to the reduction in COD during biomass build-up. Another option would be to consider that 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 a WWT service that corresponds to the reduction in COD caused by both microorganism build-up and biopolymer generation. In addition, a new alternative approach was suggested, also utilising a C (COD) basis for allocating the impact between the two functions of the system. In this case, the allocation was based on the share of the total C reduction in the studied system that occurred because it was incorporated into 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 COD-reduction-based allocation approach useful.

4.2 Summary of Paper II

Stakeholder concerns regarding sludge land application are generally related to health and environmental impacts from, for instance, emissions of heavy metals, organic compounds or pathogenic microorganisms to agricultural soil. Despite this concern, human toxicity and pathogen risks are not routinely assessed in 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 WWT followed by either land application of sludge for agricultural purposes, or incineration, was then assessed (Paper II).

Paper II reports on a full LCA in which pathogen risk was compared to other impacts on human health in order to provide an understanding of the orders of magnitude. The LCA assessed the total impact from the model systems on the burden of disease (in disability-adjusted life years, DALYs) for the endpoint human health. This calculation included impacts from the midpoints GWP, ODP, ionising radiation potential (IRP), particulate matter formation potential (PMFP), photochemical oxidant formation potential (POFP), HTP, and pathogen risk. ReCiPe characterisation methods (Goedkoop et al. 2013) were used for GWP, IRP, ODP, PMFP, and POFP. For human toxicity, USEtox was used (recalculated to endpoint results as recommended by the ILCD Handbook (EC-JRC 2011)), and for pathogen risk, the results presented in Publication A were used together with additional results calculated for the incineration system. Pathogen risk was only assessed for the foreground 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 assumptions, such as the assumed concentration of pathogens in the influent wastewater. For the model system in which sludge was used for agricultural purposes, the pathogen risk contributed up to 20% of the overall impact on human health. The overall results proved to be sensitive to the characterisation method chosen (the consensus model USEtox or ReCiPe) for human toxicity (mainly dependent on differences in characterisation factors for heavy metal emissions to agricultural soil, especially Zn and Cr).

4.3 Summary of Paper III

The interest in resource recovery from wastewater and sludge is currently increasing, due to the content of potentially valuable N, P, and C related properties. However, the destiny of these substances during wastewater and sludge treatment determines how large a share that ends up as recoverable flows, for instance, C in digester biogas, or P to arable land, and how large a share that is emitted to air, water, or soil, and thereby contributes to environmental impacts. In fact, some of the most commonly assessed impact categories in LCA, such as GWP, AP, EP, and POFP, are highly influenced by such N, P, and major C flows (Publication G). To be able to make a relevant assessment of the environmental pros and cons of a system in which resources are recovered requires an LCA that is based on ambitious and purposeful LCI work. Paper III presents a review describing which sludge N, P, and C recoverable flows and emission flows were included in LCAs of wastewater and sludge management published in 63 peer-reviewed papers in scientific journals between 2004 and 2015, and how these flows were quantified.

The study showed that while some flows, like emissions to water through the WWTP effluent, were generally included and quantified using primary data, other emissions, such as emissions to air from sludge storage before agricultural application, were generally not included. All in all, a large variation was found between studies as regards LCI practice. It was recommended to have a mass balance in mind for each substance.

A need for improved transparency in the LCIs was one of the main findings in the review. A recent increase in the use of online support information published as an appendix to papers can potentially partly contribute to solving these transparency problems, allowing for more material to be published in connection to each article. The study also highlighted a need for improved specificity and completeness of inventories. Quantification of recoverable flows in systems in which sludge is spread on arable land was highlighted as an area where inventory practices need improvement, and this was therefore followed up in another study, as reported below (Paper IV).

In addition to serving as a basis for the evaluation of LCI practice in Paper III, the review was intended to function as a reference for future LCIs in order to support conscious and well-motivated choices of which flows to include, and in some cases, how to quantify those flows.

4.4 Summary of Paper IV

Sludge spreading on agricultural land is one of the most debated routes for sludge management. In a system in which sludge is digested and then spread on arable land, resource recovery occurs via the biogas generated from C in the sludge, and as N and P, and possibly also micronutrients such as potassium (K) and soil conditioner (from the organic C), on arable land. If such a system is assessed in order to decide on future sludge handling strategies for WWTPs, the sludge treatment is likely to be the main function of the studied system, and the biogas and the sludge on arable land will be secondary functions.

Based on the findings in Paper III, a need for improved quantification of the recoverable flows in systems in which resources are recovered from wastewater and sludge was identified. In paper IV, a model system is studied, in which sludge is digested, generating biogas, and the digested sludge is pasteurised and subsequently applied on arable land. The study presented in Paper IV investigates the importance of the choice of approach to handle the multifuctionality and the quantification of the recoverable flows. Several possible ways of solving the multifunctionality issues were identified, either based on a substitution principle crediting the system for replaced activities, or by using an allocation principle to divide the impact from the system between its different products based on a common denominator. A substitution approach has been most commonly applied in previous LCAs of this type of systems, but the modelling has, prior to this, only considered replaced N and P mineral fertilisers, and using very arbitrary and generic replacement ratios, often based on a relationship between plant availability in the sludge and the mineral fertiliser, respectively. The impact of the choice of P replacement ratio was found to be small for the assessed impact categories (with the most recent data for mineral fertiliser production used – a clear improvement in data quality compared to previous studies), but the impact of the N replacement ratio was found to be more important. The study showed that choosing a replacement ratio based on common farming practice, rather than the possibility for fertiliser replacement, is relevant in some contexts. This choice can be considered to better reflect the static technosphere that is assumed in attributional studies (EC-JRC 2010). Allocation as an alternative to substitution was rejected for the studied system. The only possible common denominator for the different functions was economic pricing. However, attributing prices to the different functions was shown to be connected to very large uncertainties.

Other benefits from sludge spreading on arable land than N and P had, prior to Paper IV, been accounted for to a very limited extent, by accounting for the water retention capacity or replaced peat and straw or K fertiliser. However, in regions where neither irrigation nor organic amendments are commonly applied on fields, such approaches are not useful. Studies have shown that the fact that N and P are delivered to the soil together with organic matter can have an effect on crop yields, in regions with low levels of SOC, partly because the N mineralisation is affected and possibly also due to other soil conditioning properties of micronutrients or organic C. Quantifying this effect is, however, challenging, partly due to the lack of data on such effects. Two different ways of quantifying increased crops yields was tested for the studied model system. The results indicated that this effect might contribute to reduced impacts of the same magnitude as the replaced mineral fertilisers for some impact categories (especially GWP and POCP). The impact of the choice of the use of biogas, however, proved to be even more important for the overall LCIA results.

4.5 Summary of Paper V

Environmental life cycle assessment (LCA) is one of the tools used by the wastewater industry to inform decision-making on preferable technologies and strategies. However, to provide useful guidance, the study needs to address the central questions and be designed accordingly. Based on earlier reviews of published LCAs in this field, it is clear that they do not always provide sufficient guidance on how the results can be interpreted for the decision context of the study, which may have made it hard for the commissioners of the study to interpret which value the LCA has as decision basis and makes it impossible for others to judge what elements can be useful in other contexts. This is problematic as it could result in that both targeted decision-makers and others miss out on important perspectives brought forward by the LCA and combined with the common overreliance on the value of the LCA as decision basis, this can lead to the wrong conclusions.

Paper V presents an LCA, made to inform officials and politicians in the municipality of Gothenburg, on the consequences of different sludge strategies for the local WWTP. The assessment covered two WWT systems: one system in which the sludge is pasteurised and digested under mesophilic conditions, whereafter it is stored and then spread on arable land; and one system in which digested sludge is, instead, incinerated and P is recovered from the ashes. The study aimed also at reflecting on whether LCA at present can enable a fair and relevant comparison of the environmental consequences of the studied systems for this specific decision context, i.e., which perspectives the LCA can actually bring to the decision-making table, and if those are sufficient to cover the knowledge of environmental impacts needed for the decision-making in the studied context. The midpoint indicators GWP, AP, EP, POFP, and cancer and non-cancer HTP were assessed. The results were also translated into impact on the endpoint human health. The LCA aimed to include recent developments in LCA methodology and practice relevant for wastewater and sludge treatment systems in order to reflect the state of the art. The study evaluated, for instance, the new characterisation method SLAtox (Harder et al. 2015b), developed as an attempt to make the USEtox method more specific for exposure through sludge spread on arable land.

The findings showed that both the choice of sludge handling strategy and biogas utilisation was important for the overall LCIA results. For both systems, the credits given to the studied systems for recovered resource utilisation, by accounting for replaced production and use of natural gas and/or mineral fertilisers, were important components of the results. For the pasteurisation system, emissions during sludge storage and after spreading on arable land, e.g, of heavy metals, proved to be main contributors to the impact at midpoint level. For the incineration system, emissions from incineration and from the background system contributed the most. Based on the assessed midpoint impact indicators (except for freshwater EP), and the end-point human health, the pasteurisation scenario performed equal to or slightly worse than the incineration scenario. One of the reasons for this was the greater HTP for the pasteurisation scenario, mainly due to heavy metal emissions from the sludge use in agriculture. This difference was independent of whether the SLAtox method or USEtox was used as the characterisation method. The emissions of a few heavy metals (e.g. Zn) to soil were responsible for the higher impact from the pasteurisation system at endpoint level. However, HTP assessment is still suffering from a lack of inventory data and characterisation factors for many substances. And, as concluded by Harder et al. (2015b), there are, e.g., indications that the intake of Zn is not necessarily as high as modelled using USEtox or SLAtox (Andersson 2012), and results should therefore be interpreted with care.

5 Discussion of Research Findings

This chapter contains a discussion of how the research summarised in Chapter 4 contributes to answering the research questions defined in Chapter 3, and ends with a discussion on the usefulness of LCAs of wastewater and sludge treatment systems after the new developments discussed in Sections 5.1-5.3.

The research presented in this thesis aimed to improve LCA methodology and practice to enhance LCAs of wastewater and sludge treatment systems in which resources are recovered. In the future, there will probably be an increased focus on resource recovery from wastewater streams, which will likely challenge the view of wastewater and sludge as wastes, as wastewater and sludge are then instead important contributors to the recycling of nutrients and organic material in society, as well as a source of energy. From such a perspective, a wastewater and sludge treatment facility could be increasingly comparable to a biorefinery. Such a scenario would even increase the relevance of the research findings presented below.

Figure 6 displays the five research questions and illustrates how each paper contributes to answering those questions.

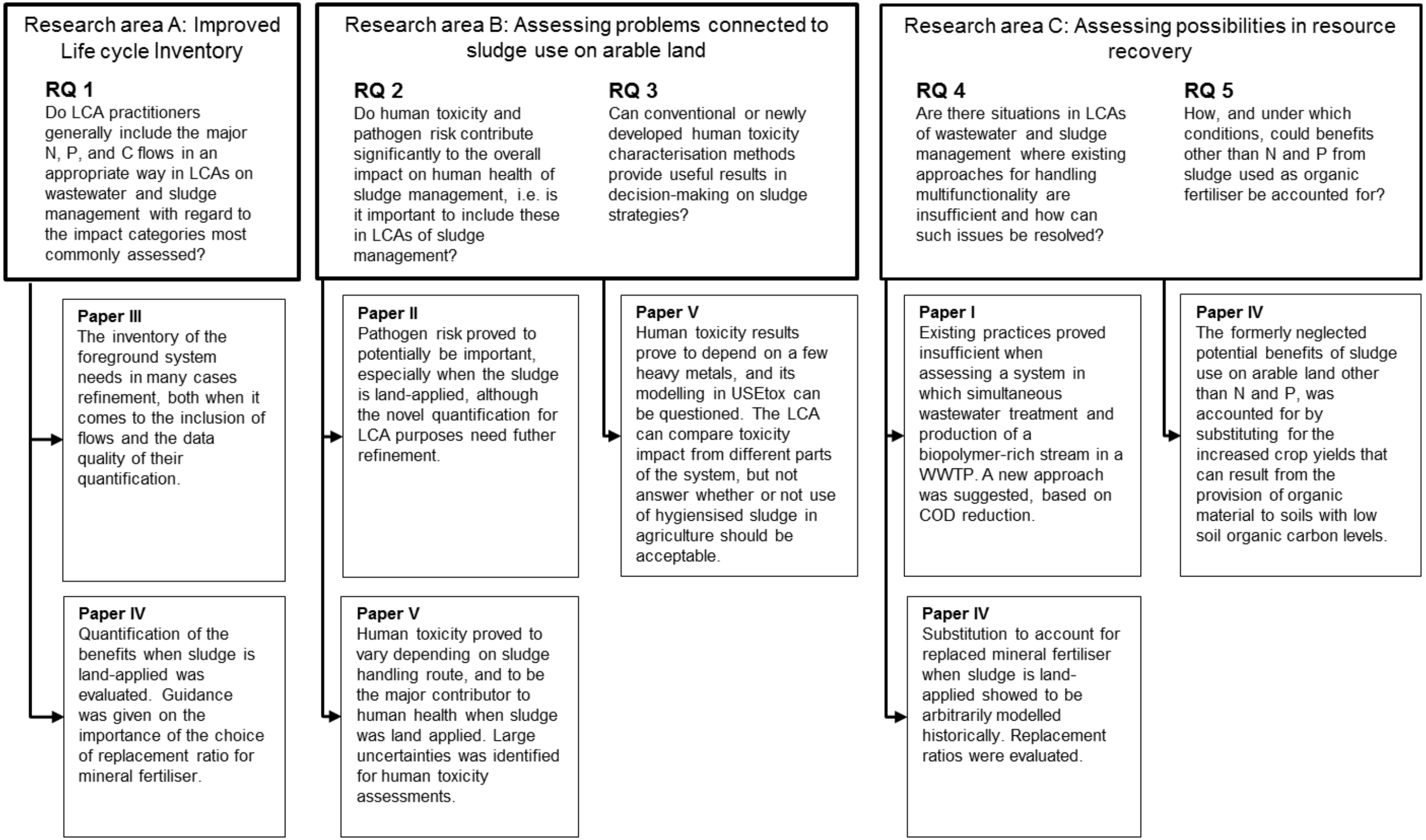

Figure 6. Summary of how the papers answer the research questions (RQs) identified for each research area in this thesis.

5.1 Research area A: Are life cycle inventories ambitious and purposeful enough?

In order to fully assess any impact category in an LCA, the LCI needs to be specific and comprehensive enough to reflect reality in a meaningful way, both as regards the coverage of emissions and recoverable flows, and as regards the quantification of these flows. Research question 1 asks if LCIs of wastewater and sludge systems have been comprehensive enough to enable relevant assessments of the most commonly assessed impact categories in such studies with regard to major N, P, and C flows.

5.1.1 Completeness and transparency of Life Cycle Inventories

In Paper III, a review was made of the modelling in LCA of N, P, and major C flows originating from wastewater and sludge. The review revealed a large variety in which flows that were included in the inventories in different studies. Some flows, such as emissions from the storage of sludge before spreading on arable land, were routinely left out of the inventories. As was shown in Paper V, emissions to air from storage can be important for GWP and AP results. Some flows, such as N and P emissions through the effluent, were consistently covered using primary or modelled data, while most other flows were inventoried using less specific data types. From the results in Paper III, it can be concluded that there is a need for increased completeness in the selection of flows and improved specificity in their quantification. It is suggested that having mass balances in mind when performing an LCA can help to avoid neglecting potentially important flows and over- or underestimating the size of flows. The review, in itself, also provides an important research contribution as a reference for future LCIs. However, the findings from the review are in many cases blurred by the lack of transparency in LCIs on which flows that were included and the type of data used to quantify those flows.

Although the LCI review presented in Paper III focused on N, P, and C flows, a similar lack of possibly relevant flows has been noted for inventories on substances contributing to toxicity, as discussed in Paper V, and pathogens, as discussed in section 5.2.1.

5.1.2 Trade-offs between foreground and background system inventories

One of the benefits of LCA methodology in comparison to other assessment methodologies is the systems perspective in the assessment, i.e., that the full life cycle of a product or a service is covered. Although the life cycle of wastewater and sludge treatment functions is not as easily defined as for many other products and services, a life cycle perspective means that both direct emissions and resource consumption in the studied foreground system and processes in the background system, like the production of heat, electricity and consumables, are assumed to contribute to the assessed impact categories. The review behind Paper III showed, in addition to the findings presented in the paper, that the background system was generally well covered in the reviewed studies; all of them included energy production, and most of them included the production of consumables. However, the shortage of inventory data for the foreground system in many studies, as identified in Paper III, limits the holistic ambitions of LCA. It is therefore vital that efforts to include the background system in the assessment (one of the main benefits of LCAs) does not lower the ambitions for the inventory of the emissions in the foreground system, so that flows are either left out or quantified in an excessively generic way. Such limitations are particularly unfortunate for this type of systems for two major reasons. Firstly, emissions from the foreground system in many cases have proved to be major contributors to environmental impact (see Paper IV and Paper V). Secondly, the main purpose of WWTPs is to avoid emissions to water bodies through the effluent, at the expense of resource input and emissions elsewhere through the sludge processing system or from background systems, which means that a proper inventory of both the foreground and background system is central for a relevant assessment of a wastewater and sludge treatment system. These limitations would disable the use of an LCA for many purposes, such as, determining whether an investment in precipitation chemicals to decrease P emissions to the recipient through the WWTP effluent would pay off (environmentally). Careful modelling of the foreground system is thus a prerequisite for an LCA to contribute with a holistic systems perspective of the assessed system, instead of just shifting the focus to the background system.

5.2 Research area B: Assessing problems connected to sludge use on arable land

The use of sludge in agriculture can give rise to environmental impacts such as human toxicity, different types of ecotoxicity, or pathogen risks to humans. These impacts are often of great concern to stakeholders and, therefore, important to consider in decision-making situations. This section discusses whether LCIA methodology can handle such case-specific impacts connected to the use of sludge in agriculture, as a response to research questions 2 and 3, in particular in terms of toxicity impacts and pathogen risk. The issue regards both whether the LCIA HTP characterisation methods are specific enough for the sludge context and if LCA, in itself, is a suitable method for evaluating whether sludge should be land applied.

5.2.1 Is it possible and is it important to include pathogen risk in an LCA?

Publication D describes an attempt to assess pathogen risks using QMRA results adjusted to fit into an LCA framework. Pathogen risks were found to be potentially important for the overall impact on human health from a system in which sludge is land-applied, assessed in Paper II. Attempts to include pathogen risk in LCA have, so far, been very limited in published literature, not only for sludge management systems but for LCAs in general. Therefore, the study presented in Publication D and Paper II can be seen as an important contribution to the field, by showing that it is possible to quantify pathogen risk for LCA purposes, and that the pathogen risk can contribute an important part of the overall impact on human health and, therefore, is relevant and possibly even important to include in LCAs on sludge treatment systems, especially in cases where the sludge is land applied.

When performing an LCA, it is important to be aware of the limitations of the method. This is especially important when results from using immature characterisation methods, such as for pathogen risk discussed above, are evaluated. In Paper II, the performed assessment of pathogen risk was not considered specific enough for a comparison between systems that involve agricultural application of sludge after different sludge treatments. Methodological shortcomings; however, were not the primary reason for why the method cannot be used for such comparisons, as the method applied in Publication A could, in principle, have been used. The main reason was, instead, a lack of case-specific input data both for the inventory on pathogens concentrations and for the characterisation of such flows. A fact that further complicated the assessment was that, in order to take pathogens into account, not only was pathogen concentration needed, but also enough information to calculate the burden of disease as a result of the exposure to the specific pathogen.

The method for including pathogen risk in LCA, described in Publication D, is limited to agricultural sludge systems, but the same principles could be used in developing methods for assessing other types of systems. This was done for a 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 are expected to be fully eliminated during incineration.

Paper II shows that it is relevant to include pathogen risk in assessments of wastewater and sludge management systems, regardless of sludge management approach chosen, because pathogen risk has the potential to make an important relative 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 is used, 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.

Paper II shows that pathogen risk might be an important contributor to the overall impacts from a WWTP system with agricultural sludge handling. Depending on sludge hygienisation technique applied, the pathogen risk could, in some cases, have a lower or higher impact. The relative importance of pathogen risk in relation to other impacts on the endpoint human health was shown to depend on the HTP results, which include large uncertainties, as described in section 5.2.3. The relative importance of pathogen risk could thus also be higher or lower than shown in Paper II.

In certain decision contexts, such as when sludge is land-applied, it would be important to include this impact category in the LCA, regardless of if it being expected to be a major contributor to the overall environmental impact or not, simply because stakeholders are concerned.

5.2.2 Is it important to assess human toxicity potential in an LCA of sludge use in agriculture, and is the available consensus method for human toxicity potential relevant for sludge contexts?

HTP was shown in both Paper II and Paper V to contribute substantially to the overall impact on human health at the endpoint level, for systems with different sludge handling, but, in particular, for systems in which sludge is used for agricultural purposes.

Paper II showed that the human toxicity impacts of a system in which sludge is spread on arable land are highly dependent on the characterisation method applied when USEtox 1.01, as recommended in the ILCD Handbook (EC-JRC 2011), and USES-LCA, as applied in the ReCiPe system (Goedkoop et al. 2013), were compared at the endpoint level. The difference in characterisation of the heavy meal Zn alone was found to contribute heavily to the much greater impact calculated by the USEtox method than by the USES-LCA. It was notable that the characterisation factors for heavy metals in USEtox 1.01 were classified as interim factors, to be interpreted with care, due to the relatively high uncertainty of fate, exposure, and effect estimates (Huijbregts et al. 2010). In the recently released USEtox 2.0, the Zn fate factor is slightly higher, but it is compensated for by an even greater decrease in the effect factor, which results in a lower characterisation factor in USEtox 2.0 than in USEtox 1.01. The implications of this for a full wastewater and sludge treatment system can be seen in Paper V, which shows that the human toxicity of Zn was still responsible for the majority of the impact for the endpoint indicator of human health.

Paper V also evaluated the potential importance exchanging USEtox for SLAtox for characterising toxic emissions from agricultural fields, in relation to HTP from other parts of the studied system. SLAtox (Harder et al. 2016) is utilising the same effect factors as USEtox 2.0, but with a fate modelling specific for sludge utilisation on arable land. For cancer HTP, the overall HTP results were slightly higher using the SLAtox model than using the USEtox model. However, for non-cancer human toxicity, which provided the dominant contribution to the overall impact on the endpoint human heath, no major difference could be seen. It can be concluded that increase in case-specificity, i.e., a characterisation more specific for a sludge context, of the toxicity impact assessment was of limited importance for the results when applied to the full life cycle of the specific studied system. However, uncertainties still remain regarding the relevance of such HTP assessments. In order to further evaluate the relevance of the HTP results for sludge contexts, their relevance compared to the results of field studies or other assessments must be judged. Harder et al. (2015b) reviewed some previous QRAs studies and found a discrepancy between which metals that were identified as of major concern in QRAs and what was seen in their LCA. The authors also found indications that the modelled uptake of heavy metals in USEtox and SLAtox does not correspond to field measurements. This indicates a need for further evaluation. This implies that despite HTP being pointed out as major contributor to the endpoint human health in Paper II and Paper V, other impacts cannot be disregarded as possibly important contributors to human health impacts, as HTP results are uncertain.

5.2.3 The usefulness of LCA as a tool for assessing human toxicity and pathogen risk

Research questions 2 and 3 ask whether or not LCAs assessing human toxicity and pathogen risk to human health, for systems studying the utilisation of sewage sludge in agriculture, can provide relevant information to decision-makers. In other words, whether or not LCA is an appropriate tool for such assessments.

Both toxicity impacts and pathogen risk can either be assessed in separate assessments, for instance, by QMRAs and quantitative chemical risk assessments (QCRAs), that are presented alongside an LCA, or be included within the LCA framework, as shown in Paper II, Paper V, and Publication A. Which of the two approaches is preferable, if any, may depend on the decision context of the specific study. The difference between QCRA and LCA, and hybridisation efforts for these methods, have been reviewed by Harder et al. (2015a).

Including assessments of toxicity and pathogen risk within the LCA framework enables comparisons between toxicity impacts and pathogen risk from the foreground and the background systems, which otherwise most likely would be overlooked. It also enables comparison of these types of impacts to each other, and to other types of impacts, assessed under the same framework and with the same system boundaries, which facilitates a holistic understanding. For many stakeholders, local impacts related to sludge use are the main concerns, and global overall environmental impact may be considered less important. In this respect, being able to assess toxicity and pathogen risk under the same framework as other environmental impacts may contribute to extend awareness of other potential impacts, which could be of use in future practical decision-making contexts.

However, due to some inherent characteristics of LCA, HTP results cannot be used to answer, e.g., if the risks to humans of applying sludge is acceptable or not. LCA commonly assesses systems under standard operations, it does not consider possible synergetic effects between different substances, it does not account for the background levels of a substance in nature and makes no comparison against reference concentrations in the human body or in nature that are considered to be safe levels.

It can be concluded that assessing human toxicity and pathogen risk in LCA can bring important perspectives, but needs to be complemented with other types of assessments or studies.

5.3 Research area C: Assessing possibilities in resource recovery from wastewater and sludge

Research question 4 focuses on the handling of multifunctionality in LCAs of wastewater and sludge treatment systems, which is increasingly relevant as a result of the increased focus on resource utilisation from wastewater and sludge.

The ILCD Handbook prescribes that if substitution or allocation is applied, "the resulting lack in accuracy shall be explicitly reported and considered in the results interpretation" and that "assumption scenarios" of data, parameters, and method assumptions shall be performed for comparative LCA studies. One such method assumption could be the importance of the chosen approach for handling the multifunctionality of a system, which can be tested by applying different approaches; however, such a sensitivity analysis had not been done in the studies reviewed in Paper III. This was however done in Papers I and IV, as described in this section. Section 5.3.1 describes a system encountered in the ROUTES project in which multifuctionality issues requiring efforts beyond common practice were identified, and the efforts to solve these multifunctionality issues are described and discussed. Section 5.3.2 reflects on choices made when accounting for recovered resources using a substitution approach in attributional studies. Research question 5 focuses on the benefits accounted for when sludge is used for agricultural purposes. This is discussed in Section 5.3.4.

5.3.1 Novel approach for handling a challenging multifunctionality issue

The focus in LCAs of wastewater and sludge management can be either on the WWT service or (any of) the (co-) product(s), depending on the decision context of the study, which is reflected in the choice of functional unit. Paper I and Publication E both discuss allocation approaches for the same system in which simultaneous WWT and PHA production occurs, but with different foci, which results in different allocation issues. In Paper I, PHA is considered the main product and WWT is a co-service. In Publication E, the WWT is considered to be the main service and PHA is a co-product.

LCAs comparing the PHA generated from wastewater in a WWTP with another type of polymer would face the challenge of how to account for the wastewater treatment co-function, as described in Paper I. The easiest approach would be to allocate all the environmental impact to one of the functions, for instance, let the waste handling function (the WWT) pay all the environmental burden. When to consider a residue as a by-product or a waste is not necessarily an objective decision and may be debated, as described in the introductory section to this chapter. The current section deals with multifunctionality issues arising when considering the WWT and the generation of PHA as co-products (Paper I and Publication E). The challenges related to substitution differed in the different papers, depending on which product was considered to be the by-product. In line with standards, the studied system should be subdivided as far as possible (EC-JRC 2010) to avoid allocation. However, in this case, it was not possible to sub-divide the studied system in order to solve the allocation issue (for neither of the two situations discussed in Paper I and Publication E).

To avoid allocation by, instead, crediting the system for the by-product or service by substitution (system expansion) was considered to be the primary option, in accordance with the ILCD Handbook (EC-JRC 2010). 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. This situation was problematic as a novel technology was studied, creating uncertainty about both the details of a future recovery process and the usage and the price of the resulting biopolymer product. 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 issue in Paper I proved to be the more challenging one.

An alternative approach could have been to allocate the impacts between the WWT service and the PHA product; however, such possibilities were found to be challenging. In both decision contexts, physical causation was not easily applied 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, due to large uncertainties on prices.

In the end, two ways of substituting the WWT service were tested in the study in Paper I. In both of these, a novel basis for comparison was used; the replacement of COD reduction in wastewater due to the generation of PHA (as a proxy for the carbon reduction that occurred) was used as a basis. As is often the case in LCIs, data availability partly determines the options at hand when choices are to be made. 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 the carbon content.

In addition to the tested substitution alternatives, one way of partitioning the impact between the WWT function and the generation of a biopolymer-rich stream was identified, using the same COD basis. A classic split between the two functions based on COD content was not possible, due to the fact that both functions utilised the same COD reduction, i.e. the flow could not be sub-divided. Instead, it was suggested that the impact be allocated based on the share of the COD reduction that was incorporated into the PHA. This novel approach for allocation could also prove useful in other situations when resources are recovered during treatment of waste streams, but would likely need refinement.

The choice of approach for handling the multifunctionality in Paper I was shown to be important for GWP results.

In order to properly evaluate possible approaches to solving multifunctionality issues, 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 1.2.1). This enabled thorough discussions with experts on the novel mixed-culture PHA production process, which facilitated the understanding of an appropriate allocation basis and the possibility to identify substitution or allocation on a COD basis. Access to expertise within the field was thus important for the outcomes in Paper I.

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 being 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 stabilisation as a "free" waste treatment function, with no impacts on the system, neither positive nor negative.

5.3.2 Substitution to solve multifunctionality in attributional studies

A much more commonly assessed system than the one discussed in section 5.3.1, but still challenging, is a system in which sludge in anaerobically digested, stored in order to fulfil hygienisation requirements, and subsequently spread on arable land. If the sludge treatment is considered as the main studied function, additional functions would be biogas and organic sludge fertiliser. Papers IV and V assessed such systems. Also in this case, the nature of the multifunctionality issue was dependent on the decision context. If the same system was studied in order to provide policymakers with the environmental consequences of utilising sludge as fertiliser, in comparison to other fertilisers, the provision of nutrients to arable land would likely be considered as the main studied function, which would give rise to other multifunctionality issues (in this case the sludge treatment and the biogas would be additional functions).

Also depending on decision context, the described system could be assessed using either an attributional or a consequential approach. An attributional study is, according to the ILCD Handbook (EC-JRC 2010), among other things, characterised by the system being studied in a static technosphere, while withn a consequential approach, the studied system is embedded in a dynamic technosphere. In both types of studies, multifunctionality issues can be solved by substituting the marginal product/service that the co-product that is going to be accounted for is replacing, according to the ILCD Handbook (EC-JRC 2010). Although substitution can be applied both in attributional and consequential studies, the practical application of the system expansion must be adjusted depending on the chosen approach, i.e., to reflect the static or dynamic nature of the technosphere in which the studied system is embedded.

One example of such a situation is when mineral fertiliser is assumed to be replaced in order to account for the benefits of N and P in sludge on arable land. Paper IV showed that replacement ratios should, in attributional studies, be selected with the attributional approach in mind, especially for mineral N fertiliser, for which the replacement ratio proved to be of greater importance for LCIA results compared to for P. The review in Paper III showed that so far, replacement ratios have been chosen rather arbitrarily, based on the plant availability in sludge compared to mineral fertiliser. Paper IV argues that a replacement ratio should instead be chosen that reflects the farming practice in the studied region, i.e., what would actually be replaced. This would also better reflect the static surrounding assumed in an attributional study.

In Paper V, three different possibilities for modelling the use of biogas was identified, which resulted in that either natural gas, diesel, or heat and electricity could be assumed to be replaced, based on options identified in Paper IV. Due to the specific decision context in Paper V (access to biogas upgrading plant and biogas distribution system) the biogas was assumed to be upgraded and used as a vehicle fuel. Due to the attributional nature of the LCA, the biogas was assumed to replace the production and use of natural gas in vehicles. As both biogas and natural gas can be used in the same vehicles, this choice was considered more in line with the static technosphere. In a consequential study, allowing for a dynamic surrounding system, assuming replaced diesel would be an option, although this would require a shift in the vehicle fleet, and thus reflect a more long-term shift. The choice of product replaced was shown in Paper V to be important for the results for many of the assessed impact categories.

5.3.3 Are all relevant benefits of sludge on arable land accounted for?

Previous sections have discussed *how* different by-functions are accounted for in LCA. However, an interesting aspect is also *which* functions are accounted for. Historically, LCAs of wastewater and sludge management systems in which sludge is utilised as organic fertiliser on arable land have typically accounted for the N and P in the sludge and their ability to replace mineral fertiliser, based on the N and P content of the sludge. However, the use of sludge in agriculture could also have an effect on soil quality in other respects, for instance, in the form of increased soil organic carbon due to the carbon in the sludge (Börjesson et al. 2012). Figure 4 shows that this issue is of interest to industry and academic stakeholders, which further identifies an important area for improvement in LCAs of wastewater and sludge management systems.

Paper IV evaluates the possibilities for accounting for the beneficial effects of sludge other than N and P, such as organic matter provision. Despite issues with quantifying this function, the study showed that it is possible to account for increased crop yields as a result of organic matter provision to soil, in regions with naturally low SOC, and suggested and tested two ways of quantifying the benefit. The resulting credit to the system proved to be important for the LCIA results for several impact categories, at least when the sludge is land applied in regions with low SOC that can particularly benefit from C build-up in the soil. The fact that this study showed that the replaced crop yields can be important for overall results calls for further method development of how to quantify this potential resource.

5.4 LCAs as decision support for sludge management strategy decisions

Sections 5.1-5.3 discussed the performed research on how to improve the LCA methodology and practice for assessment of wastewater and sludge treatment systems. Paper V identifies some of the strengths and limitations of using LCA for assessing wastewater and sludge treatment systems to decide on sludge management strategies; the assessment of several types of impacts under the same standardised framework and the possibility to include and compare impact from the foreground and the background system, being some of the most important. The paper also discusses the use of LCA as part of a multicriteria decision analysis (MCDA) or as part of an integrated techno-economic-environmental assessment (as in Publications F, H and I). This section contains a further discussion of the usefulness of LCAs of wastewater and sludge treatment systems, considering the new developments presented in previous sections.

In Paper III it was concluded that few studies state whether they use an attributional or a consequential approach (or a mixture of these), although one can assume, based on, e.g., the choice of data used for the inventories, that at least some of them apply an attributional approach. Wenzel et al. (2008), Sørensen et al. (2015) and Ishii and Boyer (2015) are examples of consequential studies. A consequential approach can be very useful for waste management studies, see, for instance, the description on use of average or marginal data in waste management studies by Ekvall et al. (2007). An attributional study enables to highlight where in the studied system that the major impact originates. Both of these perspectives are of interest when deciding on future sludge handling, as it is important to illustrate the consequences of a shift between, e.g., the choice between two end-uses of sludge, but it is also relevant to know where in the wastewater and sludge treatment system that the major impact originates, e.g. in order to see if the impact from the sludge handling is important in relation to the impact from the operation at the WWTP. It is possible that applying an attributional or a consequential approach, for two scenarios of the same system, would enable to provide answers to different types of questions, and applying only one approach limits the usefulness of the results, also, to some extent, for the case study presented in Paper V. This calls for evaluation of how the findings in this thesis can be interpreted for attributional and consequential studies, respectively.

As earlier stated, 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 (as, e.g., discussed for the ROUTES project in Publication E), and the LCIA categories assessed should preferably be selected not only based on which impact categories that are likely influenced by the studied system, but also based on stakeholder interests and responsibilities. A relevant question arises: Can LCA, although it cannot guide on if the risks of applying sludge on land are acceptable, in other ways "help" in answering the question of whether or not sludge should be land-applied? As described for human toxicity assessments in Section 5.2, an LCA brings several important perspectives, e.g., as it considers the full life cycle of a system, which helps prevent decisions that would shift the burden between different parts of the life cycle instead of reducing it. And, as also described in Section 5.2, an LCA also has a huge advantage in that it enables accounting for co-functions of the system, such as the utilisation of N, P, and C from the sludge in agriculture.

In Sweden, a very active lobby group exists with the primary goal of stopping the use of sludge in agriculture: the organisation Ren åker ren mat (http://www.renakerrenmat.se/, assessed 2015-10-30), which in English would translate into "Clean fields, clean food". The wastewater industry actively works on reducing the risks related to 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 wastewater at source, upstream of the WWTP (http://www.svensktvatten.se/Vattentjanster/Avlopp-och-Miljo/REVAQ/, accessed 2015-10-30). What is the potential of LCAs, which evaluate the global overall preference of agricultural sludge systems compared to other alternatives, to make any difference in a debate that, so far, has come to focus on risks to human health from heavy metals, organic micropollutants and pathogens? An LCA puts a life cycle perspective on the studied systems 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 and highlights trade-offs. If an LCA, 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 neglected by stakeholders. Including local risks, like toxicity and pathogen risks in a 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. It is also possible to use a community dialogue to interpret LCA results, as was done by McDevitt et al. (2013). The authors encourage the use of such community dialogues in other communities because it increases the engagement of different stakeholders in the issue.

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. Similarly, 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 can show whether agricultural sludge application is preferable from a holistic environmental point of view compared to other sludge disposal alternatives. An LCA is a useful tool in that, although such assessments are challenging, it provides the possibility of relating the impacts of great concern to stakeholders to other potential impacts. If used as part of the input for decision-makers, it could make an important contribution to evaluations of wastewater and sludge management systems, and in this way also contribute to the societal debate on agricultural sludge use.

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. In addition to resource recovery from sludge in form of, e.g., biogas or nutrients, processes for the utilisation of carbon directly from the wastewater are under development, as is discussed in this thesis for mixed-culture biopolymer production. The options for resource utilisation are likely to expand in the future, in the pursuit of a more circular society. Several LCA methodological issues remain to be solved in order to enable fair and relevant assessments of such systems. Impacts on humans and the environment from odours is one relatively unexplored area where research is needed to enable the assessment of wastewater and sludge treatment systems. Odour problems are discussed as a potential problem in the neighbourhood of WWTPs, during transport and storage, and in the end-use of sludge, but have never been assessed in an LCA of such a system, according to the presently available literature.

Despite the work in Publication D and Paper II to assess pathogen risk within the LCA framework, further method development is needed, in order to conduct a more specific assessment that enables comparisons between different wastewater and sludge management systems. There is also a need for more, and reliable, data on pathogen concentrations and characterisation data that cover more pathogens present in sludge in the specific systems under study. Method development is also needed in order for the method to be able to characterise pathogen risk also in other types of systems.

One of the main arguments for applying sludge on arable land is the possibility of replacing the use of mineral P fertiliser, and the requirement of finite resources for the production of that mineral otherwise. The results presented in Paper IV show that such a replacement made a minor contribution to the overall impact of most of the assessed impact categories. The contribution from replaced mineral P fertiliser was, for instance, much smaller than the contribution from replaced mineral N fertiliser. However, the depletion of abiotic resources was not assessed as a separate indicator. A thorough assessment of such an indicator could provide interesting perspectives.

In addition to the issues related to methodology, there remains the problem of the lack of data in many situations, which was highlighted in both Paper II and Paper V. This limits, for instance, toxicity assessments. Data refinement is also needed for emissions from sludge storage, which in this research has shown to contribute substantially to the results for systems in which sludge is land-applied.

A general issue with regard to data availability and characterisation methods that is often disregarded in LCA is the handling of uncertainties. Although the effect of uncertainties and choices made in the goal and scope definition of the LCA is often tested through sensitivity analyses of different scenarios, data uncertainty is generally not even commented on. In Paper V, the uncertainties related to human toxicity assessments in LCA was handled to some extent, by applying an alternative characterisation method developed with a fate modelling specific to a sludge context. However, the uncertainty was not quantified, neither the uncertainly relating to the inventory data, nor the uncertainty for the characterisation factors. Research is needed to quantify such uncertainties and to show where the main uncertainties are. To somehow validate the HTP assessments against field studies could also prove useful.

7 Conclusions

The research presented in this thesis contributes to the overall aim of improving LCA methodology and practice so that LCA can be used to provide more useful guidance on environmental life cycle impacts in the area of wastewater and sludge management, in particular in systems in which resource recovery from wastewater or sludge occurs. The research findings are, thus, likely to be increasingly relevant as an increased focus on resource recovery from waste streams is expected.

LCAs can contribute important perspectives to decision-making, although an LCA must be designed in a way that ensures it is relevant to the questions at hand. The research presented in this thesis provides guidance on LCA methodology and practice to enable conscious choices during the LCA process. The research contributes to answering the research questions in the following way:

Research question 1. Do LCA practitioners generally include the major N, P, and C flows in a relevant way to enable assessment of the impact categories most commonly assessed in LCA?

The review of major N, P, and C flows presented in Paper III found that the inventory of the foreground system in many cases needs refinement, both when it comes to the inclusion of flows and the data quality of their quantification.

Research question 2. Do human toxicity and pathogen risk contribute significantly to the overall impact on human health of sludge management, i.e., is it important to include these in LCAs on sludge management?

Paper II shows that pathogen risk, entirely left out in earlier LCAs, has the potential to contribute to the overall impact on human health from sludge treatment, especially if sludge is land applied. Lack of characterisation and inventory data for many pathogens limits the assessment. Paper V showed that HTP constituted the major impact on human health from a wastewater treatment system in which sludge was land applied, but that results are uncertain. It can therefore be concluded that human toxicity and pathogen risk are important areas that should not be left out but because of large uncertainties, further development is needed.

Research question 3. Will conventional or newly developed human toxicity characterisation methods provide useful results in decision-making on sludge strategies?

The introduction of the newly developed HTP characterisation method, SLAtox, with an exposure modelling adjusted especially for a sludge context, corroborated the results of more conventional LCIA methods (PaperV). In principal, toxicity assessments in LCAs can bring important perspectives, e.g., by comparing impacts from the foreground and background systems, and being able to compare toxicity impacts and pathogen risk to other types of environmental impacts assessed under the same system boundaries, and thereby contribute to a holistic perspective. However, at present the identified uncertainties in the assessment of human toxicity limits such ambitions.

Due to inherent properties of the LCA method, it will, however, not be able to answer questions like, e.g,. if use of sludge for agricultural purposes should be accepted.

Research question 4: Are there situations in LCAs of wastewater and sludge management where existing approaches for handling multifunctionality are insufficient and how can such issues be resolved?

A system was encountered in which simultaneous wastewater treatment and production of a biopolymer-rich stream in a WWTP (Paper I and Publication E) for which existing practices for multifunctionality issues was not sufficient. A novel basis for comparison of the functions was suggested, and applied in two ways for substitution and one inventive allocation approach. The choice of approach was shown to be important for the overall GWP result.

Research question 5: How, and under which conditions, could benefits other than N and P from sludge used as organic fertiliser be accounted for?

An approach was demonstrated that accounting for formerly neglected potential benefits of sludge use on arable land other than N and P, by substituting for the increased crop yields that can result from the provision of organic material (and micronutrients) to soils with low SOC, can be relevant. Further research on the quantification is, however, needed.

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