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Life cycle assessment of phosphorous management for RAS sludge

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LIFE CYCLE ASSESSMENT (LCA) OF PHOSPHOROUS MANAGEMENT FOR RECIRCULATING AQUACULTURE SYSTEM (RAS) SLUDGE

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Master Thesis

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Life Cycle Assessment (LCA) of phosphorous management for Recirculating Aquaculture System (RAS) sludge,
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ABSTRACT

Phosphorous (P) is an essential nutrient and its recovery from aquaculture sludge is the main core of this study. As the global reserves of phosphate rock are likely to be depleted in the next 50-100 years, it is crucial to investigate a more sustainable P management. The present research first introduces the situation of aquaculture in the Norwegian context and describes the main characteristics of Recirculating Aquaculture Systems (RAS). Then, the role of Life Cycle Assessment (LCA) in assessing the environmental impacts of aquaculture and sewage sludge treatment is examined. Follows the design of a hypothetical RAS for harvesting Atlantic salmon in its whole life production cycle. Different technologies for the treatment of fish-based sludge and phosphorous recovery are modelled in SimaPro, namely anaerobic digestion (AD), thermal treatment (incineration) and enhanced biological phosphorous removal (EBPR) with struvite crystallization. The different scenarios are considered in a local and in a centralized alternative. The functional unit (FU) chosen is 1 t of raw sludge, which is treated and produces phosphorous (P)-rich fertilizer, or biogas. The different scenarios were compared with the reference scenario, consisting in land spreading of sludge without prior treatment or conditioning. The anaerobic digestion of fish-based sludge in the local scenario, to produce liquid fertilizer from digestate, gives the lowest contributions in terms of environmental impact, followed by its centralized option and the reference scenarios. Negative values, in particular, show the benefits of the substitute fertilizer (triple superphosphate, TSP) compared to the commercial fertilizer. EBPR and thermal treatment show similar values, with the main difference to be found in the resource category, with low values belonging to the thermal treatment, due to the reuse of heat and electricity in the facility.

ABSTRAKT

Phosphor (P) ist ein essentieller Nährstoff und seine Rückgewinnung aus Aquakulturschlamm ist der wichtigste Kern dieser Studie. Da die weltweiten Reserven an Phosphatgestein in den nächsten 50-100 Jahren erschöpft sein dürften, ist es wichtig, ein nachhaltigeres P-Management zu untersuchen. Die vorliegende Studie stellt zunächst die Situation der Aquakultur im norwegischen Kontext vor und beschreibt die Hauptmerkmale von Recirculating Aquaculture Systems (RAS). Anschließend wird die Rolle der Ökobilanz bei der Bewertung der Umweltauswirkungen von Aquakultur und Klärschlammbehandlung untersucht. Es folgt der Entwurf eines hypothetischen RAS in seinem gesamten Lebenszyklus für die Ernte von Atlantischem Lachs. Verschiedene Technologien zur Behandlung von Fischschlamm und Phosphorrückgewinnung werden in SimaPro modelliert, insbesondere anaerobe Vergärung (anaerobic digestion (AD)), thermische Behandlung (Verbrennung) und verbesserte biologische Phosphorentfernung (EBPR) mit Kristallisation von Struvit. Die verschiedenen Szenarien werden in einer lokalen und einer zentralen Variante betrachtet. Die gewählte Funktionseinheit (FU) ist 1 Tonne Rohschlamm, der aufbereitet wird und phosphorreichen (P-)Dünger oder Biogas produziert. Die verschiedenen Szenarien wurden mit dem Referenzszenario verglichen, das in der Landausbringung von Klärschlamm ohne vorherige Behandlung oder Konditionierung besteht. Die anaerobe Vergärung von Fischschlamm im lokalen Szenario zur Herstellung von Flüssigdünger aus Gärresten liefert den geringsten Beitrag zur Umweltbelastung, gefolgt von seiner zentralen Variante und den Referenzszenarien. Insbesondere negative Werte zeigen die Vorteile des Ersatzdüngers (Dreifach - Superphosphat, TSP) gegenüber dem kommerziellen Dünger. EBPR und thermische Behandlung weisen ähnliche Werte auf, wobei der Hauptunterschied in der Ressourcen Kategorie liegt, wobei die Werte der thermischen Behandlung aufgrund der Wiederverwendung von Wärme und Strom in der Anlage gering sind.

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ACRONYMS

AD	anaerobic digestion
bFCR	biological feed conversion ratio
BMP	Best Management Practices
DAP	diammonium phosphate
DND	daily nutrition discharge
DM	dry matter
DO	dissolved oxygen
eFCR	economic feed conversion rate
EBPR	enhanced biological phosphorous removal
ES	Earth System
FCR	Feed Conversion Rate
FU	functional unit
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LW	Live Weight
MAB	Maximum Allowed Biomass
MAP	magnesium ammonium phosphate
N	nitrogen
NOK	Norwegian Krone
P	phosphorous
PAO	polyphosphate accumulating organisms
PB	Planetary Boundaries
RAS	Recirculating Aquaculture Systems
RGI	Relative Growth Index
SS	suspended solids

SSP	single superphosphate
TN	total nitrogen
TP	total phosphorous
TSS	total suspended solids
TSP	triple superphosphate
USD	US Dollars
UV	ultraviolet
VSS	volatile suspended solids
WWTP	wastewater treatment plant

Part I

INTRODUCTION

The first part of the thesis introduces the concept of Planetary Boundaries (PB) and, in particular, the importance of phosphorous (P) within this context. The role of aquaculture in Norway first, and the trend for a change in the harvesting technique from open cages to Recirculating Aquaculture Systems (RAS) is presented, with regards to the challenges it may pose in the treatment of the sludge produced. Then, the management of P is debated, in the view of its recovery and reuse, as being the core of this study.

1

INTRODUCTION

"Planetary boundaries: exploring the safe operating space for humanity", from Rockström et al. (2009) represented a call to action for the environmental sustainability of the Earth System (ES). It sets up nine Planetary Boundaries (PB) which do not have to be trespassed in order for humanity to avoid eventual catastrophic environmental changes. The boundaries within these limits are delineate a "safe operating space" for the secure global societal development.

Among the nine categories described by the article[111], the biogeochemical cycle of phosphorous (P) together with nitrogen (N), is responsible for eutrophication phenomena in water bodies, due to runoff from agricultural fields[28,116] and anoxic events in the oceans, which impact on marine ecosystems[24,28].

In a successive article[23], the features of the Planetary Boundaries were re-examined and freshwater eutrophication was added in the computation. Thus, it was observed that the safe threshold for P has already been exceeded. In addition, the article criticized the absence of the depletion of phosphate rock reserves as a variable in the analysis.

With regards to freshwater bodies, P is described as the limited factor for eutrophication, and its main source in watersheds at the global scale are fertilizers, in the magnitude of $14.2\,\mathrm{Tg_P\,yr^{-1}}$[87], from agricultural regions with very high P application rates. Fertilizers thus represent the elements more likely to contribute to the transgression of the PB. Moreover, the mobilization of high quantity of phosphate rock, the limited and non renewable source from which P is obtained, due to the intensification of the production methods and the specialization of the farming systems, has lead to a strong dependence on this finite resource for numerous anthropogenic activities[28].

The increasing scarcity of P resources, in addition with its inefficient use and the spread of eutrophication (405 dead zones around the world in 2008, according to the World Resource Institute[39]) invites for a reduction in the global demand, enhancing the efficiency and recycling the already existing and wasted P. A better phosphate management will therefore include its removal from the wastewater discharged into water bodies and the improvement of land-based activities[28,78].

In this context, the Norwegian EPA issued a report in 2015, assessing the situation for what concern P recycling in the country. The study discloses that aquaculture represents a big ratio of the phosphorous sources in Norway, with $9000\,\mathrm{t\,yr^{-1}}$, expected to increase up to 40 000 t yr^{-1} within the next 10 years. There are currently no standard solutions for its reuse, due to the lack of national guidelines.[a]

The exploration of the different options for a better phosphorous management in the context of on-shore Norwegian aquaculture of Atlantic salmon is therefore the main core of this study, as explained in details in the following sections.

1.1 RELEVANCE OF THE STUDY

This study focuses on management of phosphorous from sludge produced by Recirculating Aquaculture Systems (RAS), used in Norway for harvesting finfish, in particular Atlantic salmon.

The traditional farming system consists in a first stage production in land-based, single-pass flow-through farms, using tanks and raceways, followed by a sea-based on-growing production in floating cages[15], but the use of RAS is becoming more and more popular for its numerous advantages. Indoor tank systems are increasingly being used to ensure a healthier environment, while reducing drastically the need for fresh water by reusing it in the production line[17,55,124]. The expansion of the market demand and the need for a more sustainable aquaculture also lead to the application of more on-shore RAS.

One of the challenges represented by RAS is the significant amount of sludge produced[21], resulting in a greater attention which has to be given in matter of sludge treatment from such facilities. Moreover, expanding the grow-out period of the fish in on-shore facilities, along with other factors such as the design of the sludge treatment, turns into a modification in the composition of the sludge.

In the current situation, no prevailing treatment exists for sludge from land-based aquaculture, being the most common strategy the storage of dewatered sludge, with no standardized plans for its reuse, nor dedicated technologies capable of satisfactory treating fish-based sludge[1].[b]

Moreover, Norway's peculiar situation in terms of renewable energy (it is abundant the production of electricity from hydropower, with 133.4 TW h produced in 2017, about 95% of total production) makes harder to justify the use of fish sludge only in biogas plants, in terms of clean energy production.[c]

Provided the expected expansion of the aquaculture sector, translating to growth from current 9000 t_P yr^{-1} increasing to 40 000 t_P yr^{-1}

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[a] Phosphorous Platform. https://phosphorusplatform.eu/scope-in-print/scope-in-press/1182-recycling-of-phosphorous-in-norway. Accessed January 19, 2018

[b] ibid. a

[c] The Norwegian Water Resources and Energy Directorate. https://www.nve.no/energiforsyning-og-konsesjon/vannkraft/vannkraftpotensialet/. Accessed February 22, 2018

within the next 10 years, it is thus highly relevant to consider solutions for treatment and reuse of sludge, in the view of nutrient recovery and recycling, aiming to lower down its environmental impacts.

1.1.1 *Norwegian potential of phosphorous recovery from aquaculture sludge*

The report published by Nofima, „Estimated content of nutrients and energy in feed spill and faeces in Norwegian salmon culture" (2017) assesses the amount of sludge in the Norwegian aquaculture industry, for the smolt stage and the grow-out stage of Atlantic salmon. It considers 24 000 t of smolt production and 1 300 000 t for the grow-out phase per year. With the data provided by the report and according to data from the literature[84], it has been estimated the annual potential sludge production for Norway, and the share of phosphorous present, to approximate the magnitude of the problem and its potential scale in the future RAS systems. The calculation corresponds to the four phases of the Atlantic salmon production cycle (smolt, post-smolt, pre grow-out, grow out); the results are consistent to the Nofima report for what concern the smolt production of sludge, while they slightly differ for what concern the grow-out phase (an higher Feed Conversion Rate (FCR), coherent with the literature, has been taken into account).[d] With regards to the two intermediate phases of post-smolt ad pre grow-out, the computation has been done accordingly with data founded in the literature, in scientific papers and technical reports, and the assumptions that the post-smolt phase has similar characteristics of the smolt phase, for the economic feed conversion rate (eFCR), digestibility of feed (i. e. phosphorous) and the type of feed ingested. Similarly has been done for the pre grow-out phase and the grow-out phase. The values used are displayed in Table 11, in Appendix A.

From these calculation, taking into account the amount of feed traded and eaten by the harvested salmons in Norway, the share of P and dry matter (DM) in the feed ingredients, and the amount of P and DM eaten, excreted and lost in feed spill, the results from Table 1 have been extrapolated. [e]

Assuming a primary mechanical treatment on-site, formed by a Cornell-type dual drain, swirl separator, drum filters and clarification tank (the design will be explained in details in Section 7.1), it has been calculated that $21\,198.1938\,\mathrm{t\,yr^{-1}}$ of DM can be theoretically collected and treated, meaning $241.70\,\mathrm{t_P\,yr^{-1}}$ could be recovered from Norwegian aquaculture farms (as illustrated in Figure 1 and Figure 2 respectively).

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[d] FCR is calculated as the amount of feed (in kg) required to produce 1 kg of farmed animal (round weight)[133]

[e] Dry matter refers to the weight of a substance when the water content is removed. Oxford living Dictionaries. `https://en.oxforddictionaries.com/definition/dry_matter`. Accessed June 21, 2018

Table 1: Potential sludge production. Adapted from Aas and Åsgård (2017) and own calculation.

	Smolt	Post-smolt	Pre grow-out	Grow-out
DM in sludge (t)	10 716	10 980	42 164	323 219
P in sludge (t)	224.64	327	875	8275
Total DM after treatment (t)	21 198.1938	-	-	-
Total P after treatment (t)	241.70	-	-	-

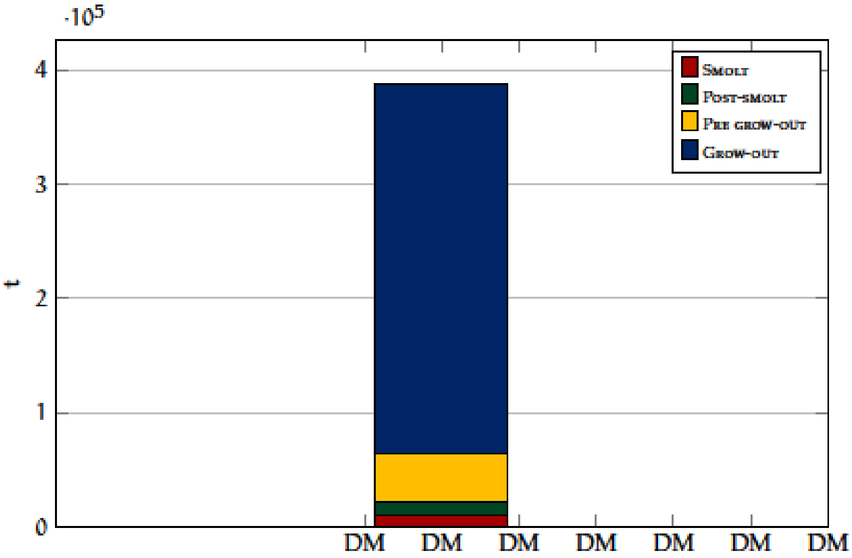

Figure 1: Estimated potential of aquaculture sludge in the Norwegian context, for dry matter (i. e. total solids), own calculation

1.2 RESEARCH QUESTIONS

The present research is located in the field of Industrial Ecology. Focusing on the impact Norwegian aquaculture of Atlantic salmon has on the environment and, in particular, on the organic waste generated by this activity, the purpose of this thesis is to evaluate the different alternatives for a better phosphorous management, in particular its recovery from sludge effluents in Recirculating Aquaculture Systems (RAS).

Besides volume growth, a second transition factor in sludge management is the introduction of RAS post-smolt facilities, internationally even for the entire grow-out stage. In these cases, sludge from RAS plants might change, as feeds for larger fish might differ from smolt feeds, and moreover, sludge from post-smolt stage is expected to be saline.

The main objective of this thesis is therefore to answer the question:

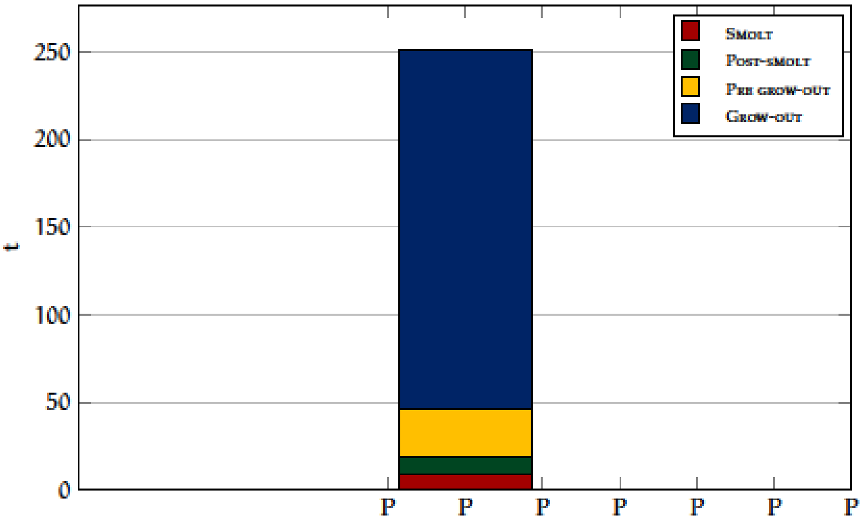

Figure 2: Estimated potential of aquaculture sludge in the Norwegian context, for phosphorous, own calculation

> What are the viable treatment technologies and thus the products of aquaculture sludge from RAS of Atlantic salmon, in the view of a sustainable recovery of phosphorous?

As further questions, the followings are defined:

- What is the impact of a longer grow-out on-shore period for the Atlantic salmon, which in turns lead to a saline composition of the sludge?
- What is the feasibility of a biogas production from saline sludge?
- What are the possible uses for the recovered phosphorous?

The potential environmental benefit of the reuse of fish-based sludge will be estimated using the LCA methodology.

Part II

LITERATURE REVIEW

The second part of the thesis presents a detailed literature review of the key concepts of the research. The first section deals with the importance of phosphorous in a global context, followed by the current situation of aquaculture in Norway, with respect to the technologies involved and its economical and legal framework. Different formulas are compared, used to predict the concentration of nutrients in the discharge flows. An overview of the contemporary methods for the recovery of phosphorous during the primary treatment of the sludge comes next . Finally, the analysis of existing life cycle assessments of both aquaculture systems and sewage sludge treatments, in their commonalities and differences, closes the chapter.

2

THE IMPORTANCE OF PHOSPHOROUS

2.1 PHOSPHOROUS SCARCITY AND IMPLICATION FOR FOOD SECURITY

Phosphorous is a fundamental component for food production, and since its extensive application in agriculture, it contributed in raising harvest productivity worldwide[116]. 79 to 90% of the worldwide demand of inorganic phosphorous mined from phosphate rocks is related to the production of fertilizers[26,108,112], being the modern agriculture heavily dependent on this non-renewable resource[27]. Other uses of P concern animal feeding (5 to 11%)[108], detergents (7%)[67], and food additives (2 to 3%)[108].

It represents a key element for the correct development of plant physiology and growth, and it is considered the scarcest among the macronutrients[74], highly present in only few countries (see Figure 3).[a] The largest mines are concentrated in Morocco and West Sahara (with 50 billion metric t of P rock).

According to Liebig's "mineral theory", the balance of the mineral elements present in the soil is a fundamental requisite for what concern soil fertility, and it is crucial to maintain and replace them in order to foster cultivation[27,98].The theory states that the yield potential of a crop is directly related to the diminution or increase of the mineral substances and, in particular, the growth is influenced by the scarcest resource available (also known as the "Law of Minimum"). Hence, the relevance of phosphorous in a balanced nutrients management in agriculture.

In the mid-late 19th century, the rapid urbanization together with the industrialization of agriculture, due to the progress of technology, changed the traditional harvesting methods based on intensive use of manure and human waste[27,116]. The discover and application of bird droppings ("guano") for fertilization purposes, the introduction of flush toilets, the development of a bio-based economy, which requires the use of crops as source of bioenergy[27,74,115] and, finally, the intensive extraction of phosphate rock impeded the return of phosphorous to the soil[27,74]. This lead, after several degrees of treatments[26], to its discharge in water bodies. According to the literature[112], 25% of the 1 billion t_P mined since 1950 has been discharged in water bodies or has been buried in landfills, while only 10% of human excreta is currently recirculated, either intentionally or unintentionally, back

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[a] Adapted from Phosphate rock reserves. https://www.statista.com/statistics/681747/phosphate-rock-reserves-by-country/. Accessed March 1, 2018

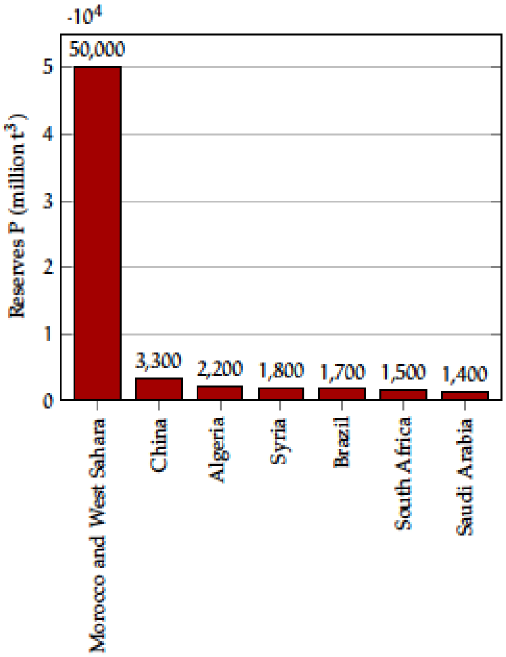

Figure 3: Phosphate rock reserves (2017)

through agriculture or aquaculture, especially in developing countries through diverting sewage systems or composting latrines.

Several studies on wastage of food and water from the point of view of global food production estimated the phosphorous (P) losses throughout the whole production and consumption chain, revealing an amount close to 55% of phosphorous (P) in food being lost between "farm and fork"[86]. P flows unilaterally from the mines to the oceans via agriculture and food consumption, at a rate that is three times its natural flow[53] and close to 100% of the P present in the total food eaten is excreted and subsequently lost due to the absence of efficient recovery measures in the wastewater treatment plants, denoting an additional significant loss in the system[68].

Currently, humans have altered the natural biogeochemical cycle of P, mobilizing four times the natural level of phosphate rock into the environment[53], adding $22\,\mathrm{Mt_P\,yr^{-1}}$ to enter the ocean[11], thus leading to negative environmental impacts such as eutrophication in freshwaters and coastal areas[78] and aggravation of the water quality[53,117]. Despite the stabilized need in European and North America's market, the global demand of inorganic P for fertilizers production is expected to increase until the exploitation of the phosphate rock reserves.

The current worldwide reserves account for $67\,000\,\mathrm{Tg_P}$, with $220\,\mathrm{Tg_P}$ mined in 2013.[b] Moreover, the quality of phosphate rock intended for agricultural purposes is decreasing, while the production costs for its refining are increasing[27].

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[b] 1 Tg=1000 million kg

This makes phosphorous scarcity an urgent matter on a global scale[78]: being the actual reserve estimated to be 69 295 million metric t of phosphate rock worldwide, the availability of the resource is estimated to be for 50 to 100 years[27,115].[c]

The theory of "peak production" of non renewable resources, first expressed by Hubbert in his „Energy from fossil fuels" (1949) and referring to oil production, is then appropriate for describing the future phosphorous scarcity from a resource point of view. It highlighted that the maximum production of a resource is reached when the high-quality easy-accessible reserves are depleted. The concept has been now applied in relation to the inorganic phosphorous (P) obtained from phosphate rock reserves[27], estimating the "phosphorous (P) peak" to be in 2033[20,81], when the high quality reserves will become harder to access, meaning also higher waste generation per tonne extracted[28]. Nevertheless, phosphorous (P) differs from oil in its nature of mineral element which cannot be produced or synthesized and, in addition, in its potential to be recovered from excreta and waste streams.

2.2 CLOSING THE PHOSPHOROUS CYCLE

The principal reserves of phosphorous are located in Morocco and West Sahara, China, Algeria, Syria and Brazil, being the first three the main producing countries, and the only European supply is located in Finland[67] (see Figure 3).

In Europe, hence, there is a net accumulation of P, due to the import of phosphorous fertilizers[130]; moreover, being the phosphate mines very limited, the overall export is only 22% of the total amount imported, thus resulting in a high accumulation in water and soil[27]. Due to the limited reserves, the urgency of closing the phosphorous cycle becomes evident. Moreover, above a certain level, the application of P fertilizers becomes nearly ineffective for the overall fertility of the soil, representing an inefficient use of the resource[45]. In fact, only 15 to 20% of phosphorous in fertilizer is actually recovered by crops[113], often because the application of fertilizers does not correspond to the plant's actual need.

The prevailing trend for what concern phosphorous resource administration currently regards Best Management Practices (BMP) related to agriculture rather then sludge management[78]. Some of this practices includes a customized feed ratio to better meet livestock requirements and improved the application of phosphorous in the cultivations to meet crop nutrient's needs more efficiently[116]. Nonetheless, the return of phosphorous from other resources (i. e. fertilizers)

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[c] Adapted from Phosphate rock reserves 2017. https://www.statista.com/statistics/681747/phosphate-rock-reserves-by-country/. Accessed March 1, 2018

to agricultural land does not always represent an efficient recycling strategy[50], due to the risk of accumulation of high fractions of residual phosphorous in saturated soil, which in turn poses an environmental risk for agricultural run-off.

For a sound phosphorous management, P in fertilizers should be equal to P removed in harvested crops plus P lost due to leakages in the various processes[27]. According to studies with a focus on the Norwegian context, phosphorous from waste has the potential to be self-sufficient with regards to P fertilizers (assuming a fair geographical distribution of the resources)[51]. The research disclosed that, in both short and long term perspectives, P fertilizers obtained from manure and sludge have the theoretical potential to meet the requirement for all Norwegian crops. Control of agricultural losses, thus prevention of P run-off, and its removal from wastewater streams which discharge in water bodies[78] and causes water quality deterioration, eutrophication[28,116] and adverse environmental effects in the marine ecosystems[24,28], are efficacious practices for a sustainable management of phosphorous, in the view of ecosystem protection and the recovery of a finite resource.

According to a study from Withers et al. titled „Stewardship to tackle global phosphorus inefficiency: the case of Europe" (2015), the BMP for increasing phosphorous efficiency and reduce losses should comprehend a more holistic approach, the "5R stewardship for closing the P cycle" in Europe. The approach suggested includes[130]:

- realignment of P inputs to match crops and livestock's requirements;
- reduction of P losses in water bodies;
- recycling of P in bioresources;
- recovery of P in wastes, and
- redefining P throughout the food system.

In this context, recovery of phosphorous from waste streams is promising, to close the nutrient loop of soil-crop-animal/human-soil, with the aim of improving organic waste management in urban areas[27,67].

2.3 PHOSPHOROUS RECOVERY FROM WASTE

Waste streams from human settlements are already used as fertilizer by poor farmers, being a cheap and reliable source of nutrients; in particular, 67% of the global yields of farmed fish are currently fertilized by wastewater[37]. Technologies already exist for the recovery of nutrients from urine[27], for instance Ecological Sanitation (EcoSan) systems which focus on urine diversion[47]. These methods also include proper management of storage and transport by transforming

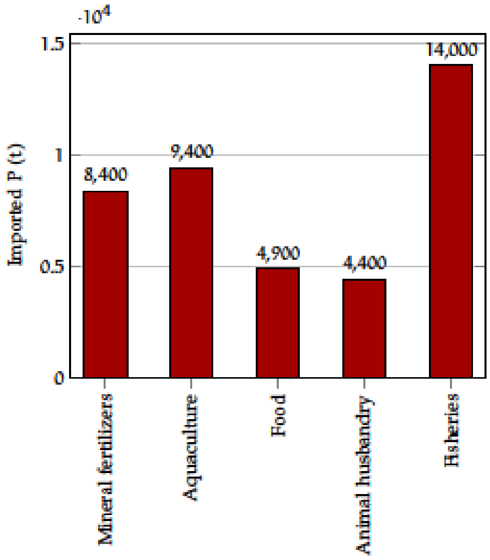

Figure 4: Sources of imported phosphorous for Norway (2009-2011)

urine into a more handling solid mineral form[82]. While small-scale separation systems and urine diverting dry or flush toilets are becoming more and more popular[66], and studies have been developed for this technology to be improved, very little is going on for nutrient recovery from either municipal or industrial sludge.

As mentioned in Chapter 1, Norway's aquaculture represents a big portion of the phosphorous source of the country, accounting more than 9000 $\mathrm{t\,yr^{-1}}$, and the trend is increasing (see Figure 4).[d]

In particular, Recirculating Aquaculture Systems (RAS) are becoming more and more prominent and with them the need for a proper sludge treatment rather then its discharge in water bodies. The amount of P in secondary resources generated in Norwegian aquaculture has not yet been estimated, although few studies have considered their P potential, from manure (considered for 10.9 kt plant-available P $\mathrm{yr^{-1}}$), and from fish sludge (6.1 kt plant-available P $\mathrm{yr^{-1}}$) with the aim of satisfying Norwegian P fertilization demand (5.8 kt plant-available P $\mathrm{yr^{-1}}$)[50].

Therefore, the potential of a more efficient phosphorous management through its recovery from sludge and, specifically, from onshore aquaculture plants needs to be explored. Currently, 1.8 to 10.3 kt plant-available P $\mathrm{yr^{-1}}$ of fish sludge and 0.1 to 0.6 kt plant-available P $\mathrm{yr^{-1}}$ of fish waste are discharged in water bodies without prior treatment, and 0.5 to 1.3 kt plant-available P $\mathrm{yr^{-1}}$ are incinerated, landfilled or exported, thus preventing any form of recovery[50].

Analysing the anthropogenic cycle of phosphorus is therefore becoming an effective approach for the global understanding of the phosphorous losses throughout the system. Those activities, which

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[d] Norwegian Environment Agency. http://www.miljodirektoratet.no/Documents/publikasjoner/M351/M351.pdf. Accessed February 15, 2018

comprehend mining, production of fertilizers, fertilization of the farming land, harvesting, food processing and consumption, and excretion, do not currently lead to any recirculation of the element back in the system[27], and the future scarcity of phosphorous along with its implication for food production is still largely ignored in the food security discourse[113].

P management and the potential of its recovery from waste is then introduced in the following sections, with particular emphasis on the Norwegian context and aquaculture as a promising activity.

3

AQUACULTURE

3.1 AQUACULTURE IN THE NORWEGIAN CONTEXT

The first part of Chapter 2 discussed the future scarcity of phosphorous worldwide, its sources and its importance for crop harvesting, from manure to phosphate rock mines. It also explored the P losses throughout the system, and the need for closing the cycle and thus avoid wastage. The following part examines the Norwegian aquaculture sector more in detail, specifically the farming of Atlantic salmon and the introduction of RAS.

Norwegian commercial aquaculture was first introduced in 1970s, and Atlantic salmon and Rainbow trout were farmed in a small scale mainly to supply food for the coastal population[60]. Aquaculture represents nowadays one of the most prominent industries in Norway, with a total production of 1 326 156 t of fish for food purposes, accounting for 64 039 million Norwegian Krone (NOK) in 2016. Harvesting of Atlantic salmon, in particular, covers 93% of the total share, with 1 233 619 t of fish for food production, followed by Rainbow trout (6.6% of the share) and others minor species. During the years 2015-2016 the production experienced a contraction (with a decrease of 5%), due to the spread of parasitic sea lice.

Thanks to the ideal conditions of the entire Norwegian coastline (90 000 km^2 of sea, extensive and deep fjords, optimal temperature of the water[60]) particularly suitable for salmon farming, aquaculture became a major business, from Agder in the south to Finnmark in the north.[a]

Globally, Norway is the second main exporting country, behind China and followed by Vietnam and the United States[44]. Moreover, the Nordic country counts 5939 fishing vessel, in constant decreasing since 1995, when the fleet was about 14 187, due to the progressive shifting to inland aquaculture farms. Accordingly, the number of fish farmers is increasing, from 4616 in 1995 to 6872 in 2015. The total aquaculture production volume (including fish, crustaceans, molluscs etc) in 2015 accounted for 1 380 839 t, 1.8% of the world total, with a value of 5823.110 million US Dollars (USD)[44].

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[a] Statistics Norway. https://www.ssb.no/en/fiskeoppdrett/. Accessed February 21, 2018

Table 2: List of Acts related to aquaculture farming in Norway

List of Act related to aquaculture farming in Norway	Year
Act Relative to Prevention of Cruelty to Animals	1974
Pollution Control Act	1981
Aquaculture Act	1985
Act Relative to Sea Ranching	2000
Act Relative to Food Production and Food Safety	2003
Salmon Allocation Decree	2004
Licensing Regulation	2004

3.2 ATLANTIC SALMON PRODUCTION

3.2.1 *Legal framework*

Fish farming in Norway is highly regulated, with the Aquaculture Act (1985, amended in 2003) and the Act Relative to Food Production and Food Safety Act (2003) being the two most important laws (see Table 2).

The Aquaculture Act (2003) organizes the production of fish through a licensing system, and prescribed the number of licences, their geographical distribution, the prioritisation criteria, the selection of qualified application and the licence fee. It also regulates the management, control and development of fish farming in freshwater, brackish water (water with appreciable but not constant high level of salinity, due to seasonal fluctuation and marine water infiltration) and marine water.

The Food Safety Act addresses issues related to the production, cultivation and distribution of foodstuffs, seeds and feeds, and aspects related to animal (and plant) health, thus fish health. It concerns also food safety and quality, and it is implemented by the Ministry of Fisheries and Coastal Affairs, while the Norwegian Food Safety authority has the power to enforce the act.[b]

Harvesting of minor species for commercial purposes, such as crustaceans, molluscs and echinoderms, is regulated by the Act Relative to Sea Ranching (2000, amended in 2003). The Act Relative to Prevention of Cruelty to Animals (1974, amended in 2003) dictates the basic principles for the keeping and treatment of animals.[c]

With respect to finfish production, the Regulation relative to authorization for the breeding of Atlantic salmon, trout and Rainbow trout (Salmon Allocation Decree, 2004) defines the legislative conditions for the reproduction of these species.

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[b] FAO. Fisheries and Aquaculture Department. National Aquaculture Legislation Overview. Norway. `http://www.fao.org/fishery/legalframework/nalo_norway/en#tcNB0019`. Accessed January 13, 2018

[c] ibid. b

Finally, under the Licensing Regulation (2004), the maximum breeding biomass is determined by the Ministry of Fisheries and Coastal Affairs: for Atlantic salmon the limit is set to 780 t Live Weight (LW) per each county, except for Troms and Finnmark, where the limit is at 945 t (LW)[52]. The production limit is called Maximum Allowed Biomass (MAB), and it is defined as the maximum volume of fish hold by a company at sea.

In January 2017 the Norwegian government had revised the aquaculture regulation, introducing a new flexible MAB rule, which allows the farmers to extend the period in the water for Atlantic salmon production during the summer months. One of the reasons has to be found in the spread of sea lice in 2015-2016, which turned out in a decrease of the production[80,129].

The total breeding biomass varies during the year due to the variation of the sea water temperature, and the new rule is going to affect the period with the lowest amount, May and June, with the aim of incrementing the volume growth of 3 to 5%, according to the provision of Nordea Bank.

This can in turn mean an additional 50 000 metric t out of Norway, a 2.2% higher global production year-on-year and a global supply growth. The scheme is voluntary, and will cost aquaculture companies 1.5 million NOK per license, with proceeds going to local communities as well as the state.

For what concern the discharge or disposal of wastewater from aquaculture activities, a permit indicates the allowed level of discharge. It is regulated by the Pollution Control Act (1981), which goes back to the status of the water body in accordance with the Norwegian standard NS 9410, "Environmental monitoring of benthic impact from marine fish farms".[d]

3.2.2 *Atlantic salmon production cycle*

The Atlantic salmon production cycle can be divided into two main steps, depending on the anadromous life cycle of the fish itself. The total cycle length of 24 to 40 months comprehends a first period of permanence in freshwater of about 10 to 16 months, followed by 14 to 24 months in seawater. The length of the production period heavily depends on the water temperature, being salmons ectotherm (coldblodeed) animals, living at the optimum temperature of 14 °C.

In autumn, the eggs are removed from the broodstock, and the fertilization lasts from November until March[52]. The fry growth takes 6 to 12 months, but the process can be speed up by the producer through light manipulation up to 6 months; when it reaches the size

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[d] ibid. b on the facing page

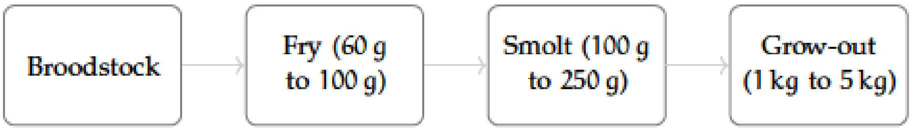

Figure 5: Atlantic salmon production cycle

of 60 g to 100 g is described as "smolt" and it is released in seawater. These preliminary steps are called "smoltification" (see Figure 5).[e]

The next step of the salmon production occurs in seawater, and it is referred as "grow-out" phase. It is completed after 14-24 months, when the fish is 4 kg to 5 kg and it is ready to be harvested. The process of releasing smolts in seawater occurs in Norway twice a year, while harvesting takes place mostly in the last three months of the year, which are ideal for fish growth[52].

The current trend is to build post-smolt facilities, corresponding to the first stage of the on growing phase on the smolt farm, in order to increase the size on-shore and shorten the time in seawater cages. This expedient helps in controlling the spread of sea lice, being the fishes stronger and more resilient against parasites attacks. Another strategy is, instead of having post-smolt, to keep the smolt until the weight of 250 g[80].

In the final step, the salmons are harvested, slaughtered and further processed for food consumption.

3.2.3 *Recirculating Aquaculture Systems (RAS)*

As mentioned in Chapter 1, Recirculating Aquaculture Systems (RAS) are becoming more and more popular, due to their numerous advantages. They are currently used by Marine Harvest and Lerøy for smolt production[3], and during hatchery operations for harvesting marine and brackish water species[91].

In general, RAS refers to fish farming in a controlled environment, using indoor tanks[55]. Mechanical and biological filters clean the water prior its recirculation, and additional freshwater (make-up water) is needed to replace the losses due to splash out and evaporation.

Important parameters for the well-being of the harvested fishes are: water temperature, water quality in matter of total suspended solids (TSS) and dissolved oxygen (DO) content. Other variables are salinity and land availability[88].

The implementation of RAS raises the opportunity for the production of smolt up to 170 g, thanks to the containment of the production

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[e] Smoltification refers in particular to a number of physiological changes (in the biochemistry, physiology, morphology and behaviour) of juvenile salmon, which result in their adaptation to change from freshwater to seawater. If the fish is unable to enter the marine environment during the "smolt window" (complete smoltification period), the changes revert quickly[16,119].

cycle in a close environment[15], which allows a better control of the temperature in winter, a constant water supply and an improved water quality. Thus, a better water quality leads to lower mortality rates in the grow-out phase[64,125]. Furthermore, it minimizes the problem of parasitic sea lice, enhancing production efficiency[13], and maximizes fish growth throughout the year[55].

A RAS consists of the following elements[55,88]:

1. growing tank;
2. mechanical filter, for the removal of volatile suspended solids (VSS);
3. biofilter, for the removal of dissolved solids and ammonia (NH_3);
4. oxygen injection and carbon dioxide (CO_2) removal, for balancing the dissolved gas level in water;
5. pumps for water recirculation, back-washing of biofilters and pressurised cleaning of the mechanical filter.

The size of the tanks is dimensioned according to the type of fish to grow and their optimal density, in order to ensure system stability. Usually fish density is lower for broodstock, and higher in the grow-out phase.

Most of the nutrient in RAS are present in the particulate form[70], thus a primary treatment consisting in a series of filters (screen filters, drum filters). The final removal of solids is carried out by a clarification device, placed upstream the biofilters, capable of filtering particulate fraction of 1 µm to 100 µm.

The main physical processes used to remove suspended solids are: sedimentation, screen filtration or air flotation.[f] The most common microscreens used for mechanical filtration are drum filters, utilized to collect faecal matter and uneaten feed, and consequently ensure a low and stable concentration of organic matter, with the ultimate goal of keeping an optimal biofilter performance at all times[17], a critical issue in the solid management operations[9].

After the primary treatment, the biological content of the waste stream is degraded by the biofilter system. The most common types of biofilters are: fixed film filters, such as trickling filters, rotating biological contactors, and submerged filters; fluidized bed filters, such as sand and bead biofilters; recirculated suspended solids filters, such as activated sludge, biofloc systems and neutral-buoyancy packing material biofilters[126].

The biological treatment has the main goal of removing fine particles, ammonia (NH_3) and phosphorous. It is usually designed in multiple chambers, for the optimal condition of the different strains

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[f] Biofilters. http://biofilters.com/webfilt.htm. Accessed March 1, 2018

of bacteria. The heterotrophic bacteria in the first step of the biological process decompose the biomass and produce carbon dioxide, ammonia and sludge, by consuming oxygen. In the following chambers the nitrification is carried out by nitrifying bacteria, which convert ammonium (NH_4) to nitrite (NO_2), and finally to nitrate (NO_3)[17].

The choice of the particulate filter, i.e. its efficiency, influences the size of the biofilter, which in turn influences the designing of the pump, increasing or decreasing the dynamic head the pump system must work against.[g]

A filtration loop guarantees the recirculation of water, through a water pump or an air blower. The recirculation flow depends on the circulation tank design and the daily feed ratio.

In the first steps of fish farming, and for small fish harvesting, ultraviolet (UV) treatments are recommended, in order to prevent harmful bacteria to enter the system[17].

For what concern aeration, the most common methods consist in blowing air or pure oxygen in the system, whereas carbon dioxide is removed by blown air or unpressurised packed columns[88]. The effective removal of CO_2 is essential for the welfare of the fishes, along with their optimal growth and a low feed conversion rate[17]. More parameters regarding the welfare of salmonids according to Norwegian legislation, are described in Table 12, in Appendix A.

In order to maximise growth and minimize production costs, feed and feeding of farmed fishes are carefully designed, and feeding controlled systems are a common tool used in all farms[52]. Through the Relative Growth Index (RGI), the maximum growth in relation to the amount of feed is guaranteed, and it is usually ensured when the fish has the lowest FCR.

3.2.4 *Sludge generation and current treatment*

Recirculating Aquaculture Systems (RAS) use a combination of mechanical and biological filters to clean closed tanks, and thus recirculating and reusing water. As aforementioned, sludge begins to be produced when the smolts are raised, and the water undergoes several treatments prior its recirculation.

Fish waste depends on different factors, such as[110]:

- type and age of fish;
- feed composition;
- feeding regime;
- water condition of the system (temperature and water quality).

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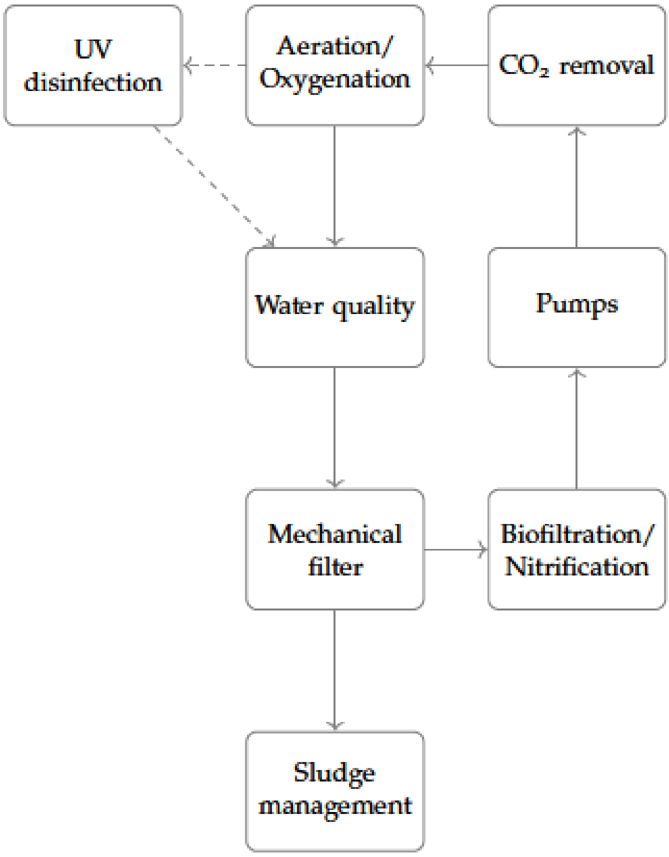
[g] ibid. f on the previous page

Figure 6: Unit processes associated with RAS. Adapted from Timmons, Timmons, and Ebeling (2006)



According to the composition of fish sludge, different treatments are required. Fish sludge is usually collected and removed as a concentrated waste stream, which might be treated on-site, but which is usually stored or dumped without further treatments. Especially in Norway, being the RAS plant situated along the coastal line, the most common practice is waste discharge into the sea. If post treatment is not carried out, serious environmental impacts may results from its release, at a similar magnitude of the impacts resulted from sea cage aquaculture[110].

For a feasible reuse and recycling of fish waste, it is crucial to carry a proper collection of the suspended solids. Total suspended solids comprehend particles with a diameter bigger than 1 µm, both in the volatile and in the settleable form. The volatile suspended solids (VSS) are responsible for oxygen consumption and biofouling, while the settleable solids, mainly uneaten feed and faeces, forms the sludge.

If the removal does not occur quickly, faecal particles are more likely to be exposed to mechanical forces, thus degrading and dissolving into the water, or breaking into smaller particles difficult to capture. Sedimentation methods are suitable only for particles with a range size of 100 µm to 500 µm; filtration through screening is applicable to smaller particles, however meshes smaller than 60 µm are prone to clogging, hence requiring backwashing and consequently dilution of the sludge[29,32].

Common mechanical filters with a 350 µm pore size are used in onshore salmon farming, meaning that suspended solids smaller than that are not trapped, and it may result in pollution of the fish environment. Filters with a screen mesh pore size of 60 µm to 200 µm are also reported to be used in on-shore fish farms in Europe[32].

There is very poor documentation in the scientific literature about the composition of the fish sludge and the size distribution of the particles, this being influenced by the type of feed, the amount of feed spill and the mechanical treatment the sludge undergoes during its management[1]. The DM content of faeces and feed has also to be considered for a proper sludge treatment, being usually the former 10 to 12%, and the latter around 94%[21,133].

A proper design of microscreens should be revised with the aim of particle removal, being the commercially available ones developed primary for the treatment of drinking water, which implies a focus on entrap the particles instead of removing them[33]. It is thus suggested a different setting for the screen, at 30 ° with respect to the water surface, which has the potential to remove the particles with minimal damage, and further treats the primary sludge.

Depending the composition of the sludge, and the further treatments, on the ingredients of the feed, its nutritional analysis might help in deciding the most suitable technology. Norwegian salmon

Figure 7: Primary treatment of RAS sludge

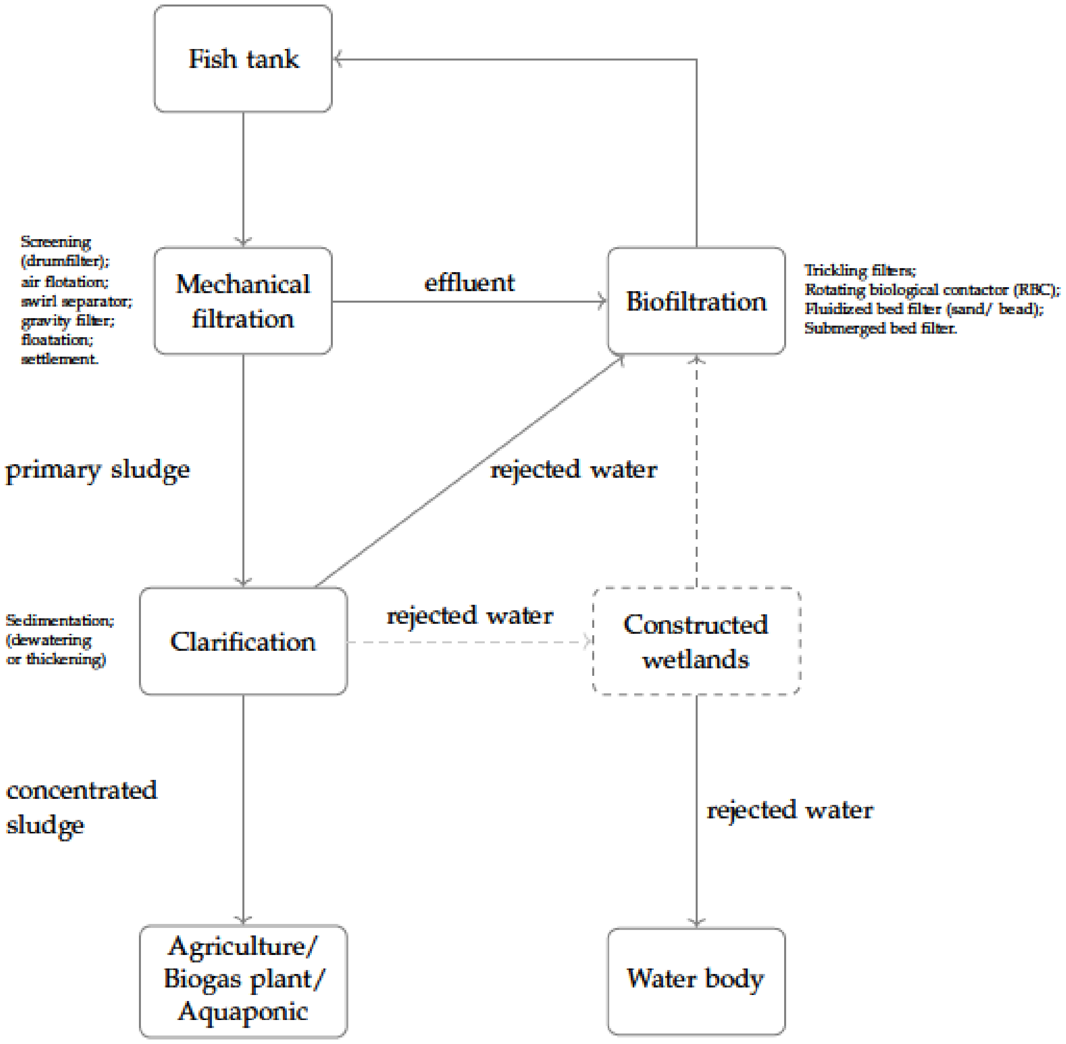


Table 3: Average feed composition and total amount of nutrients used in Norwegian salmon feed (2012). Adapted from Ytrestøyl, Aas, and Åsgård (2015)

	Composition (% or MJ kg^{-1})	Nutrients (t or gigaJ)
Dry matter	93.8	1 528 108
Energy	24.5	39 930 108
Protein	35.5	578 994
Lipid	32.5	529 904
EPA	1.5	24 903
DHA	1.1	18 106
P	0.9	15 011

Table 4: Amount of nutrients and energy in feed ingredients retained in whole salmon. Adapted from Ytrestøyl, Aas, and Åsgård (2015)

	Retention in whole body (%)
Energy	40
Protein	38
Lipid	51
EPA	30
DHA	68
P	39

ate up 1.63 million t of feed ingredients in 2012[133], of which 580 000 t were proteins and 530 000 t lipids. Approximately 65 to 75% of the dry matter from the commercial salmon feed is digested, meaning that 25 to 35% is then converted and excreted by the fish[101] .

Of this, due to the moderate digestibility of phosphorous in salmon, 30 to 60% of P presents in the feed is excreted and ends up in the fish sludge and in the water[1].

Feed spill should be kept at minimum, having feed and faeces a different chemical structure which might alter the sludge composition overall. Proteins and lipids are almost completely digested, and faeces contains mostly undigested carbohydrates and minerals. A detailed composition of Norwegian salmon feed is displayed in Table 3, while Table 4 discloses the nutrients retained by the Atlantic salmon itself.

Finally, the evaluation of the composition of the sludge from the production of Atlantic salmon, with respect to the P concentration, for both the smolt and the grow-out phase is displayed in Table 5.

Table 5: Composition of fish-based sludge. Adapted from Brod et al. (2017) and own calculation

Chemical composition		Smolt	Grow-out
Dry matter (DM)	%	13	16
Organic matter (OM)	%	79	79
Total Nitrogen	$\mathrm{kg\,t^{-1}}$	11	13
Total Phosphorous	$\mathrm{g\,kg_{DM}^{-1}}$	24	n/a
Total Organic Carbon (TOC)	%	23	8.2

3.3 SALINE RECIRCULATING AQUACULTURE SYSTEMS

The tendency of extending the grow-out phase of salmon in land-based fish farms raises the question of how the composition of sludge changes, with respect to the use of a more brackish water (the optimum growth happening at 12‰in post-smolt RAS[2]). In this case, the sludge from a more saline water will contain chloride, which might be a challenge for its treatment, and sulfur compounds which may produce H_2S under anaerobic conditions[110], thus growth inhibition[129].

In the study carried out by Tal et al. titled „Environmentally sustainable land-based marine aquaculture" (2009), a pilot reactor running with saline sludge was reported to succeed in the production of biogas through marine methanogenesis. More than 80% (v/v) of the organic waste introduced was digested into methane and carbon dioxide, and the production of biogas was maintained relatively constant and efficient.

In order to obtain low salt concentration in the sludge, however, few changes in the dewatering methods are suggested, e. g. filtering off the water instead of drying. Particle size, water chemistry and flow, retention time, digestibility of the diet and feed processing, interaction with other nutrients, dry matter concentration are also variables in the characteristic of the sludge, which in turn impact the effective filtration and dewatering process.

4

THE RECOVERY OF PHOSPHOROUS

4.1 NUTRIENT ACCOUNTING OF AQUACULTURE SLUDGE

In aquaculture effluents, the particulate fraction of the wastewater stream includes suspended solids (SS), total nitrogen (TN) and total phosphorous (TP), the concentration of TP, in particular, amounting to $0.13\,\mathrm{mg\,L^{-1}}$ to $1\,\mathrm{mg\,L^{-1}}$[33].

With respect to phosphorous, a study on fish waste of salmonid aquaculture in Scotland[73] reveals that, with a mesh of 60 µm to 100 µm, 66% of TP is retained, meaning a potential for improve phosphorous recovery in the primary treatment.

In order to improve fish faeces stability, the feed formulas can be manipulated, by adding dietary binders to fish feed (e. g. *Alginate, Guar gum*). Thus, larger particles are formed, leading to a higher mechanical removal potential during the primary treatment[127], using rotating microscreens with the pore size of 60 µm to 200 µm.

Concentrating solids prior clarification leads to a better environment in the tank, along with an increased efficiency in the further treatments, less pressure on the biofilter and less treatment capacity required[32]. In particular, being the total phosphorous from aquaculture bond in the particulate form, and being the particles in a range from $67.9\,\mathrm{\mu g\,L^{-1}}$ to $131.7\,\mathrm{\mu g\,L^{-1}}$, thus increasing in concentration with decreased particle size[31].

Another relevant variable, in order to minimize the amount of N and P discharged for a fish farmer, while maximizing biomass production, is to keep the FCR at minimum[41]. This has been proved by the following formula[41]:

$$\mathrm{Discharge}_n = \mathrm{biomass\ gain} * \mathrm{FCR} * D_n * (1 - R_n)$$

where:

$\mathrm{Discharge}_n$ is the discharge of the element taken into consideration from the fish farm (kg);

FCR is the Feed Conversion Rate (FCR), in feed fed (kg) or biomass gain (kg);

D_n is the element n per kg of diet;

R_n is the proportion of the element retained in growth, depending on FCR, average Live Weight (LW) and element concentration present in the fish.

Assuming a constant body concentration, the formula can be expressed as:

$$\mathrm{Discharge}_n = \mathrm{biomass\,gain} * \mathrm{FCR} * (D_n - C_n)$$

with C_n the body concentration of the element n.

An even simpler formula for the phosphorous discharged in the environment from aquaculture production, is the following[75]:

$$P_d = P_f - (P_b + P_e + P_s)$$

with:

P_d as P discharged;

P_f as P in feed;

P_b as P retained in the body of the fish;

P_e as P eaten; and

P_s as P in solid waste.

The daily nutrition discharge (DND)[32] can be described as:

$$\mathrm{DND(P)} = P_e - P_b$$

with

$$P_e = \mathrm{ration\,fed} * P_f$$

and

$$P_b = \mathrm{growth} * P_b$$

The formula gives, with a FCR of 1, an estimated discharge of $7.5\,g_P\,d^{-1}$ from juvenile salmonids, of which 80 to 90% is solid bound.

Moreover, two types of FCR can be considered, the economic feed conversion rate (eFCR) and the biological feed conversion ratio (bFCR). The eFCR considers the amount of feed used to produce certain quantity of fish, while the bFCR considers the amount of feed actually eaten by the fish.

$$\mathrm{eFCR} = \frac{\mathrm{feed\ used\ (kg)}}{\mathrm{fish\ produced\ (kg)}}$$

$$\text{bFCR} = \frac{\text{feed eaten (kg)}}{\text{fish produced (kg)}}$$

In the report by Cripps and Bergheim titled „Solids management and removal for intensive land-based aquaculture production systems“ (2000), the efficiency of different technologies designed to increasingly entrap particles is reviewed. Devices like particles concentrators can be added at the tank outlet, assisting the settlement and concentration of solids, and separating the concentrated sludge from the primary flow. The combination of such a unit with separate outlet and a sludge dewatering unit removed 38% of TP. Moreover, studying the different concentration of P on the "bottom" and on the "surface" section of the effluent, the average phosphorous concentration results to be more the double in the bottom than in the surface, if no flushing of the tank is applied, and the P removal increases to 46% using a stationary microscreen unit at the bottom of the tank (e. g. a Cornell type dual-drain tank)[120].

Another confirmation of the higher phosphorous recovery from a treatment unit which does not use back-flushing, but instead vacuum suction, has been found in the literature[12], revealing $0.6\,\text{mg}\,\text{L}^{-1}$ to $5.6\,\text{mg}\,\text{L}^{-1}$ of phosphorous concentration in removed sludge water using back-flushing, compared to $134\,\text{mg}\,\text{L}^{-1}$ to $391\,\text{mg}\,\text{L}^{-1}$ using vacuum suction.

4.2 PHOSPHATE RECOVERY TECHNOLOGIES

The disposal of organic waste from fish farming has been studied in relation with its nutrient content, and treated sludge can be applied on farmed land being a "slow release" fertilizer[12,14], if mixed with livestock manure in order to reduce the concentration of metals such as zinc and cadmium, and adjusting the content of potassium. As mentioned in Section 2.1, the major part of phosphorous mined is used in agricultural applications, as magnesium ammonium phosphate (MAP) or diammonium phosphate (DAP)[100].

4.2.1 *Anaerobic digestion AD*

A common treatment for RAS sludge is its transport to biogas plants, which implies a greater effort in the dewatering phase, in order to lower down the costs and energy used for transport[1]. AD is already widely used for treating municipal and agricultural organic waste and from it obtaining digestate and methane[10], and its application for what concern the treatment of sludge from aquaculture is starting to get attention as a new field of research[42]. AD takes place in the biogas plant and comprises four steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis[5]. Two different products are obtained, biogas and digestate. Biogas, composed of methane and carbon dioxide, is a source of renewable energy and could be used as a substitute of fossil fuels, thus enabling to lower down environmental impacts such as climate change or acidification of rain. The second product of AD is digestate which, with the proper post-treatment, is suitable for fertilization purposes[42]. Being considered a novel application, literature on anaerobic digestion of fish sludge is rare. An article describes the suitability of RAS sludge for biogas production from three farms in Israel, harvesting striped bass and tilapia[94]. Salinity ranged from 2.5 to 5 ‰. The study concluded the potential generation of methane from fish waste, although an optimization of the system is needed. Another study assessed the anaerobic digestion of fish farming waste and sewage sludge[77]. Methane yield was measured, along with the fertilizing value of the treated sludge, demonstrating the value of performing a co-digestion process, in an increased CH_4 yields and a more stable sludge to then apply as bio-fertilizer. Finally, a case from Portugal focused on biogas production from sludge coming from fish processing plants, for ardine and Atlantic mackerel as an alternative to landfilling[25]. The experimental study confirmed the value of fish sludge as substrate for anaerobic digestion, its potential in the production of biogas, and the advantage of performing a substantial reduction in the volume of waste.

4.2.2 *Incineration (Thermal treatment)*

Mono-incineration of sewage sludge with the view of fostering nutrient recovery have been developed in the framework of the European project SUSAN (Sustainable and Safe Re-use of Municipal Sewage Sludge for Nutrient Recovery). In the first phase of the thermal process, the organic pollutants are broken down, and the results of the incineration are ashes with high phosphorous and heavy metal content. Therefore, the second step consists in the chemical removal of the heavy metals (cadmium (Cd), copper (Cu), lead (Pb), Tin (Sn), and Zinc (Zn)) with thermal treatment at 1000 °C, The thermochemical process is also necessary in order to increase the phosphorous availability, transforming it into its mineral phase, suitable for plants[4,128].

During the thermo-chemical treatment, incineration ashes are mixed with salts (NaCl, KCl, $MgCl_2$ and $CaCl_2$) at 900 °C to 1100 °C, thus converting the present phosphorous into a plant-available form[40].

Another article points out the importance of the logistic aspect of building an incineration and ash treatment (ASH DEC)[54], which require large mass for its operation. In this case, in addition to the clarification step usually present (e. g. dewatering by gravity or thickening), it is recommended to add thermal drying before the transportation of the masses.

Recovery of phosphorous is also possible by leaching of fly ashes with acidic solutions, and few cases can be found in the literature, using mainly co-incineration of sewage sludge with wood[105], or mono-incineration. The most common acids used are sulfuric acid and phosphoric acid[40].

The choice of the method to apply in order to extract valuable phosphorous highly depends on the composition of the sludge[71], and example in the literature fro what concern the incineration of fish sludge are scarce.

A study on sludge from a trout farm[70] disclosed the suitability of bioleaching compared to chemical leaching because of the better control of the processes involved and the better nutrient recovery in the product obtained. This can then be treated with calcium (Ca), ferrous (Fe) or magnesium (Mg) ions in order to obtain different compounds, such as amorphous calcium phosphate (ACP), hydroxyapatite, vivianite or struvite, the latter suitable as soil enhancer[70].

4.2.3 *Biological phosphorous removal (EBPR)*

Few new techniques are found in the literature with respect to biological removal of phosphorous from wastewater effluent, such as the one developed by Hias IKS[1]. It consists in the bacterial degradation of dissolved P (PO_4), by bacteria with an absorption rate up to 30% of their biomass. The research discloses the highest amount of P to be found after the primary treatment (in this case a swirl separator), and the experiment for P reclamation from brackish water seemed to be a success, with 98.5% of the PO_4 reclaimed. However, Hias method is able to remove only the dissolved phosphorus, which amounts to 10% of the TN, being 90% of it bond in particles. Thus, leading to the need for a pre-treatment (anaerobic digestion is suggested), to release the remained PO_4.

In wastewater treatment plant (WWTP) it is also applied a biological process called EBPR. It uses a specific group of bacteria, polyphosphate accumulating organisms (PAO), which are able to store ortophosphate ($PO_4{}^{3-}$) in addition to their normal biological requirements. The action of the PAOs occur in the aerobic phase, storing polyphosphate as an energy reserve, and releasing them in the following anaerobic conditions[69,131].

WWTP which operates biological phosphorous removal are then able to control the precipitation of phosphorous into the mineral form of struvite. Struvite corresponds to the formula $NH_4MgPO_4 \cdot 6\,H_2O$, with the following composition: Mg: 9.90%, P: 12.62%, N: 5.71%, O: 65.20%, H: 1.64%, H: 4.93%.[a]

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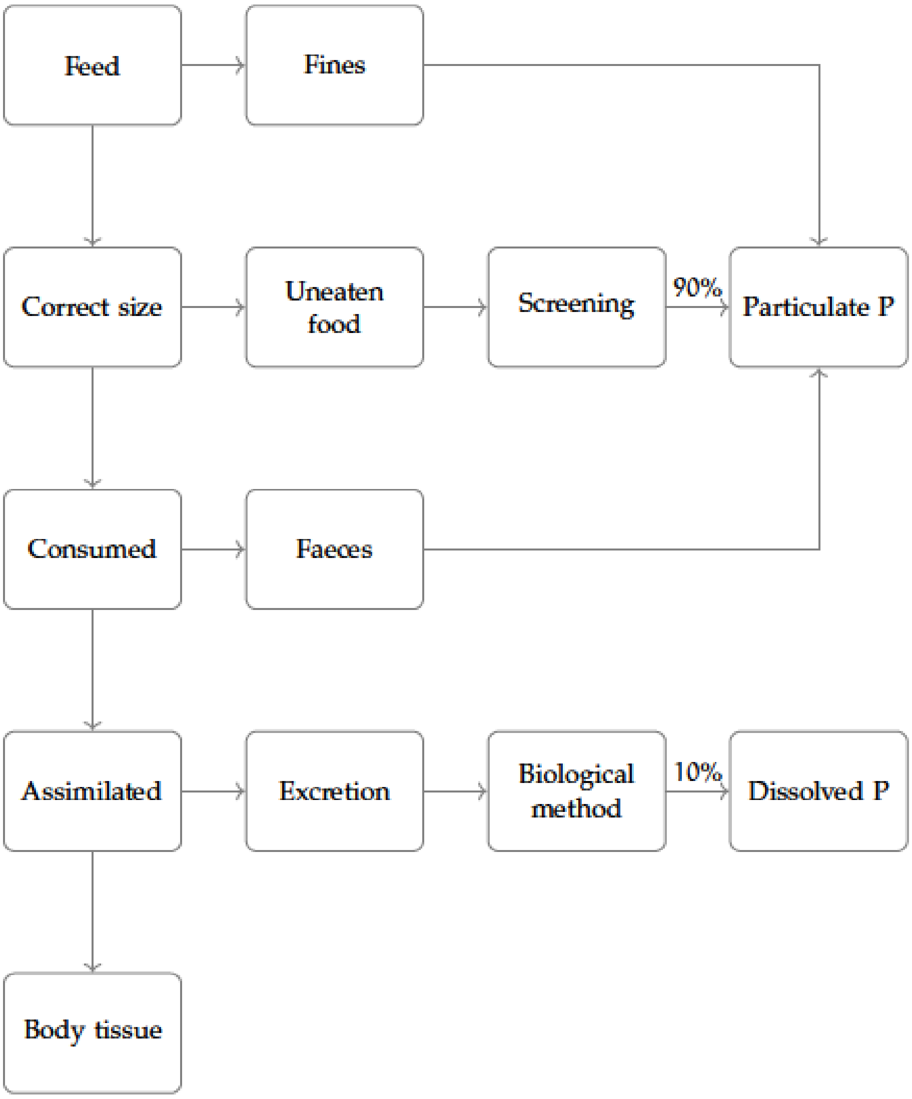
[a] Struvite Mineral Data. `http://webmineral.com/data/Struvite.shtml`. Accessed June 16, 2018

The crystallization process is heavily influenced by the characteristic of the sludge[90]. Although the crystallization of struvite is not a new process, its application in a controlled environment in large scales is a relatively recent development, and few studies have research on its requirement and further application[99]. Its high content of phosphorous and nitrogen makes struvite an ideal precipitate in the view of the recovery of phosphorous from wastewater streams, and its water soluble property makes it ideal for fertilization purposes, including it in the category of "slow release" fertilizers.

Figure 8: Phosphorous generation from feed. Adapted from Kibria et al. (1996)



5

LIFE CYCLE ASSESSMENT (LCA)

5.1 AQUACULTURE SYSTEMS

Life Cycle Assessment (LCA) is a methodological framework, firstly developed in an industrial context, used to assess the environmental effects of a product during its whole life cycle[109].

LCA is still a relatively new tool in its application with respect to aquaculture practices, and there is not a comprehensive literature about it, focusing the LCAs mainly on specific case studies. Another factor which makes difficult to find exhaustive studies is the diverse nature of aquaculture methods, species harvested and different focuses of the case studies themselves, from fish feed to marketable fish products at the end of the production chain.

This part examined various publications retrieved from the literature, regarding LCA of aquaculture, their commonalities and differences in methods and approach used. A summary of the review is shown in Table 6.

Table 6: Literature review of LCA for aquaculture, summary of commonalities and differences

Reference	Species	System	Country	FU	System boundary
Ayer and Tyedmers (2009)	Atlantic salmon and char	Various	Canada	1 t LW	Farm gate
Aubin et al. (2009)	Rainbow trout, sea bass, turbot	Various	France	1 t LW	Farm gate
Buchspies, Tolle, and Jungbluth (2011)	Various	Various	Swiss, Denmark	1 kg fish sold	Market
Cao et al. (2011)	Shrimp	Various	China	Various	Farm gate
Dekamin et al. (2015)	Rainbow trout	Various	Iran	1 t^3 LW	Farm gate
d'Orbcastel, Blancheton, and Aubin (2009)	Trout	Various	Model	1 t LW	Farm gate
Ellingsen and Aanondsen (2006)	Atlantic salmon	Net cage	Norway	200 g fillet	Market
Gronroos et al. (2006)	Rainbow trout	Net cage	Finland	1 t DW	Farm gate
Henriksson et al. (2015)	Various	Various	Various	1 t frozen fish	Market
Iribarren, Moreira, and Feijoo (2010)	Blue mussel	Rafts	Spain	1 kg dry mussel flesh	Consumer
Jerbi et al. (2012)	Sea bass	Various	Tunisia	1 t LW	Farm gate
McGrath, Pelletier, and Tyedmers (2015)	Salmon	SWAS	Canada	1 t LW	Farm gate
Mungkung (2005)	Shrimps	Ponds	Thailand	1.8 kg shrimps tails	Waste
Pelletier et al. (2007)	Atlantic salmon	Salmon feeds	Canada	1 t LW	Farm gate
Pelletier et al. (2009)	Atlantic salmon	Cage	Global	1 t LW	Farm gate
Pelletier and Tyedmers (2010)	Tilapia	Net cage and ponds	Indonesia	1 t fillets	Market
Phong (2010)	Various	Ponds, integrated	Vietnam	1 kg LW/1 kcal	Farm gate
Samuel-Fitwi et al. (2013)	Rainbow trout	Various	Various	1 t LW	Farm gate
Sun (2009)	Shrimps	RAS	USA	1800 kg fresh shrimps	Market

The main differences founded during this comparison pertain to:

- FU;
- type of system;
- system boundaries;
- impact assessment categories.

The first, main distinction concerns the functional unit (FU), used as a basis to compare and analyse the performance of the system. The FU strongly depends on the scope and goal of the study, requiring different goals different functional units, which then contributes in defining the system boundary for the subsequent LCI[57]. The most common FU is 1 t of Live Weight (LW) fish, used in 9 studies out of 20, all limiting themselves at the farm gate. In only one study, 1 t of dead weight has been chose as functional unit[49], and another one refers to 1 kcal prior to 1 kg of LW[106].

For the studies with a focus on fish as a marketable product, the following FU are chosen: 1 kg of fish sold[19], 200 g of fillet[43], 1 tonne of frozen shrimps[56], 1 kg of dry mussel flesh[61], 1.8 kg of shrimp tails[95], 1 t of tilapia fillets[103] and, finally, 1800 kg of fresh shrimps[121].

According to the International Standard ISO 14 044 (2006)[48], the system boundary has to be consistent with the goal of the study, and the criteria used in compliance with the system chose has to be justified. Among the papers reviewed, the choice of limiting the study to the farm gate seems to be the most prevailing, common for 13 studies. Four studies includes in their system the following phases of the supply chain, namely slaughtering, processing and selling of the fish products[19,43,56,103,121]. Only one considered the whole aquaculture production, from the initial stages of harvesting, to the final disposal[95].

The existing studies examined also present dissimilarities for what concern the choice of the environmental impact categories taken into consideration during the Life Cycle Inventory (LCI). A detailed summary is displayed in Table 7. The main category explored is the global warming potential, present in 17 studies out of the 20 considered, followed by acidification (16) and eutrophication (14). Few studies made a distinction between marine, freshwater and terrestrial ecotoxicity, while the most common practice was to include all the respective emissions under the main category of eutrophication potential. The fourth most included environmental impact category amongst all the studies was energy use (8), preferred over cumulative energy demand (4) for the nature of the different studies considered.

An unusual impact category, biotic resource use, so far rarely considered within LCA practices, was selected and quantified by five studies. In particular, biotic resources which are the ground for a product were never included in an LCA and therefore accounted for many case studies[30], being a standardized protocol still missing from the literature[102]. In the aquaculture context, it was thus relevant to include biotic resource use, in order to understand the carbon-based energy derived from biological systems involved in the fish production[30].

Five different studies also covered the category of water dependence, and four researches adopted abiotic resource depletion and ozone depletion potential, along with net primary production use.

Numerous other categories related to the eventual toxicity of the product analysed were quantified, in relation to the various goals taken into consideration, such as: human toxicity potential and photochemical oxidant formation (2), greenhouse gas emissions, respiratory impacts from inorganics (which can also be included in the human toxicity category, along with carcinogenic effects on humans, depending on the degree on specificity of the case study), solid waste, heavy metals, nutrient emissions, use of antifouling agents and the more general depletion of fossil fuels.

Pointing out the main features of the aforementioned literature review with respect to aquaculture LCAs, it is evident that the selection of the appropriate FU and system boundary largely depends on the goal and scope of the study, which is often site-specific, peculiar for each specie harvested and requires a well-defined delimitation and understanding of the context in which the study take place. The range of the relative environmental impact categories also vary accordingly, and new categories are introduced in the discourse in consequence to new, upcoming needs.

The next paragraph analyses the current position of LCA with respect to sewage sludge treatment processes, and identifies the gap existent in its application to this matter in general, and to aquaculture sludge in particular.

5.2 SEWAGE SLUDGE TREATMENT

Very few studies have been carried out with the aim of assessing the environmental impact of sewage sludge from municipal treatment plants, and even less attention has given to the impacts of sludge from aquaculture systems. Being this research focused on the recovery of phosphorous from different sludge treatment technologies, and their consequences in the view of their interaction with the environment, 11 studies which illustrate the utilization of LCAs for sewage sludge have been examined.

This section assesses the main commonalities and differences among the studies, in particular the FU, the choice of the system boundary and the selection of the environmental impact categories.

Table 7: Literature review of LCA for aquaculture, summary of selected impact categories

Impact category	Frequency	Reference
Global warming potential	17	Ayer and Tyedmers (2009), Aubin et al. (2009), Buchspies, Tolle, and Jungbluth (2011),Cao et al. (2011),Dekamin et al. (2015), d'Orbcastel, Blancheton, and Aubin (2009), Gronroos et al. (2006), Henriksson et al. (2015), Iribarren, Moreira, and Feijoo (2010), Jerbi et al. (2012), McGrath, Pelletier, and Tyedmers (2015), Mungkung (2005), Pelletier et al. (2007), Pelletier and Tyedmers (2010), Phong (2010), Samuel-Fitwi et al. (2013), Sun (2009);
Acidification	16	Ayer and Tyedmers (2009), Aubin et al. (2009), Cao et al. (2011),Dekamin et al. (2015), d'Orbcastel, Blancheton, and Aubin (2009), Gronroos et al. (2006), Iribarren, Moreira, and Feijoo (2010), Jerbi et al. (2012), McGrath, Pelletier, and Tyedmers (2015),Mungkung (2005), Pelletier et al. (2007), Pelletier et al. (2009), Pelletier and Tyedmers (2010), Phong (2010), Samuel-Fitwi et al. (2013), Sun (2009);
Eutrophication	14	Ayer and Tyedmers (2009), Aubin et al. (2009), Cao et al. (2011),Dekamin et al. (2015), d'Orbcastel, Blancheton, and Aubin (2009), Henriksson et al. (2015),Iribarren, Moreira, and Feijoo (2010),Jerbi et al. (2012), Pelletier et al. (2007), Pelletier et al. (2009), Pelletier and Tyedmers (2010), Phong (2010), Samuel-Fitwi et al. (2013), Sun (2009);
Energy use	8	Aubin et al. (2009), d'Orbcastel, Blancheton, and Aubin (2009), Ellingsen and Aanondsen (2006), Jerbi et al. (2012), Mungkung (2005), Pelletier et al. (2007), Pelletier and Tyedmers (2010), Phong (2010);
Surface use	7	Dekamin et al. (2015), d'Orbcastel, Blancheton, and Aubin (2009), Ellingsen and Aanondsen (2006), Jerbi et al. (2012), Mungkung (2005), Phong (2010), Samuel-Fitwi et al. (2013);
Marine aquatic ecotoxicity	6	Ayer and Tyedmers (2009), Gronroos et al. (2006), Henriksson et al. (2015), Iribarren, Moreira, and Feijoo (2010), McGrath, Pelletier, and Tyedmers (2015), Pelletier et al. (2007);
Biotic resource use	5	Cao et al. (2011), McGrath, Pelletier, and Tyedmers (2015), Pelletier et al. (2007), Pelletier et al. (2009), Pelletier and Tyedmers (2010);
Water dependence	5	Aubin et al. (2009), Dekamin et al. (2015), d'Orbcastel, Blancheton, and Aubin (2009), Jerbi et al. (2012), Mungkung (2005);
Cumulative energy demand	4	Ayer and Tyedmers (2009), Cao et al. (2011), McGrath, Pelletier, and Tyedmers (2015),Pelletier et al. (2009);
Net primary production use	4	Aubin et al. (2009), d'Orbcastel, Blancheton, and Aubin (2009), Jerbi et al. (2012),Mungkung (2005);
Abiotic depletion potential	4	Ayer and Tyedmers (2009), Dekamin et al. (2015), Iribarren, Moreira, and Feijoo (2010), Pelletier et al. (2007);
Ozone depletion potential	4	Gronroos et al. (2006), [61], Pelletier et al. (2007), Sun (2009);
Terrestrial ecotoxicity	4	Gronroos et al. (2006), Henriksson et al. (2015), Iribarren, Moreira, and Feijoo (2010), Pelletier et al. (2007);
Freshwater aquatic ecotoxicity	3	Henriksson et al. (2015), Iribarren, Moreira, and Feijoo (2010), Pelletier et al. (2007);
Human toxicity potential	2	Ayer and Tyedmers (2009), Iribarren, Moreira, and Feijoo (2010);
Photochemical oxidant formation	2	Iribarren, Moreira, and Feijoo (2010), Pelletier et al. (2007);
Greenhouse gas emissions	1	Pelletier et al. (2009);
Respiratory impacts from inorganics	1	Sun (2009);
Carcinogenic effects on humans	1	Sun (2009);
Solid waste	1	Sun (2009);
Heavy metals	1	Sun (2009);
Nutrient emission	1	Ellingsen and Aanondsen (2006);
Antifouling	1	Ellingsen and Aanondsen (2006);
Depletion of fossil fuels	1	Gronroos et al. (2006).

For what concern the FU, a certain coherence can be observed, being the most common practice the preference for a mass or volume-based method. 6 of 11 studies opted for 1 t of sludge as a basis for the LCA, either in the form of dry, raw, or digested/activated sludge. One study preferred the use of 1 t^3 of dry sludge[85]; two studies decided for a FU directly correlated with the amount of nutrient recovered by the different treatment options, one using 1 t of pure P, the other using 11 kg of P addresses to agricultural land[72,83]. Only one study used person equivalent as a qualitative/quantitative FU[97].

The system boundary has found to be more diverse, each including raw sludge as a starting point, and later diversifying the structure accordingly with the objective of the LCA. 9 of 11 studies presented a geographic boundary, linked to the location of the treatment plant; in one case the country in which phosphorous is most produced was included (Morocco), whereas the treatment facility was located in Sweden[72]. Another one opted for a more general approach, selecting 15 EU member countries as their system boundary[79].

Construction and operation are included in one article[96], along with transportation and infrastructure, also considered by a second article[58]. One case study used the method of the system expansion for avoided processes related to the production, transport and utilization of artificial fertilizers[65]. 6 of 11 studies followed the life of the sludge from production to its final stage, either application on agricultural field, recycling, or waste incineration plant.

Finally, in relation to the Life Cycle Inventory (LCI), Table 9 summarizes the selection of the different impact categories and the frequency of their utilization among the studies selected. The most common impact category was the global warming potential, included in 9 articles, followed by acidification (6) and eutrophication (5). Other common categories are considered, such as land use and use of finite resources (1 each). Different categories related to toxicity are then present, as related to human health (2), aquatic ecotoxicity (2) terrestrial ecotoxicity (2) photochemical ozone formation (2), freshwater ecotoxicity (1), or covered by the general term toxicity (1), ecotoxicity (1) or human toxicity (1). Depending on the scope and goal of the study, several other more specific impact categories have been sorted, e. g. NO_x emissions, emission to the atmosphere, heavy metals accumulation in soil, phosphorous recycled and available for plants, substance concentrating efficiency, cadmium flows to farmland, greenhouse gas emissions and biogenic carbon. At the end, categories related to the use of energy (primary energy, cumulative energy demand, electricity and fuel used) are present in 4 of 11 studies.

This section covered the literature review of existing LCA studies with a focus on sewage sludge and nutrient recovery. Nor specific case studies performing LCA on sludge streams from aquaculture, neither studies on the potential for the recovery of phosphorous from it have been found in the literature, reinforcing the need for this study, which recognizes the gap present in this particular research field.

Table 8: Literature review of LCA for sludge treatment, summary of commonalities and differences

Reference	Country	FU	System boundary
Hong et al. (2009)	Japan	1 t of dry solids	Heavy metal and dioxin emissions, energy consumption, energy recovery, transport and the infrastructure;
Johansson et al. (2008)	Sweden	1 t of dry solids of digested sludge	Transportation and handling, treatment + system expansion to avoid production, transport and utilization of fertilizer;
Kalmykova et al. (2015)	Production in Morocco, recycling in Sweden	1 t 100% phosphate (P_2O_5) produced or recycled	Gate-to-gate;
Lederer and Rechberger (2010)	15 EU member countries	1 t of raw sludge	Various (depending on the treatment);
Linderholm, Tillman, and Mattsson (2012)	Sweden	11 kg_P (25.2 kg P_2O_5) to agricultural land	Production to application on farmland;
Lundin et al. (2004)	Sweden	1 t^3 of sludge in DM	Production to application on farmland;
Mills et al. (2014)	UK	1 t of dry solids	Production to recycling;
Murray, Horvath, and Nelson (2008)	China	n/a	Construction and operation of the facilities, transportation of the end product included;
Nakakubo, Tokai, and Ohno (2012)	Japan	Processing capacity to provide disposal services for 100 000 people	Various (including and excluding the waste incineration plant);
Sørensen, Dall, and Habib (2015)	Denmark	1 t ()!DM activated sludge	Drying, gasification, chemical extraction of P and drying of the product;
Yoshida, Scheutz, and Christensen (2014)	Denmark	1000 kg of raw sludge	Sludge treatment, rejected water treatment, disposal or utilization.

Table 9: Literature review of LCA for sludge treatment, summary of selected impact categories

Impact category	Frequency	Reference
Global warming potential	9	Hong et al. (2009), Johansson et al. (2008), Kalmykova et al. (2015), Linderholm, Tillman, and Mattsson (2012), Lundin et al. (2004), Mills et al. (2014), Murray, Horvath, and Nelson (2008) Sørensen, Dall, and Habib (2015), Yoshida, Scheutz, and Christensen (2014);
Acidification	6	Hong et al. (2009), Johansson et al. (2008), Kalmykova et al. (2015), Mills et al. (2014), Sørensen, Dall, and Habib (2015), Yoshida, Scheutz, and Christensen (2014);
Eutrophication	5	Johansson et al. (2008), Kalmykova et al. (2015), Linderholm, Tillman, and Mattsson (2012), Lundin et al. (2004), Mills et al. (2014);
Human toxicity	2	Hong et al. (2009) Lundin et al. (2004);
Abiotic depletion	2	Kalmykova et al. (2015) Mills et al. (2014);
Photochemical ozone formation	2	Mills et al. (2014) Sørensen, Dall, and Habib (2015);
Aquatic ecotoxicity	2	Lederer and Rechberger (2010) Yoshida, Scheutz, and Christensen (2014);
Terrestrial ecotoxicity	2	Lederer and Rechberger (2010) Yoshida, Scheutz, and Christensen (2014);
Land use	1	Hong et al. (2009);
Use of finite resources	1	Johansson et al. (2008), Lundin et al. (2004);
Primary energy	1	Johansson et al. (2008);
Toxicity	1	Kalmykova et al. (2015);
Human health	1	Lederer and Rechberger (2010);
Freshwater ecotoxicity	1	Lederer and Rechberger (2010);
NO_x	1	Lederer and Rechberger (2010);
Emissions to atmosphere	1	Lederer and Rechberger (2010);
Heavy metals accumulation in soils	1	Lederer and Rechberger (2010);
Cumulative energy demand	1	Lederer and Rechberger (2010), Linderholm, Tillman, and Mattsson (2012);
P recycled in agriculture and available for plants	1	Lederer and Rechberger (2010);
Substance concentrating efficiency	1	Lederer and Rechberger (2010);
Cadmium flows to farmland	1	Linderholm, Tillman, and Mattsson (2012);
SO_2, CO, NO_x, VOC	1	Murray, Horvath, and Nelson (2008);
Electricity and fuel used	1	Murray, Horvath, and Nelson (2008);
Greenhouse gas emissions	1	Nakakubo, Tokai, and Ohno (2012);
Biogenic carbon	1	Sørensen, Dall, and Habib (2015);
Ecotoxicity	1	Yoshida, Scheutz, and Christensen (2014);
Human toxicity (cancer, non-cancer)	1	Yoshida, Scheutz, and Christensen (2014);
Particulate matter	1	Yoshida, Scheutz, and Christensen (2014);

Part III

METHODS

The third part of the thesis consists in the methodology used for the research. The first chapter defines the method of Life Cycle Assessment (LCA), with its phases and the choices made for the sake of the study. Data from the literature, hypothesis and assumptions are defined in the first and in the second chapter, along with a detailed description of the model, run using the software SimaPro.

6

THESIS METHODOLOGY

6.1 LIFE CYCLE ASSESSMENT

The aim of Life Cycle Assessment (LCA) is to compare the environmental impacts of different treatment technologies for the sludge from aquaculture and, in particular, for the recovery of phosphorous from the aforementioned sludge, in order to identify the less impactful among all. LCA is chosen because it is a well-established, methodological framework[48], which allows this correlation by selecting a basis to compare the performance of the system and quantifying and evaluating the use of the resources and the emission connected. The ISO Standard which regulate the LCA are ISO 14 040, for what concern principles and frameworks, and ISO 14 044, for requirements and guidelines[48]. The selection of the functional unit, the system boundary and the subsequent environmental impact categories are consistent with the aim of the study. The potential-impact appraisal is calculated by a characterisation model, which converts the data from the Life Cycle Inventory (LCI).

6.1.1 *Goal definition and scoping*

The scope and goal definition is the first step of the LCA, and it provides the characterization of the system considered, in terms of the functional unit and the system boundary associated with it[109].

LCA of industrial sludge are still rare in the literature, as mentioned in Chapter 5.2, especially in consideration of the most appropriate technologies for sludge treatment with respect to its environmental impacts, at first, and the option of nutrient recovery, at second. Hence, the need for executing an LCA on aquaculture sludge, in the view of phosphorous recycling.

The FU used in this study is 1 t of raw sludge, being the mass-based method the most preferred among the literature. Raw sludge, also called primary sludge, is considered the sludge coming from the primary mechanical treatment at the aquaculture farm, after the clarification step in the sedimentation tank.

The report published by Nofima in 2017, „Estimated content of nutrients and energy in feed spill and faeces in Norwegian salmon culture," documents the dry matter content in fish faeces to be 10 to 15%, from this the choice of considering the average value of 13% DM in the present research. The choice is also supported by the literature, in particular the article titled „Drying or anaerobic digestion of fish sludge: Nitrogen fertilisation effects and logistics," from Brod et al. (2017), in which is carried out a comparison of different technologies (simple drying and anaerobic digestion) in order to treat fish sludge in Norway, with the aim of obtaining fish sludge-nitrogen based fertilizers, in the view of facilitating the recovery of this nutrient[18]. Moreover, the report discloses the amount of phosphorous present in the sludge from both the smolt and the grow out phase, as follows: 1.4% of P content in smolt-derived sludge, 1% of P content in grow out-derived sludge.

The present research considers sludge, and consequentially phosphorous management, from cradle to grave: the cradle being defined as when excreta and uneaten feed leave the fish tanks, the grave being defined as when phosphorous is recovered and collected, or reused.

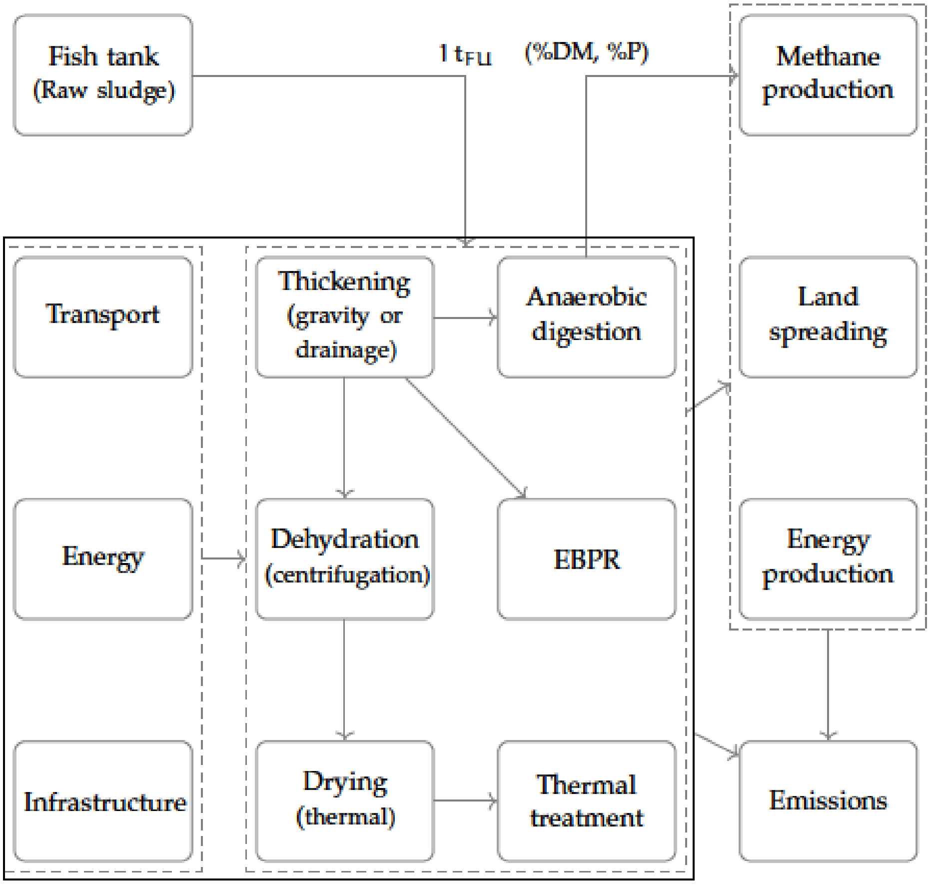
The life cycle stages are collection and primary treatment, storage, transportation and the further treatments needed for the recovery of phosphorous, namely anaerobic digestion (AD), thermal treatment (i.e. incineration), enhanced biological phosphorous removal (EBPR) with struvite recovery. The different options chosen for the phosphorous recovery are selected upon the most promising P restoration methods according to the literature. Transportation is considered in different ranges, consistent with the different distances the sludge has to cover to reach the treatment facilities.

6.1.2 *System boundaries*

The geographical boundary for formation, collection, transportation and treatment of sludge is considered to be Norway. The statistical data used are mainly from 2010 on. Formation and collection of the sludge from the fish tank are the starting point of the LCA, which includes primary mechanical treatment, storage and transportation to the subsequent treatment facility. Recycling and ultimate disposal are considered the final stage of the sludge life cycle. Construction materials and land use are included in the system, being the main output the recovery of P in the different treatment facilities. Cultivation, processing and production of fish feed, in the meaning of fish products (fish meal, ensilage and oil), vegetal products (maize- and wheat gluten, say products and oil, wheat) and additional minerals, vitamins and colour are not included in the system boundary.

The process trees for the different treatment methods are reported in Appendix C and they also show the system boundaries per each scenario. The general representation of the system boundaries is illustrated in Figure 9. The input for the processes includes infrastructure, transport and energy required; the outputs are the production of methane, the spreading of fertilizer and the production of energy. From the products, emissions (to air or soil) are generated. The processes considered regard the treatment of the sludge, and prior to

Figure 9: System boundaries



them is a dewatering step of the raw sludge, explained in details in Paragraph 7.1.2.1.

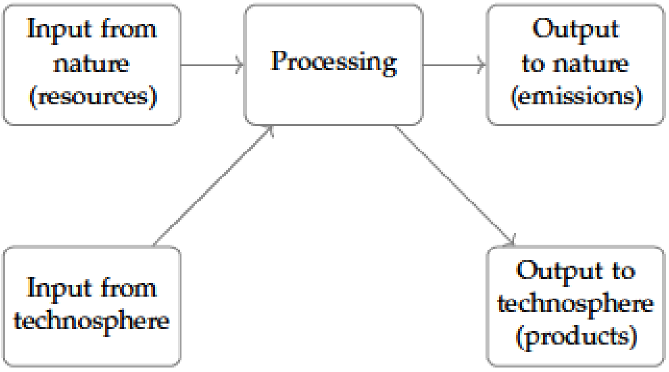
6.1.3 *Life Cycle Inventory (LCI)*

The next step in the LCA is the Life Cycle Inventory (LCI) and it consists in the collection and categorization of the primary data, in the form of inputs and outputs involved in the processes, along with the preliminary analysis of all environmental changes[109]. Primary data are obtained from the databases present in SimaPro for what concern emissions, transport, energy and chemical used, and infrastructures, interviews with experts and literature review of relevant studies. The classification of data follows the schematic of Figure 10, inputs and outputs are listed in Appendix D.

6.1.4 *Life Cycle Impact Assessment (LCIA)*

LCIA is the next step of the LCA and refers to the evaluation of the potential environmental impacts consequences of the Life Cycle Inventory (LCI) outputs. As analysed in Chapter 5, the selection of the

Figure 10: Rationale of the LCI



impact categories is erratic and largely depends on the type of study conducted, based on what is more relevant to the practitioner, and on the magnitude of the environmental impacts after their classification and characterization.

The characterization is conducted using the common FU by both midpoint and endpoint characterization, based on the goal and scope of the research. In this study, ReCiPe Endpoint (H) V1.12 / Europe ReCiPe H/H is used for a general overview of the impacts related with the different sludge treatment methods.

The Hierarchist (H) perspective has been chosen in SimaPro, based on the most common policy principles[62] and with a time frame of 100 yr. Moreover, the selection of the environmental impact categories for what concern the midpoint characterization is done after running the model, and not based on the literature review, due to the unpredictability of the results.

After characterization, the next step is normalization, used to interpret the results from the LCIA, and obtained dividing the scores by a reference's situation. After that, it comes the weighting step which, from the normalised results per each impact category, gives the relative importance of the selected category by multiplying it for a weighting factor. The results thus obtained are then added up to generate one single score per impact, per scenario.

In Chapter 8 both normalization and weighting methods are used, based on which one gives the clearer explanation of the comparison which is discussed.

The impact categories chosen for the study, according to the outcomes of SimaPro, and respected units, are explained in the next paragraph.

6.1.4.1 *Characterization factors at the midpoint level*

In Appendix F the graphical representation of the contribution of all environmental categories present in SimaPro by default is reported

(Figure 30). From this, the most relevant impact categories have been chosen to be discussed in this study.

The midpoint categories chosen are[46]:

- human toxicity and ecotoxicity (here intended as terrestrial ecotoxicity, resulted more relevant than freshwater and marine ecotoxicity), characterized by the exposure and the toxicity effect of a chemical in the environment and in the human food chain. It is measure in $kg_{14DCM}\,yr^{-1}$, where DCB indicates dichlorobenzen;
- particulate matter formation, characterized by the intake proportion of PM_{10}. It is measured in $kg_{PM10}\,yr^{-1}_{equivalent}$;
- climate change, characterized by the global warming potential. It is measured in $kg_{CO_2}\,yr^{-1}_{equivalent}$;
- fossil fuel depletion, characterized by the amount of extracted fossil fuels. It is measured in $kg_{oil\ equvalent}$.

6.1.4.2 *Characterization factor at the endpoint level*

The broader perspective of the endpoint characterization allows to refer at three main categories:

- human health, the unit is years and it is related to the DALYs index (Disability Adjusted Life Years);
- ecosystems, the unit is years and refers to the area-specific loss of species;
- resources, the unit is in 2000 USD and refers to the surplus costs that the production of a resource will have in the future, for an infinitive time frame, and considering a discount rate of 3%.

7

SYSTEM MODELLING

7.1 MODEL

Technological assumption had to be made in order to draft a model for assessing the life cycle of sludge from aquaculture, due to missing or incomplete data sets, and for the peculiarity of RAS in Norway today. The " typical" RAS does not exist, hence the model is based on a compendium of the different designs described in the literature, choosing the most efficient sequence of processes and related technologies.

7.1.1 *Process design*

The growing phase of the Atlantic salmon phase is assumed to be carried out in four different tanks, due to the different physiology of the fishes in their development state, as displayed in Figure 11. In the first tank, parr under 100 g are harvested in freshwater, until they reach the smoltification stage and can be transferred in the post-smolt tank. The trend is to have post-smolt of 200 g, in brackish water with 0.3 to 3.4‰of salinity. Then, the pre grow-out tank hosts salmon until 1 kg, with a water slightly more saline (data varies largely in the literature, from 0.3 to 18.2‰). The last step is the grow-out stage, where salmons reach the weight of 5 kg and are ready to be collected and slaughtered.

In the model, it has first been decided to refer to two main phases, separating the smoltification phase and considering the last three (post-smolt, pre grow-out and grow-out) theoretically together. The decision has been taken according to the data found in the literature (e. g. production volume reported only for smolt and grow-out stages of the salmon production cycle), as well as the calculation regarding the concentration of salt (optimum growth happening at 12‰[2]) and the consistency of the feed used (change in volume but not in composition).

Two different types of effluent thus come from the fish tanks, with a different composition in terms of nutrient and dry matter present, according to the different FCR and digestibility of smolts and salmons. The effluent which comes from the smolt tank is expected to be, in proportion, higher in phosphorous content, being the digestibility of P higher in smolts in comparison with grown salmon (40% for the former, 35% for the latter). The feed is also better digested in smolts (75% compared to 70%), but the eFCR and bFCR are lower then the values for grown salmon. The specification for the different stages of production are listed in Table 10.

Table 10: Physiological characteristics of Atlantic salmon in its production cycle. Adapted from Campo et al. (2010)

	Smolt	Post-smolt	Pre grow-out	Grow-out
Size	<100 g	100 g to 200 g	200 g to 1000 g	1 kg to 5 kg
eFCR	1	1.14	1.14	1.15
bFCR	0.7	0.95	1	1.1
digestibility of feed (%)	75	75	70	70
DM content in feed (%)	94	94	94	94
digestibility of P (%)	40	40	35	35
P content in feed (%)	1.3	1.3	0.9	0.9
P content in DM (%)	1.4	1.4	1.4	1

A first trial has been run in SimaPro, taking into consideration the assumption of two types of sludge effluent. The results are described in Section 8.1. It was then decided to consider only one sludge effluent.

7.1.1.1 *Primary mechanical treatment*

Other assumptions considered concern the processes involved in the primary treatment of the sludge and placed on-site. As well as the harvesting modules, there is no typical state-of-the-art for what concern the sludge treatment in RAS and the process designed is a review of the most common, yet efficient technologies present in the market. The design of the sludge treatment system is thus based on the volume of wet sludge produced in the fish tanks, as well as the dry solid content.

It has been assumed that the fist step of filtration happens already in the fish tank, with the application of a Cornell dual-drain type tank, in combination with a swirl filter. The former has an efficiency of 92% for what concern the removal of TSS, while the second has an efficiency of 23%. During the second step, the effluent undergoes the drum filters, which placed after the Cornell dual-drain type tank, guarantees 40 % to 45 % of TSS removal. The last step is the clarification, mainly consisting in a sedimentation tank, capable of removing 75 % to 90 % of the remaining particles and giving a well-clarified effluent as outcome. The different technologies reviewed and the relative efficiencies are listed in Table 14, in Appendix A. Figure 11 shows the graphic representation of the RAS hyphothesized and used in the model.

7.1.1.2 *System expansion*

Each sludge treatment gives fertilizer and/or energy as outcome, in a ratio depending on the technology. The amount of avoided fertilizer was accounted in the different scenarios, in order to highlight the amount of P (in the form of mineral phosphorous, produced by phosphate rock) in standard fertilizers which is substituted by the recovered P obtained from the sludge treatment, either from digestate, fly ashes or struvite. In SimaPro, this is represented by the amount of single superphosphate (SSP) or triple superphosphate (TSP), already in use as commercial fertilizer.[a] [b] The difference between single and triple superphosphate is related to the content of phosphorous. The choice of considering SSP or TSP in the scenarios depends on the amount of P that can be retrieved from the different treatments, i.e. which treatment is more efficient in terms of P recovery. In particular, single superphosphate (21% P_2O_5) is the chosen fertilizer that can be obtained from the thermal treatment of fish-based sludge ashes[4]. For what concern the anaerobic digestion treatment and the EBPR with struvite precipitation, triple superphosphate (48% P_2O_5) represents the substitute fertilizer[99].

7.1.1.3 *Emissions accounting*

The processes modelled in the software include the treatment technology itself and the emissions (in air and soil) resulting from transport and storage of the sludge. Emissions from storage are calculated according to the method proposed by IPCC (2006) for farm fertilizers, also implemented in the ACV's method "SALCA" (Swiss Agricultural Life Cycle Assessment), used in Dauriat et al. (2011). The detailed calculations are reported in Appendix A, while the schematics of the scenarios are reported in Appendix C and the input data used in the modelling of the processes in SimaPro are listed in the tables in Appendix D, for the dewatering and the treatment technologies.

7.1.1.4 *Transport routes*

Finally, for what concern the transport data, the use of a medium size truck, 10 t to 20 t has being chosen from Ecoinvent, Euro4 (common truck currently used in Norway), which drives partially load from the aquaculture farm to the treatment facility, and turns back empty. For the azonic application of the products (e.g. export of fertilizers), the transport by sea was considered, in particular the use of

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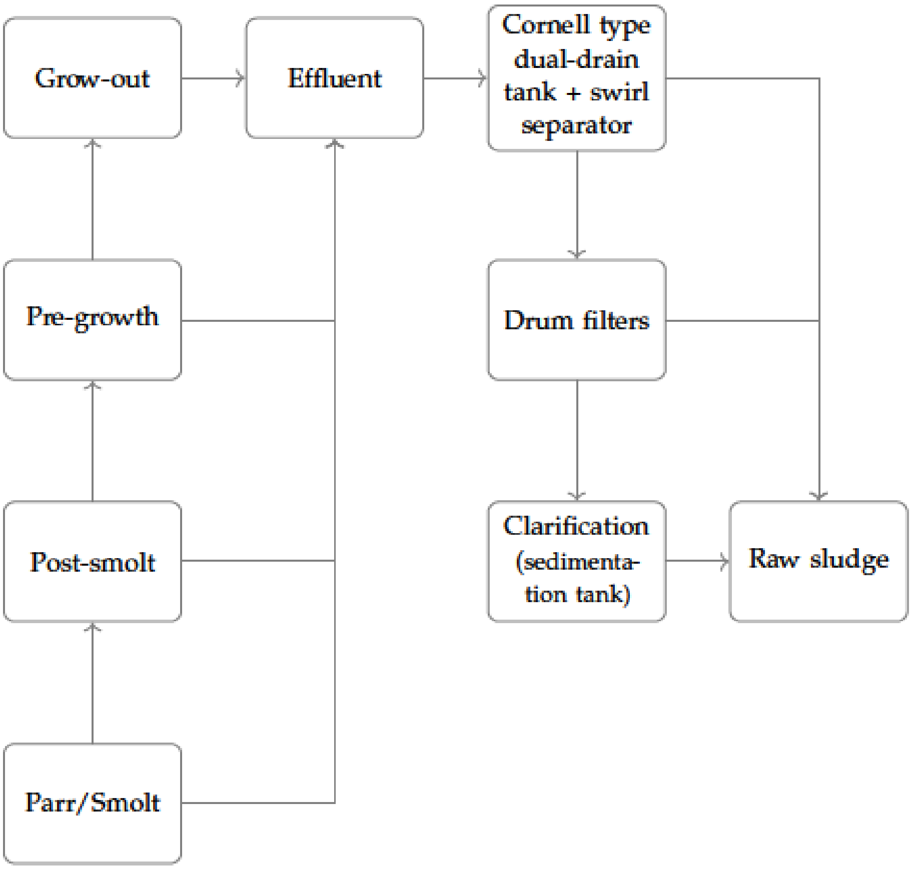
[a] International Plant Nutrition Institute. `https://www.ipni.net/publication/nss.nsf/0/5540C741907C7657852579AF007689EC/$FILE/NSS-21%20SSP.pdf` Accessed July 1, 2018

[b] International Plant Nutrition Institute. `https://www.ipni.net/publication/nss.nsf/0/35039C5F78D8740C852579AF0076567A/$FILE/NSS-14%20Triple%20Superphosphate.pdf`. Accessed June 29, 2018

Figure 11: Process design of the RAS model



a transoceanic ship (also retreived from Ecoinvent). The transport is considered to cover different distances, according with the different scenarios, in relation to the FU of 1 t km_{DM}).

The distances have been selected taking into consideration actual sites in Norway, selected on the basis of personal communications with experts and own assumptions (see map in Appendix E):

- Lerøy Midt, aquaculture farm set placed in Belsvik;
- Gangstad Gårdsysteri Farm, Inderøy;
- Ecopro biogas plant, Verdal;
- Heimdal incineration plant, Trondheim;
- Langøya hazardous waste landfill, Langøya;
- Leirfallet wastewater treatment plant, Trondheim.

7.1.2 *Scenarios*

For the comparison of the different treatment technologies, different scenarios are drafted and modelled in SimaPro, retrieving the necessary data for the LCI from relevant reports present in the literature and in Ecoinvent, and communication with experts of the sector.

In relation to the further steps the sludge undergoes after the primary mechanical treatment, an extra dewatering step is hypothesized, necessary for several reasons[89]:

- to reduce the high water content of the fish sludge;
- to reduce the volume of the sludge, thus the transportation costs;
- to reduce the operating costs.

Different methods are applied in each aquaculture plant, from the addition of flocculation agents and subsequent belt filter (350 µm) to dewatering technologies to dry the sludge up to 85% DM (Julia Fossberg, researcher at Lerøy Midt, Belsvik, personal communication). Thus, the choice to add different dewatering methods per each scenario, which are chosen accordingly with their different efficiency and their suitability for the different treatments hypothesized. The inventory data for the dewatering methods are based on the report „Analyses du cycle de vie des filières de traitement et de valorisation des boues issues du traitement des eaux usées," from Marilys, Marion, and Reverdy (2013).

7.1.2.1 *Pre-treatment: dewatering techniques*

As aforementioned, it is considered 1 t of raw sludge containing 13% DM, which means that its major component is water. Thus, it is assumed an additional step, usually refers as pre-treatment in the case of municipal wastewater treatment, or as dewatering phase, with the aim of reducing the water content and, with it, its volume[89]. The composition of the sludge that undergoes the dewatering process is a function of the feed composition and the primary mechanical treatment upstream. Table 5 in Section 3.2.4 illustrated the chemical composition of fish-based sludge, according to the literature[2,18]. After the clarification phase, hypothesized to occur in a sedimentation tank at the aquaculture plant, the sludge undergoes different thickening processes, depending on its next treatment.

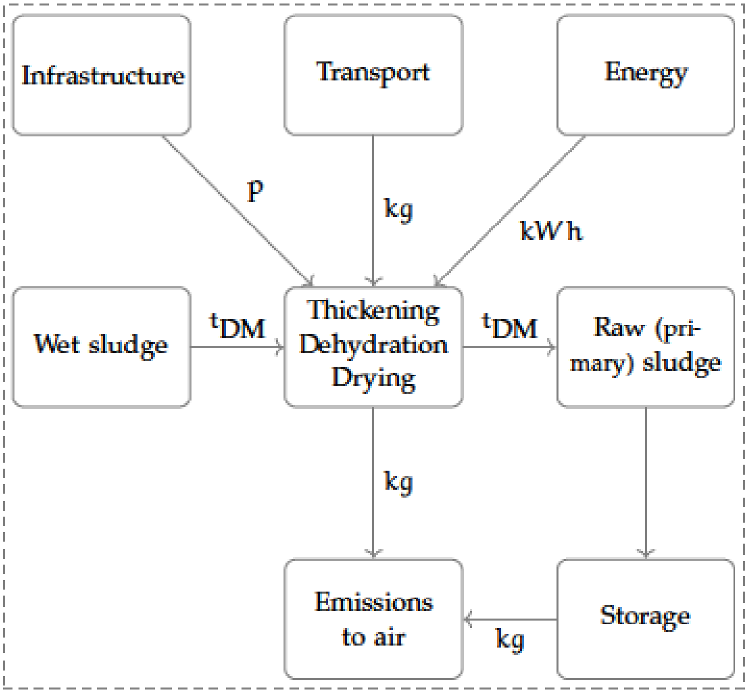
7.1.2.2 *Thickening*

The different thickening techniques adopted in the model are: gravitational thickening and drainage thickening. For what concern the gravitational thickening, it uses gravity to reduce the water content in wet sludge, it is easy to implement, it does not require previous conditioning and it has a low electricity demand. As downside, it requires space, it may causes odours and its performance is suboptimal when there is a high organic content in the sludge. The reduction rate of DM in the sludge is 5%. Thickening by drainage can be implemented through drip tables, drip grids or drums, has a low space requirement and it is equally easy to implement. As disadvantage, requires a careful and constant maintenance, prior sludge conditioning is necessary and requires a high amount of water for thefilter cleaning. The reduction of the DM for what concern wet sludge is set around 10%[89].

7.1.2.3 *Dehydration*

The dehydration of the sludge allows the removal of greater water content then thickening, and it can be mechanic or not mechanic. In the model, it has been decide to consider dehydration by centrifugation. It separates the solid and the liquid phase by centrifugal forces, with the advantages of working continuously, with low space requirements and the option of being a mechanized process. As downsides, it has a high energy demand, and it might requires the addition of polymers in order to obtain a good separation of the solid-liquid phase. The percentage of the reduction rate for the centrifugation method is 5.5%.

Figure 12: System boundary, dewatering process



7.1.2.4 *Drying*

The last dewatering technique considered is thermal (or heat) drying, necessary to further dehydrate the sludge prior incineration, and it can reduce the volume up to 20% of its dry matter content. It is also efficient for what concern odour reduction and, if present, it destroys potential disease organisms, while retaining the fertilizing properties of the sludge.[c]

Figure 12 illustrate the dewatering processes, as implemented in SimaPro, according to their specification for what concern inputs and outputs, and the relative units used in the software.

Consequential to the definition of the system, its boundaries and its functional unit, the different treatment technologies are analysed and compared in SimaPro. The specification of the different scenarios are listed in Appendix C. It has been decided to refer to the Norwegian market when the option was available in Ecoinvent (e. g. "electricity, low voltage, NO"), to the global market elsewhere.

7.1.2.5 *Reference scenario*

Two reference scenarios are modelled in SimaPro, in which 1 t of raw sludge, 13% DM is thickened by gravity and then used a fertilizer, locally or elsewhere. As aforementioned, the method of gravitational thickening gives a 5% reduction of the content of dry matter (DM),

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[c] JSTOR. Water Environment Federation. https://www.jstor.org/stable/25034313?seq=1#page_scan_tab_contents. Accessed June 30, 2018

and the sludge thus obtained is applied in an agricultural field as liquid fertilizer. The co-product considered is therefore TSP, in the amount of 950 kg t_{FU}^{-1}, selected because it is hypothesized that the majority of P which is present in the particulate form in the sludge remains after the thickening step. The distance for the use of fertilizer in the local option is 5 km, for the direct application in a local farm nearby the aquaculture facility. The distance has been chosen in accordance with an experimental approach currently run by Lerøy Midt, Belsvik (Julia Fossberg, personal communication). The transport distance for the azonic option is 250 km, used in order to highlight the importance of considering transport logistic when transferring raw sludge. Thus, the choice of considering an approximation of the distance from Lerøy Midt, Belsvik, to Gangstad Gårdsysteri Farm, Inderøy, which is of 237 km. The sludge undergoes the gravitational thickening only, and no other treatment nor conditioning is applied, in order to represent a basic situation. The process trees of the two reference scenarios are displayed in Appendix C, Figures 21 and 22.

7.1.2.6 *Biogas scenario*

From the two reference scenarios, the comparison with the other possible treatments are modelled in the program, to show the different environmental impacts peculiar of each methods. The anaerobic digestion of sludge dewatered by gravity is designed for both smolt-based sludge and grow-out-based sludge, at the local level (distance from Lerøy Midt, Belsvik, to a biogas plant run by a local farmer, 50 km) and for a centralized plant (distance from Lerøy Midt, Belsvik, to Ecopro biogas plant, Verdal, which currently process biowaste, 215 km). 1 t of raw sludge, 13% DM undergoes the gravitational thickening step; after that, the thickened sludge is transported for 50 km to the local biogas plant, or for 215 km to the centralized biogas plant. It is treated with an anaerobic digestion process, for the production of biogas and digestate. The digestate obtained is accounted as TSP in the software, for the local option in the amount of 855 kg t_{FU}^{-1}, after the 5% dewatering by gravitational thickening, and another 10% volume reduction because of the anaerobic digestion. It is then used as liquid fertilizer, directly spread in the agricultural field. In the centralized option, the sludge undergoes a supplementary dehydration step, by centrifugation, where it loose an additional 5.5% DM, reaching the calculated amount of approximately 808 kg t_{FU}^{-1}, which is then hypothetically shipped abroad (distance used in the model of 1500 km). The biogas plant produces also heat and electricity through combined heat and power (CHP), considered as substituted products, as per the digestate/fertilizer, in the following amounts: 6836.4 MJ t_{FU}^{-1} of heat, and 6076.8 MJ t_{FU}^{-1} of electricity[107].

7.1.2.7 *Incineration scenario*

Another option for the recovery of phosphorous is the incineration of sludge, highly dependent on an efficient dewatering process. The method of drainage thickening is thus chosen for modelling this scenario, given its higher efficiency (10% DM reduction) in comparison with the gravitational method. This first step is, however, not sufficient for obtaining sludge suitable for incineration, hence the choice of adding two further steps: centrifugation, and thermal drying, which dries up the sludge for another 20% DM. After this secondary dewatering steps, the sludge is suitable for thermal treatment and sent to the incineration plant (a distance of 117 km is used, real distance from Lerøy Midt, Belsvik, and Heimdal incineration plant, Trondheim). The incineration plant gives heat and electricity as output, fly ash from which P fertilizer is obtained, and bottom ash which is landfilled. The electricity obtained corresponds to 610.25 $\mathrm{kW\,h\,t_{FU}^{-1}}$, while the heat is in the amount of 563.6 $\mathrm{MJ\,t_{FU}^{-1}}$, considered to be reuse in the incineration facility itself. For what concern the P recovered, it is mainly present in the fly ashes, accounting for 1 to 3% of the total amount of sludge[6,70,76]. Thus, it is considered an amount of 30 $\mathrm{kg\,t_{FU}^{-1}}$ of fly ashes, which are treated for P recovery and give SSP as substitute fertilizer.

The incineration scenario models a centralized option, being the incineration plants usually located in cities and being small household-size waste incinerator not yet common as waste disposal alternatives. However, two scenarios are developed, in which the transport distance for the application of the obtained fertilizer is considered local (within the region in which the incineration plant is located, e. g. Heimdal incineration plant in Trondheim and the surroundings of the city as recipient, 50 km) or azonic (e. g. for export purposes, assigned distance of 1500 km). The final discarding of bottom ashes, considered as hazardous waste and thus needed for separate disposal, occurs at Langøya, hazardous waste landfill 562 km from Trondheim, located in the Eastern Norway region, ca. 70 km south of Oslo.

7.1.2.8 *Biological P removal scenario*

In the biological P removal (EBPR) scenario, the sludge is stabilized and thickened by anaerobic digestion, similarly to the biogas scenario. The reference facilities used in the model to calculate the distances are from Lerøy Midt, Belsvik, to Leirfallet, Leinøra, Trondheim (ca. 115 km).[d] Leirfallet has been chosen because is one of the two facility in the surroundings of Trondheim which implements the chemical-biological treatment of wastewater (the other being Byneset aldersh-

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[d] Norwegian Environmental Agency. https://www.norskeutslipp.no/en/Wastewater-treatment-plants-/?SectorID=100. Accessed June 20, 2018

jem renseanlegg), hence it might be more likely a biological approach for the removal of phosphorous in the future.

The digestate resulting after the AD presents a high concentration of phosphate ions and, after the centrifugation step, is sent to a crystallization reactor for the precipitation of struvite. Depending on the conditions of the plant, the pH might be adjust by adding $MgCl_2$ and, or NaOH. In the reactor, the precipitation occur and it is considered an amount close to 90% of phosphorous recovered from the digestate as struvite[83,99]. The substitute fertilizer modelled was TSP, in the amount of 21.6 kg t_{FU}^{-1}, being the lattest the amount of struvite whch can be recovered per tonne of sludge[99]. No other avoided products, rather then TSP were selected in the biological P removal scenario, the treatment supposed to occur in a wastewater treatment plant, and being the controlled precipitation of struvite a secondary benefit from the main aim of the bio-chemical treatment of municipal wastewater. The inventory for the scenario is based on two studies found in the literature[83,99], and own calculations. The transport of struvite to the place of application has been assumed to be the same as in the case of the treated sludge from the biogas plant, as no information are available in the literature. For what concern the emissions to air, the same data of the biogas scenarios are considered, given the need to store the substrate and the digestate.

Part IV

RESULTS

The fourth part of the thesis presents the outcomes of SimaPro, namely the environmental impact assessment, derived from the LCI. The impact assessment has been carried out recurring to the midpoint level first, and then aggregating the midpoint impact categories through the damage factors, in order to obtain endpoint categories. When necessary, the following steps have been used: normalization and weighting.

8

OUTCOMES

The Life Cycle Assessment (LCA) has been implemented in SimaPro to identify the environmental impacts peculiar of each different sludge treatment. The analysis was carried out with the ReCiPe Endpoint (H) V.1.12 / Europe ReCiPe H/H method. The relations between the processes and variables which constitute the results will be discussed in the following chapter. The main results are displayed below.

8.1 IMPACT ASSESSMENT FOR SMOLT AND GROW-OUT PHASES

The model was first run for the anaerobic digestion scenario only, in its two alternatives of local and centralized, for two different types of sludge, as mentioned in Paragraph 7.1.1. It was supposed a sludge effluent from the smolt phase, and a different one from the grow-out phase. The two types of sludge have been modelled according to their different chemical composition (see Table 10), in particular for what concern the different content of phosphorous and dry matter which result in the sludge after the digestion of the feed. The results disclose a difference in the amount of sludge, as illustrated by Figure 13, but not a significant difference in the environmental impacts in relation to the composition itself. From this, the decision to model the anaerobic digestion scenario only for grow-out-derived sludge, and to use it in the comparison with the other scenarios.

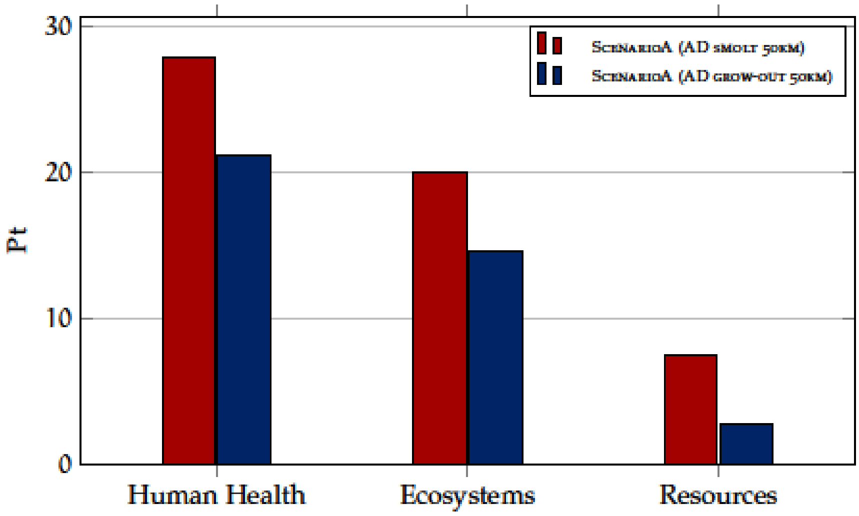

Figure 13: Environmental impacts for smolt-derived sludge and grow-out-derived sludge. Endpoint normalization

8.2 IMPACT ASSESSMENT

The first analysis, in Figure 14 concern the endpoint impact categories of human health, ecosystem and resources, of which the data have been normalized. It has been chosen to include the normalization and the weighting steps, optional in the ISO 14 040 and ISO 14 044, to have a better overview of the environmental impact categories which have the higher values compared to each other, based on a common reference. The reference used in SimaPro is the average environmental impact of an European citizen in one year.

The results, however, are shown in their single score values in the figures, for better graphical clarity.

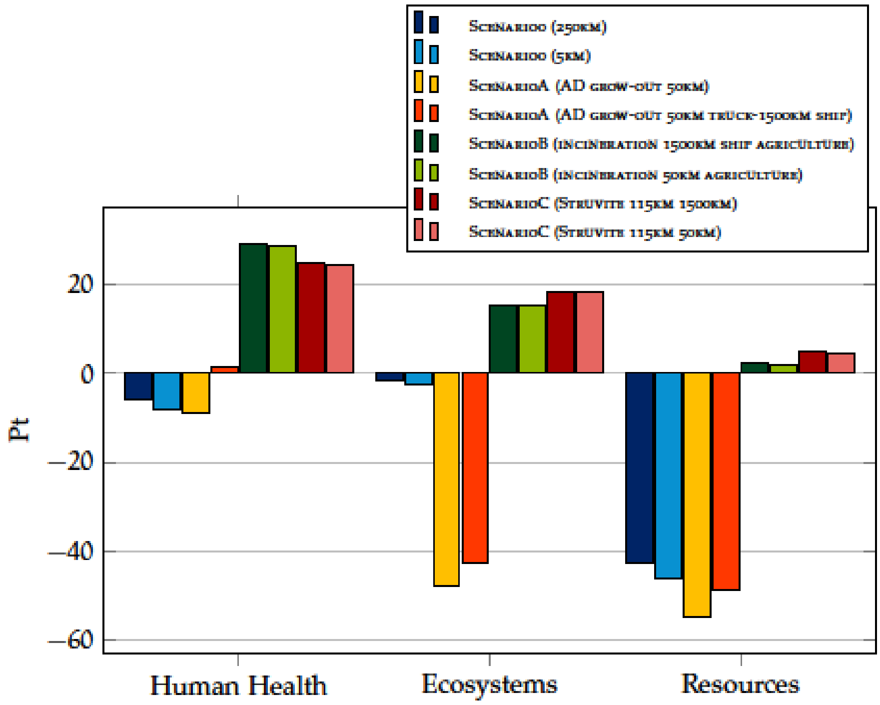

Figure 14: Endpoint, single score

It is clear in the figure the different contribution of the scenarios, in particular the thermal treatment scenarios as the most prominent for what concern the category related to human health. biological P removal scenarios follow, and then come the anaerobic treatment in its centralized option, and the reference scenarios and the anaerobic treatment, local option, with negative values.

The proportions are different in relation to the ecosystems category, where the highest values are related to the biological P removal, followed by the thermal treatment, the reference scenarios with negative values, and at last anaerobic digestion in its azonic and local alternatives, also displaying negative values.

With respect to the resources category, it is again the biological P removal scenario which shows the higher value, followed by the thermal treatment. The azonic reference scenario comes next, followed by its local alternative. The comparison is closed by the centralized option first and the local option for anaerobic digestion.

Figure 15 shows in which extent the different scenarios contribute to climate change.

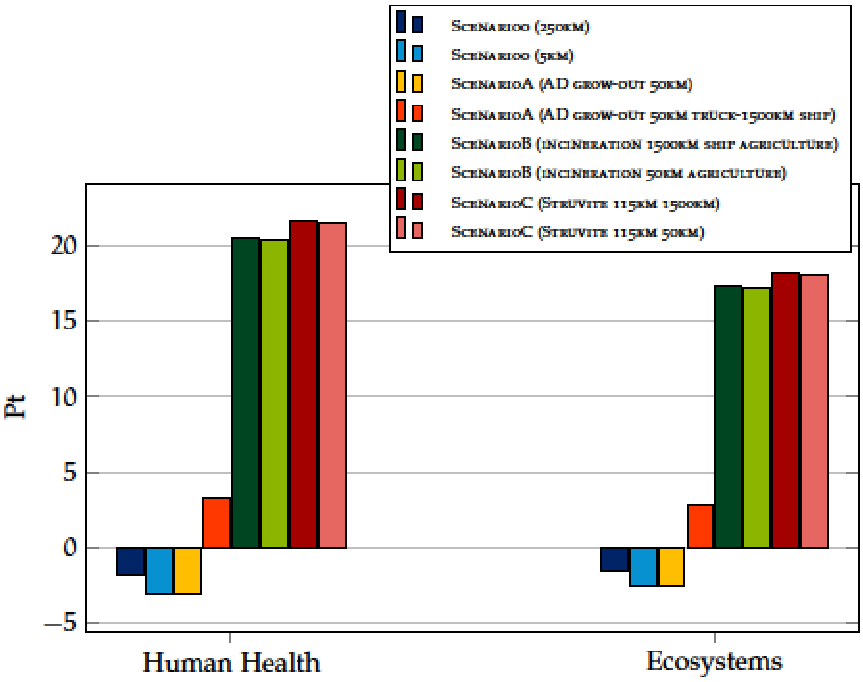

Figure 15: Climate Change, single score

The higher contribution to climate change for what concern human health comes from the biological P removal treatment, followed by the thermal treatment scenarios. It follows the centralized option anaerobic digestion. The azonic reference scenarios comes next, with a negative value, followed by the local options for both the reference scenario and the anaerobic digestion. Similar trend, with lower absolute numbers, is reported for the impacts in climate change related to ecosystems.

For what concern human toxicity and ecotoxicity, the results are displayed in Figure 16. In this case, the higher values in both cases belong to the thermal treatment scenarios, compared to the not significant values of the other scenarios.

In terms of particulate matter and fossil depletion, the results are displayed in Figure 17. In the case of particulate matter emissions, the major contribution comes from the incineration scenarios, followed by the biological P removal. The reference scenarios (centralized first and local option as second) display negative values, concludes the comparison the anaerobic digestion treatment, in its both alternatives.

Different situation is evident in the impacts related to the use of fossil fuels, where the greater contribution is from the incineration

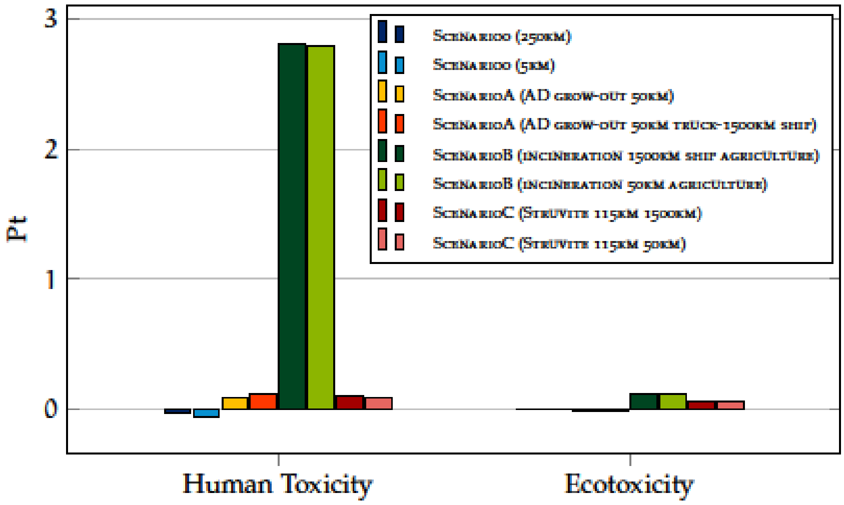

Figure 16: Human Toxicity and Terrestrial Ecotoxicity, single score

scenarios, followed again by the biological P removal scenarios. The reference scenarios come next with negative values, and the local and centralized anaerobic digestion show the lower impacts.

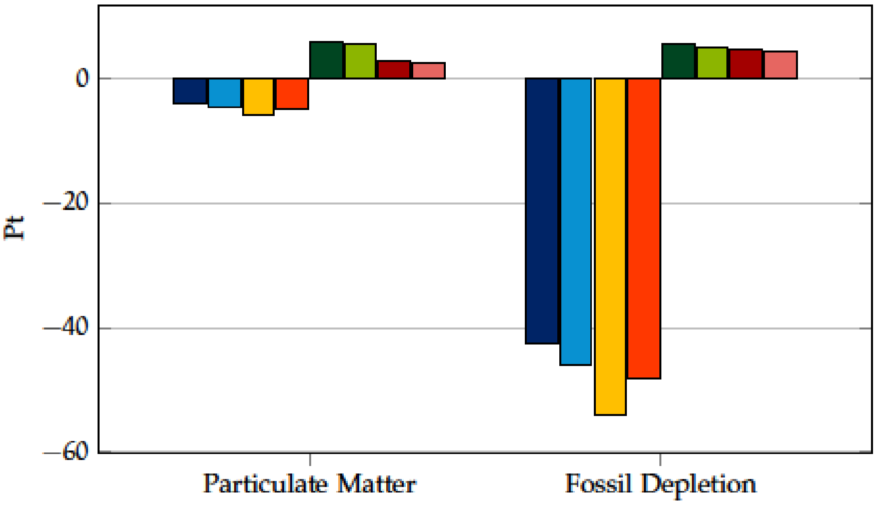

Figure 17: Particulate Matter and Fossil Depletion, single score.

Finally, the different contribution to the environmental impact categories considered are shown in Figure 18. The figure was obtained using weighting, the fourth step of the LCIA, and shows the single environmental impact per each scenario, considering only the impact categories aforementioned. The thermal treatment scenarios have the largest environmental impact, while the lowest is the local option of the anaerobic digestion treatment. It can be seen, as confirmed by the previous comparison, the high contribution in relation to fossil depletion from the reference scenarios, and the similar contribution the incineration scenarios and the biological P removal scenarios have in terms of global warming potential (i.e. climate change, human health and ecosystem). In Figure 19 are displayed the environmental impacts the different scenarios have, in relation to the endpoint categories.

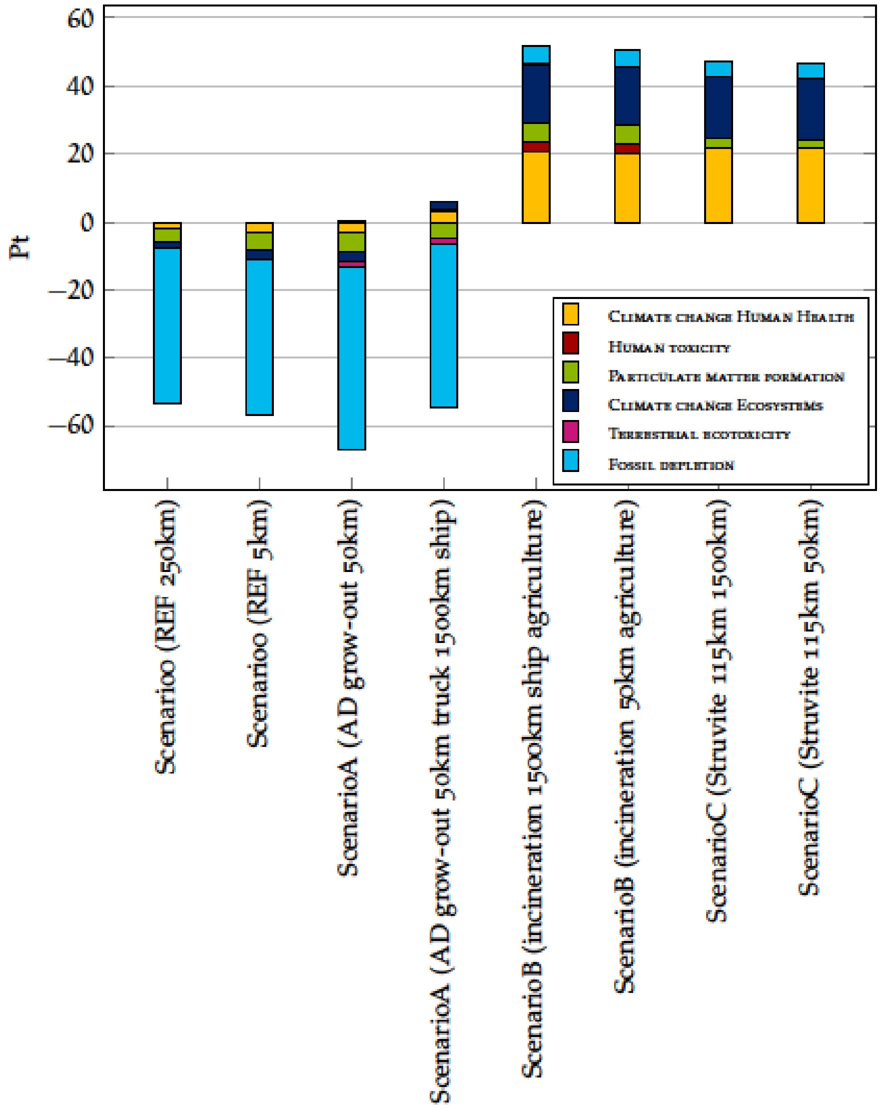

Figure 18: Weighting comparison for all scenarios, single score, midpoint categories

A closer look into the processes involved in each scenario was done in SimaPro, setting the cut-off value at 2.5% in order to visualize only the processes which contribute in a equal or higher percentage. The dewatering methods of gravitational thickening of raw sludge and centrifugation of digested sludge appear in the calculation set-up, meaning they contribute in the emissions related to the human health category. With regards to the ecosystems category, transportation, in addition to the dewatering methods, plays a role, in particular for the centralized alternatives of each scenario, with the highest values related to incineration. Finally, concerning the resource category, de-

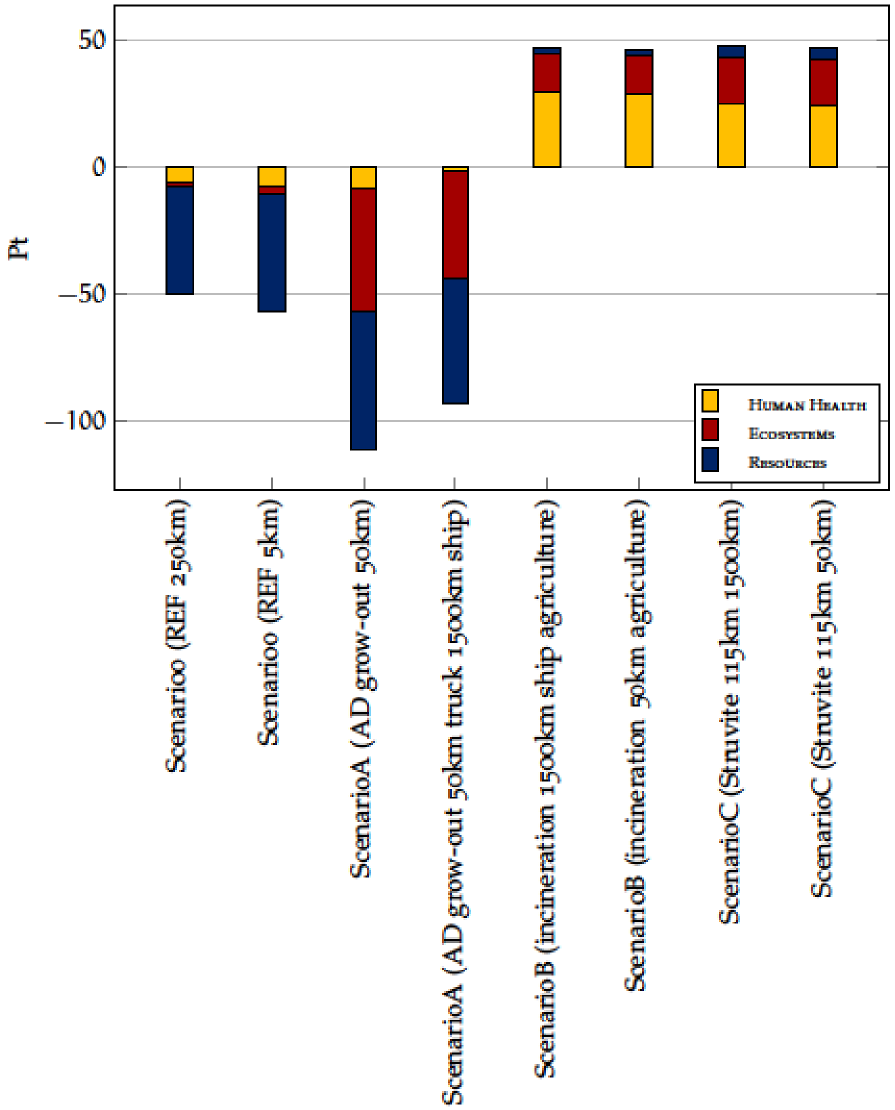

Figure 19: Weighting comparison for all scenarios, single score, endpoint categories

watering methods do not appear relevant, while it is more significant the diesel used for land spreading, the chemical conditioning agent used in the drainage thickening (methyl methalcrylate) and the heat produced from the thermal treatment and reuse in the incineration facility itself (which gives a negative value, thus a reduction in its overall impact). To illustrate the weight of the different processes in each treatment, Figure 20 shows the process contributions, for what concern the centralized option of the reference scenario.

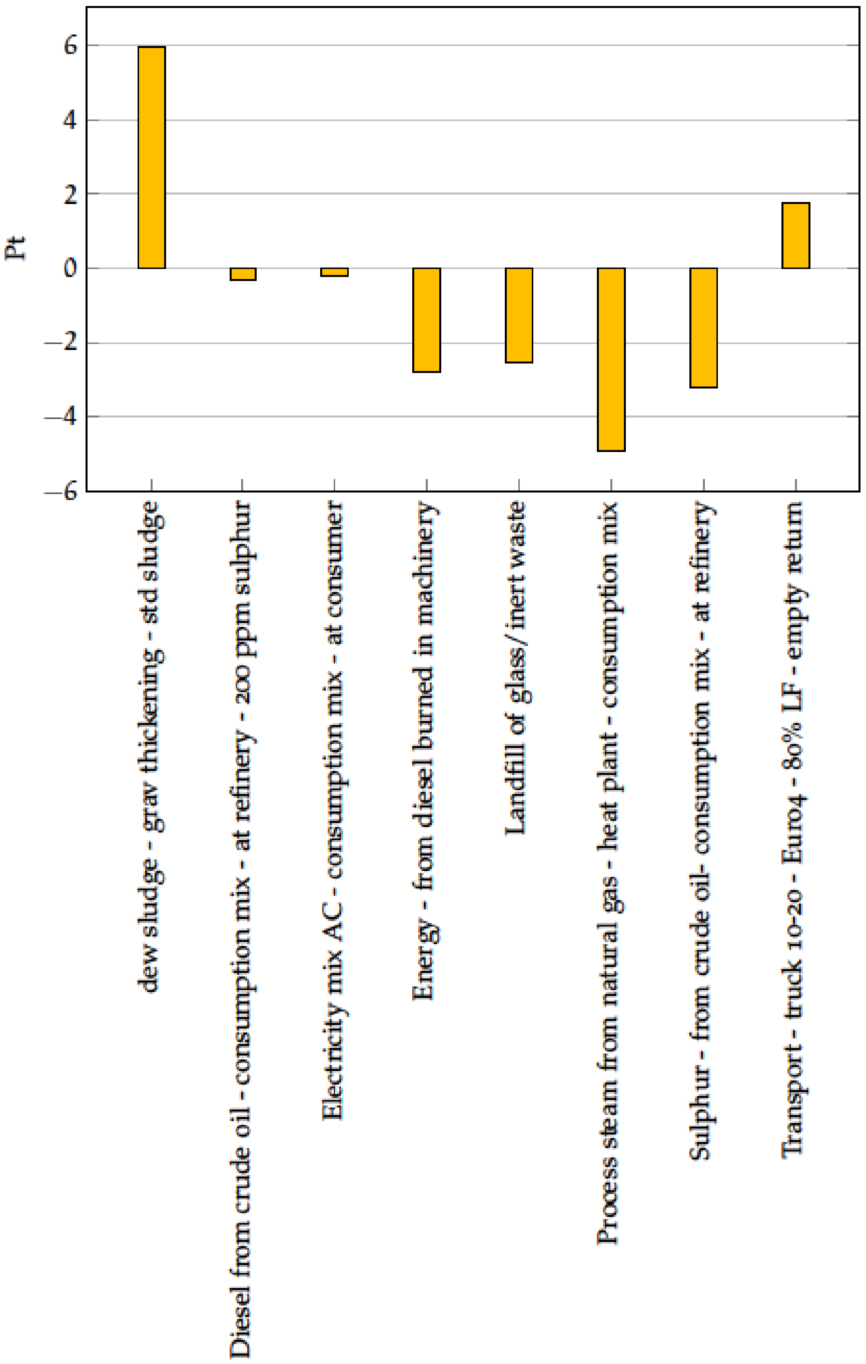

Figure 20: Weighting comparison for azonic reference scenarios, Human Health

9

DISCUSSION

The following section discusses the results presented in Chapter 8. The considerations which derived from the analysis of the outcome of the model are presented according to the research questions introduced in Chapter 1, in particular Paragraph 1.2.

What are the viable treatment technologies and thus the products of aquaculture sludge from RAS of Atlantic salmon, in the view of a sustainable recovery of phosphorous?

According to an extensive literature review, presented in details in Chapter 2, the following methods have been selected for treating fish-based sludge: anaerobic digestion (AD), thermal treatment (incineration) and EBPR (with struvite precipitation). The different scenarios have been compared with the reference scenario of simple thickening and land spreading of the sludge as fertilizer.

The results disclose that the treatment of fish-based sludge through EBPR gives the highest contribution in terms of potential environmental impacts, related to human and terrestrial toxicity. High values are displayed also for what concern the thermal treatment scenarios, with slightly lower absolute values for what concern the resources category. This is due to the higher electricity consumption the biological P removal need, compared to the partial internal energy reuse assumed in the incineration plant.

It can be retrieved from the figures and the data from the inventory that the dewatering methods contribute in the environmental impacts, and simple thickening by gravity, used in the reference scenarios and in the anaerobic scenarios, account less then drainage thickening and thermal drying, due to its not high requirement of electricity.

The results also show that the local option of anaerobic digestion gives the lower values in terms of environmental impacts. The negative values of the impacts show, in particular, the reduction of the impacts obtained with the replacement of commercial fertilizers with the substitute fertilizer (triple superphosphate (TSP) 48% P_2O_5). The alternative of using the digested sludge as liquid fertilizer, of which the use is suitable for agricultural application as discussed in Paragraph 4.2.1, in the local context (the area been defined within 50 km) and for the production of biogas from the methane generation, appears to be the more sustainable scenario derived from the model. The main environmental contributions are related to the global warming potential (climate change, human health and ecosystems), which comprises the emissions of greenhouse gases to air. They are mainly caused by the dewatering method of gravitational thickening and by the storage of sludge and digestate. The centralized option of anaerobic digestion presents a higher, although still partially negative, environmental impact, due to transportation of the sludge for longer distances, thus computing in the calculations the use of fossil fuels (fossil depletion category) and the formation of particulate matter generated from their extraction and combustion (particulate matter category), which result in higher impacts related to the resource and human health categories.

The favourable use of substitute fertilizer is evident also in the reference scenario results. However, the lack of treatment of the sludge still accounts for high impacts with regards to human toxicity, in particular in the lack of a stabilization step.

The scenarios of biological P removal show similar values for all environmental categories, with a slightly higher results in correspondence of the centralized scenario, due to longer travel distances (see Figure 19). Similar are also the values for the thermal treatment scenarios, higher in the human toxicity, in the particulate matter and in the fossil depletion categories. Low values for what concern the resources category are justified by the generation of heat from the incineration plant and its reuse in the facility (evident from the values in Figure 19).

What is the impact of a longer grow-out on-shore period for the Atlantic salmon, which in turns lead to a saline composition of the sludge?

As shown in Figure 13, the choice of expanding the Recirculating Aquaculture Systems (RAS) for the entire production cycle of the Atlantic salmon results in a higher amount of sludge which needs to be treated. This in turns calls for adequate facilities, in terms of infrastructure and efficiency of the treatment. The practice of using the same feed for smolt and grow-out salmon leads to a similar composition of the sludge, thus the possibility of not differentiate the two effluents. As discussed in Section 3.3, few articles have been found in the literature which assess the feasibility of using sludge with a certain saline content: the studies assert the need for a proper dewatering treatment first, and conditioning at second, in order to clean the sludge from chloride and sulphur compounds.

What is the feasibility of a biogas production from saline sludge?

The literature about the feasibility of biogas production from a slightly saline substrate is scarce. However, few experimental studies (see Section 3.3) have developed pilot biogas plants[122] and shown the viability of generating methane from a saline (15 to 17‰) substrate. In particular, the production of biogas from the pilot reactor examined was constant and efficient, and the methods was highly efficient in terms of sludge volume reduction.

What are the possible uses for the recovered phosphorous?

The products considered from the different sludge treatment, and referred as "avoided products" for their property of substitute existing commodities, are: fertilizer (liquid or solid, from digestate, incineration ashes and precipitation of struvite), electricity and heat (from the production of biogas). As co-products which need proper disposal, are the bottom ashes from incineration. A high amount of P is to be found in particular in digestate from anaerobic digestion, and in the generation of struvite from controlled precipitation and subsequent crystallization. Fertilizer obtained from incineration ashes is considered to have a lower P content (21% compared to 48% of P_2O_5), and it needs a dedicated chemical conditioning, for example acid leaching, in order to be converted in a more suitable plant-available mineral form.

9.1 LIMITATIONS

Although the study has delivered results able to answer the research questions, some inevitable limitations have to be mentioned. First of all, being the research placed in a new field of study, it was not possible to count on a broad literature for the assumptions which had to be made. In particular, Recirculating Aquaculture Systems (RAS) are still not widely present in the market and along with it the recognition for a proper sludge management is missing. The consequence of this is the lack of available data and the necessity to appeal to own assumptions and calculations. Treatment of fish-based sludge is however in the interest of research centers like SINTEF, in Trondheim, from which it was possible to retrieve technical reports and organize interviews with expert of the sector.

Second, the lack of a comprehensive inventory in SimaPro resulted in a self-made inventory, product of data from the literature review and own calculation, which might results incomplete. In particular, the data concerned the different dewatering methods (thickening, centrifugation and thermal drying) are consistent, thanks to a detailed technical report found in the literature[89] and the same is for the calculations regarding the emissions[35]. The energy accounting instead, in the meaning of usage and production of heat and electricity, for both the anaerobic digestion first and thermal treatment then, is a summary of the data found in the literature, compared and adjusted to the peculiar situation described for the study, that is mono-incineration of fish-based sludge, instead of the more common co-digestion, or combined incineration of manure and sewage sludge. This also reflects in a A similar situation is for the data concerning the EBPR scenarios, where they were assumed some commonalities with the anaerobic digestion treatment, due to lack of different informations.

Finally, do to time availability, a sensitivity analysis is missing, and it might have been useful in the global understanding of the system, highlighting the most relevant variables per each scenarios (e. g. a different range of distances, for what concern the transport variable in a logistic point of view).

10

CONCLUSIONS

10.1 FURTHER CONSIDERATIONS

Few considerations are possible with regards to the collection and reuse of fish-based sludge in a more general context.

First of all, the production of sludge in Norway, calculated in Paragraph 1.1.1, was based on the assumption of having the same feed for both smolt and grow-out Atlantic salmon. It is however more reasonable to develop more specific feed formulas in the future, and with that a different ratio in the ingredients used, to meet the requirements the fish have in its different development stages. This in turn could lead to a different sludge composition, hence the recovery of P might be more efficient through other technologies then the ones considered.

Second, the option of treating sludge through delocalized biogas plant is possible and, following the studied LCA, beneficial in terms environmental impacts in Norway due to the peculiar characteristic of the country. That is the presence of agriculture everywhere, hence the possibility to refer to small-medium farms to be the recipient for the sludge which has to be treated. Moreover, being hydropower the predominant source of electricity, it is more practical the use of the heat and electricity generated from biogas in local, decentralized conditions, rather then its integration in the national grid. This can be different in other countries, with an energy country mix based on fossil fuel, where the thermal treatment would have a lower impact in terms of global warming potential since electricity and heat are partially reused and partially sold to be integrated in a, for instance, district heating system. On the other hand, struvite might have a higher impact in terms of emissions, running the wastewater treatment plants on fossil-fuels based electricity.

Finally, recovered P from fish-based sludge is considered a "slow-release" fertilizer, meaning that its primary characteristic is to lower down the rate at which P is released in soil. This is considered an advantage when a long term source of P is needed, such as in the case of the later stages of plants growth[123]. As another benefit, slower dispersion means lower risk of agricultural run-off, hence eutrophication. On the other hand, biologically available phosphorous (BAP), that is the amount of P exhibiting a rapid incorporation rate in the living cells, is crucial in the early phases of plants growth, playing a role in several functions such as photosynthesis and energy transfer.[a] As downside, BAP leads to high P concentration in soil, which in turns lead to risk of land run-off after the application of this types of fertilizers, hence higher risk of freshwater eutrophication.

10.2 CONCLUDING REMARKS

The present research focused on the cradle-to-grave Life Cycle Assessment (LCA) of 1 t of raw fish-based sludge, from aquaculture of Atlantic salmon harvested in Recirculating Aquaculture Systems (RAS) in Norway.

The different scenarios for the possible sludge treatments were modelled in SimaPro, subsequent to an extended literature review of RAS, of the more suitable technologies for sludge treatment already in use in the valorization of sewage sludge, and the design of a hypothetical primary mechanical treatment to place on-site, followed by a dedicated dewatering step and the transport in the chosen facility. The different methods have been selected in the view of their potential to recover phosphorous, present in a great extent in fish-based sludge.

The LCIA gave an indication of the technology which has the lower environmental impacts, in the view of phosphorous recycling. The study indicates the potential for sludge treatment by means of anaerobic digestion in a local context, producing digestate as liquid fertilizer and electricity and heat from biogas.

It is also clear that the highest environmental impacts belongs to the EBPR scenarios, for its high technical and energy requirements. Using fish-based sludge directly an agricultural land is also beneficial in terms of environmental impacts, in particular considering the low impacts on the ecosystems.

However, in the view of potential phosphorous and resource recovery, the local alternative of anaerobic digestion is preferable, as it reduces the volume of sludge to be transported and produces heat and electricity from biogas.

The results of the research endorse the need for more investigations towards a more sustainable management of fish-based sludge in general, and phosphorous in particular. Thus, the need for national guidelines and standardized practices, which can be supported by the implementation of the LCA, as a tool to facilitate the process of decision making. Hence, the importance of additional research, which will enable to build further knowledge upon this preliminary results.

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[a] Biologically Availability of Phosphorous. `http://www.ijc.org/files/publications/F17.pdf`. Accessed July 1, 2018

Part V

APPENDIX

A

REPORTED DATA FOR FINFISH PRODUCTION

Appendix A reports data retrieved from the literature concerning the characteristics of Atlantic salmon (*Salmo Salar*). In Table 11, the physiological properties of the four different phases of the Atlantic salmon production cycle are displayed, with the actual production in Norway. The table shows the results presented in the report from Nofima, „Estimated content of nutrients and energy in feed spill and faeces in Norwegian salmon culture“ (2017) for the smolt and grow-out stages, while for post-smolt and pre grow-out phases the results are based on data from the literature and own calculations.

Table 12 describe the chemical characteristics of water in land-based aquaculture farms, according to the Norwegian legislation, for the harvesting of salmonid species (Atlantic salmon and Rainbow trout), while in Table 13 are listed the thresholds in regards to the water quality of Recirculating Aquaculture Systems (RAS).

Finally, Table 14, also from a Nofima report[21], tabulates the efficiencies of the different methods for the mechanical removal of SS in case of RAS tanks, for single or combined implementation.

Table 11: Characteristics of the four phases of the Atlantic salmon production. Adapted from Aas and Åsgård (2017)

	Smolt	Post-smolt	Pre grow-out	Grow-out
Size (kg)	0.08 to 0.1	0.1 to 0.2	0.2 to 1	1 to 5
Production (piece)	300 000 000	178 200	-	-
Production (t)	24 000	35 640	131 155	130 000
eFCR	1	1.14	1.14	1.15
bFCR	0.7	0.95	1	1.1
Digestibility of P (%)	40	40	35	35
P content in feed	1.3	1.3	0.9	0.9
Digestibility of feed (%)	75	75	70	70
DM content in feed (%)	94	94	94	94
P content in DM (%)	1.4	1.4	1	1
Mortality	-	0.01	0.08	-

Table 12: Norwegian salmonid welfare. Mattilsynet. The Norwegian Food Safety Authority. https://www.mattilsynet.no/language/english/. Accessed February 21, 2018

Norwegian salmonid welfare	Value
pH level in inlet to fish tanks	6.2 to 7.8
Oxygen level in fish tanks	not more than 100%
Oxygen saturation in outlet of fish tanks	Not less than 80%
Carbondioxide level - Salmon	$<15\,\mathrm{mg\,L^{-1}}$
Carbondioxide level - Rainbows	$<10\,\mathrm{mg\,L^{-1}}$
Nitrite – fresh water	$<0.1\,\mathrm{mg\,L^{-1}}$
Nitrite - saltwater	$<0.5\,\mathrm{mg\,L^{-1}}$
Total-N	$<2\,\mathrm{mg\,L^{-1}}$
Ammonia	$<0.002\,\mathrm{mg\,L^{-1}}$

Table 13: Water quality variables for RAS. Adapted from Warrer-Hansen (2015)

	Smolt	Grow-out (34‰ saltwater)
Temperature	14 to 16	12 to 14
Total ammonia TAN	<1	<1
Nitrite NO_2N $mg\,L^{-1}$	<0.4	0.8
Nitrate NO_3N $mg\,L^{-1}$	<75	75
BOD $mg\,L^{-1}$	<10	<10
Alkalinity as $CaCO_3$ $mg\,L^{-1}$	>80	>80
TSS	<10	<10
O_2 % saturation	>80	>90
CO_2 $mg\,L^{-1}$	<12	<20
pH	6.9 to 7.8	7.2 to 7.8
fish stocking density $kg\,m^{-3}$	<55	<80

Table 14: Reported efficiency of solid removals. Adapted from Campo et al. (2010)

Filter	Removal efficiency	Reference
Cornell Dual Drain	92% of TSS	Timmons, Timmons, and Ebeling (2006)
Swirl separator	63%	Couturier et al. (2009)
Swirl separator (Eco-trapTM-SINTEF)	80% of TSS	Ebeling and Vinci (not pub)
Swirl separator (after Cornell-tank)	23% of TSS	Davidson and Summerfelt (2005)
Radial flow settler (after Cornell-tank)	48% of TSS	Davidson and Summerfelt (2005)
Drum filter	63%	Couturier et al. (2009)
Drum filter (after Cornell-tank)	40 to 45%	Davidson and Summerfelt (2005)
Drum filter (SS inlet$<5\,\mathrm{mg\,L^{-1}}$)	31 to 67%	Ebeling and Vinci (not pub/ppt)
Drum filter (SS inlet$>50\,\mathrm{mg\,L^{-1}}$)	68 to 94%	Ebeling and Vinci (not pub/ppt)
Sedimentation tank	75 to 90%	Bergheim, Cripps, and Liltved (1998)

B

EMISSION ACCOUNTING

Appendix B describes the formula used for the calculation of the emissions (to air) in the anaerobic digestion scenarios and in the biological P removal scenarios. The emissions regards the storage of the substrate (i.e. raw sludge) and of the consequent digestate obtained as a product of the anaerobic digestion, and are calculated based on the report from Dauriat et al., titled „Analyse de cycle de vie de la production centralisée et décentralisée de biogaz en exploitations agricoles“ (2011).

Equations for the calculation of the emission of CH_4, NH_3, N_2O and CO_2:

$$E_s(CH_4) = 0.670 * B_0 * C(OM) * EF_1 * t$$

where:

E_s (CH_4) are the emission of methane, in $kg_{CH_4}\ t^{-1}_{substrate}$;

B_0 = 0.3014 is the methane emission potential of the substrate, in $m^3_{CH_4}\ kg^{-1}_{OM}$;

$C(OM)$ is the content of organic matter, in $kg_{OM}\ t^{-1}_{substrate}$;

EF_1 = 10% is the emission factor for methane;

t is the percentage of time the substrate is stored for the biogas production, assumed to be 10%.

$$E_s(NH_3) = (\frac{17}{14}) * C(N_t) * 62 * EF_2 * t$$

where:

E_s (NH_3) are the emission of methane, in $kg_{NH_3}\ t^{-1}_{substrate}$;

$C(N_t)$ is the content of organic matter, in $kg_N\ t^{-1}_{substrate}$;

EF_2 = 1.35% is the emission factor for ammonia, assuming the stock to be stored covered;

t is the percentage of time the substrate is stored for the biogas production, assumed to be 10%.

$$E_s(N_2O) = (\frac{44}{28}) * (C(N_tot) - (\frac{14}{17}) * E_s(NH_3)) * EF_3 * t$$

where:

E_s (N_2O) are the emission of nitrous oxide, in $kg_{N_2O}\, t^{-1}_{substrate}$;

$C(N_t)$ is the content of organic matter, in $kg_N\, t^{-1}_{substrate}$;

EF_3 = 0.5% is the emission factor for nitrous oxide;

t is the percentage of time the substrate is stored for the biogas production, assumed to be 10%.

$$E_s(CO_2) = (\frac{44}{12}) * C(C) * EF_4 * t$$

where:

E_s (CO_2) are the emission of carbon dioxide, in $kg_{CO_2}\, t^{-1}_{substrate}$;

$C(C)$ is the content of organic matter, in $kg_C\, t^{-1}_{substrate}$;

EF_4 = 0.7% is the emission factor for carbon dioxide;

t is the percentage of time the substrate is stored for the biogas production, assumed to be 10%.

C

SCENARIOS

Appendix C collects the eight scenarios used in SimaPro, to model the environmental impacts of the different fish-based sludge treatments, in the view of the recovery of phosphorous. The scenarios are represented as follow:

- Figure 21 illustrates the local option of the reference scenario;
- Figure 22 illustrates the centralized option of the reference scenario;
- Figure 23 illustrates the local option of the anaerobic digestion scenario;
- Figure 24 illustrates the centralized option of the anaerobic digestion scenario;
- Figure 25 illustrates the local option of incineration scenario;
- Figure 26 illustrates the centralized option of the incineration scenario;
- Figure 27 illustrates the local option of the biological P removal scenario;
- Figure 28 illustrates the centralized option of the biological P removal scenario.

The scenarios refer to the functional unit (FU) of 1 t of raw sludge, 13% DM. The system boundary per each scenario is represented by the dashed line, within which the system is reproduced. The input and output of the processes, "from/to technosphere" as called in SimaPro, and the respective units are specified as follow:

- input, infrastructure, piece [p];
- input, transport, tonne-kilometer, [t km];
- input, energy, kilowatt-hour, [kW h];
- output, emissions, kilogram, [kg].

The different dewatering techniques and the reduction rate of DM considered are indicated in the graphs: the dashed line which relates the dewatering method to the raw sludge highlights the occurrence of the first on-site (i. e. in the aquaculture farm), and the subsequent transport of the obtained (dewatered) sludge to the application site or the treatment facility.

The products derived from the treatment processes, and the units related, are:

fertilizer, tonne, [t];

biogas, cubic meter, [m^3];

digestate, tonne, [t];

electricity, kilowatt-hour, [kW h];

heat, mega-joule, [MJ];

bottom ash, tonne, [t];

fly ash, tonne, [t].

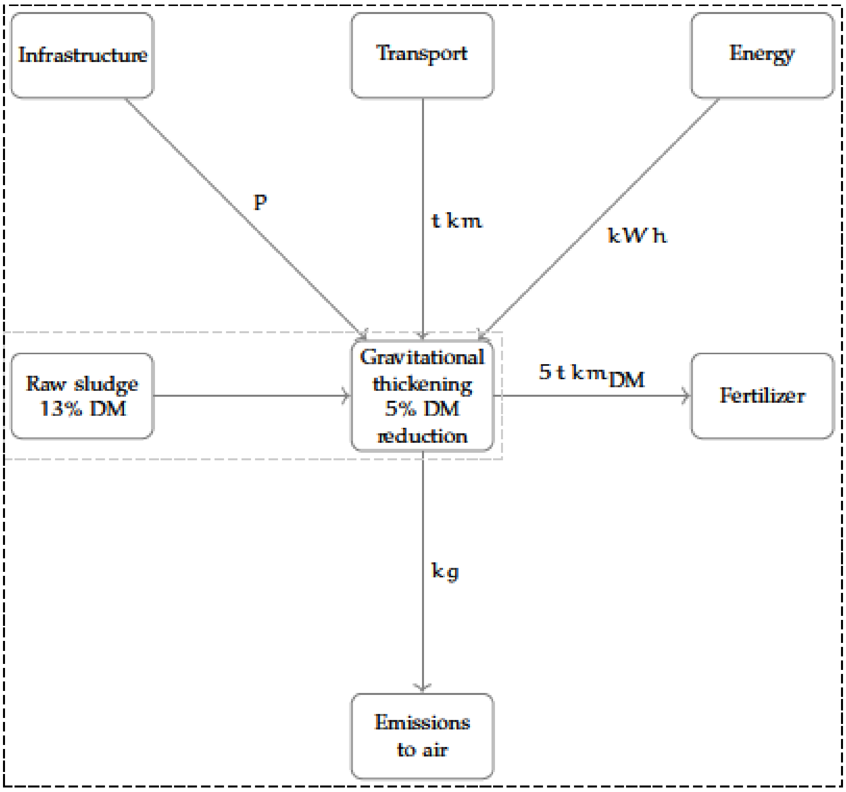

Figure 21: Process tree for reference scenario, local option for agricultural application

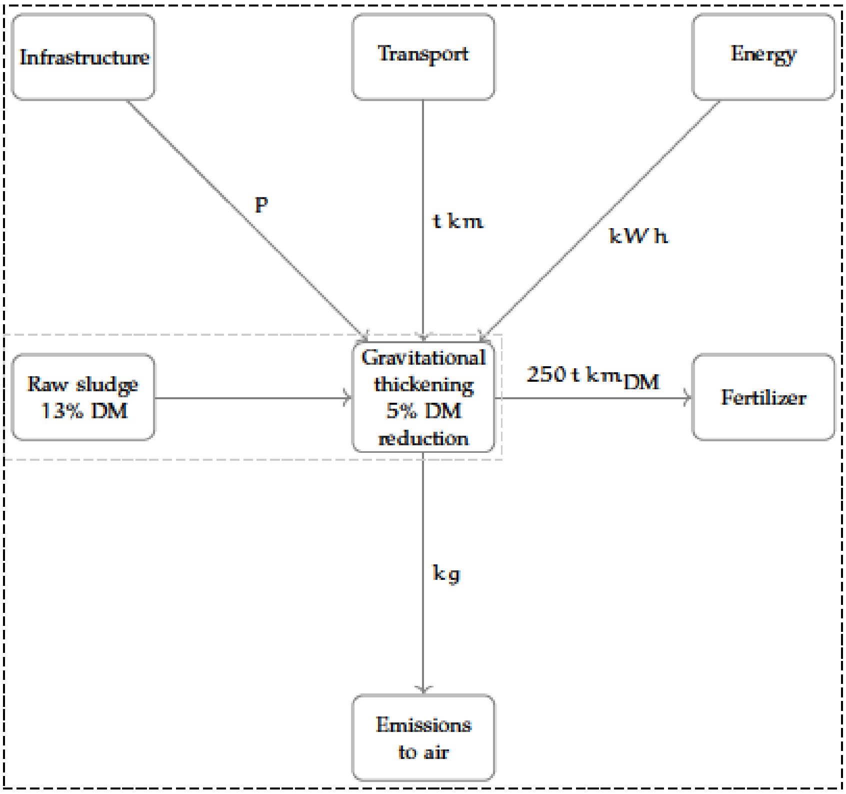

Figure 22: Process tree for reference scenario, centralized option for agricultural application

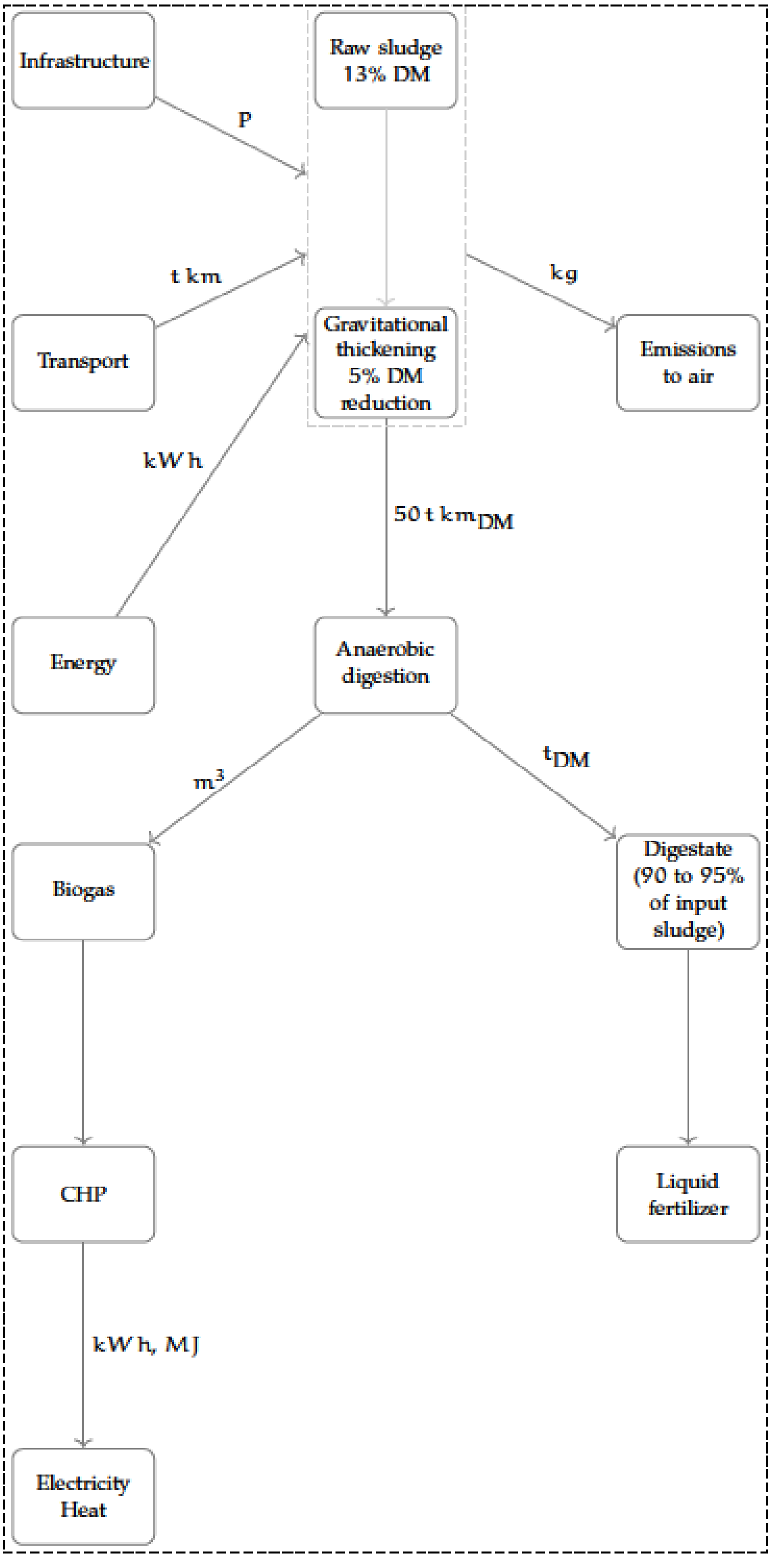

Figure 23: Process tree for anaerobic digestion scenario, local option

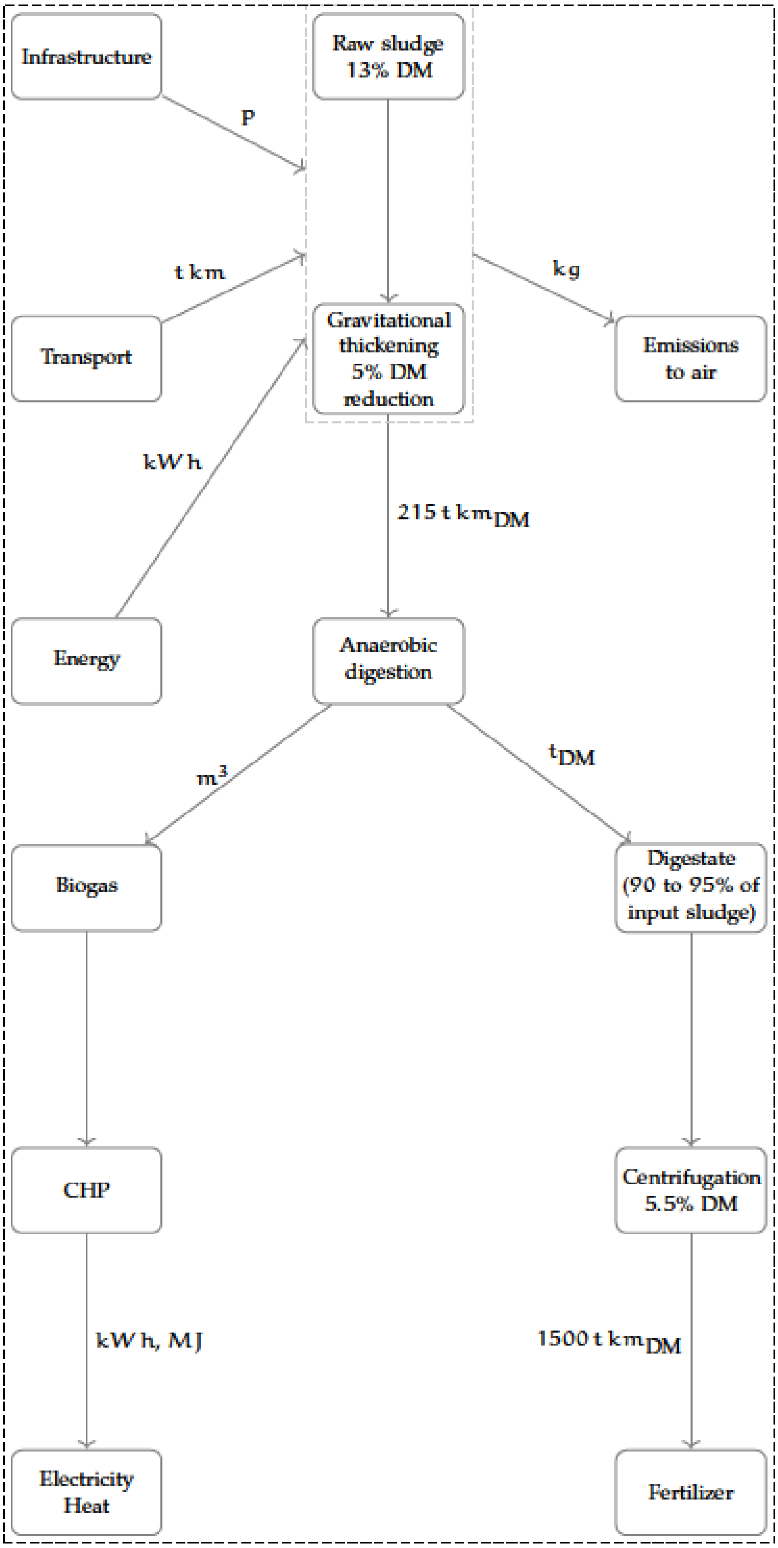

Figure 24: Process tree for anaerobic digestion scenario, centralized option

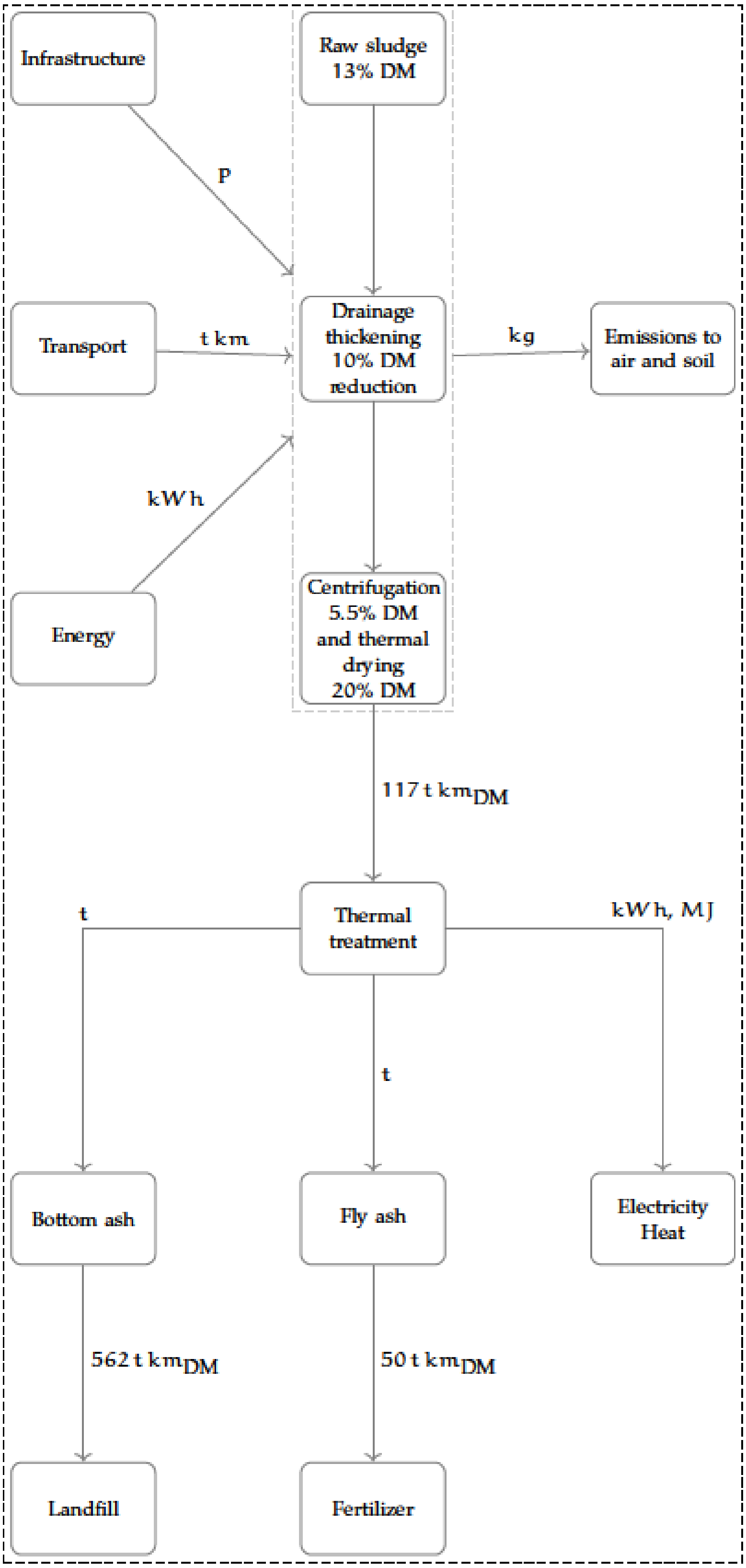

Figure 25: Process tree for incineration scenario, local option

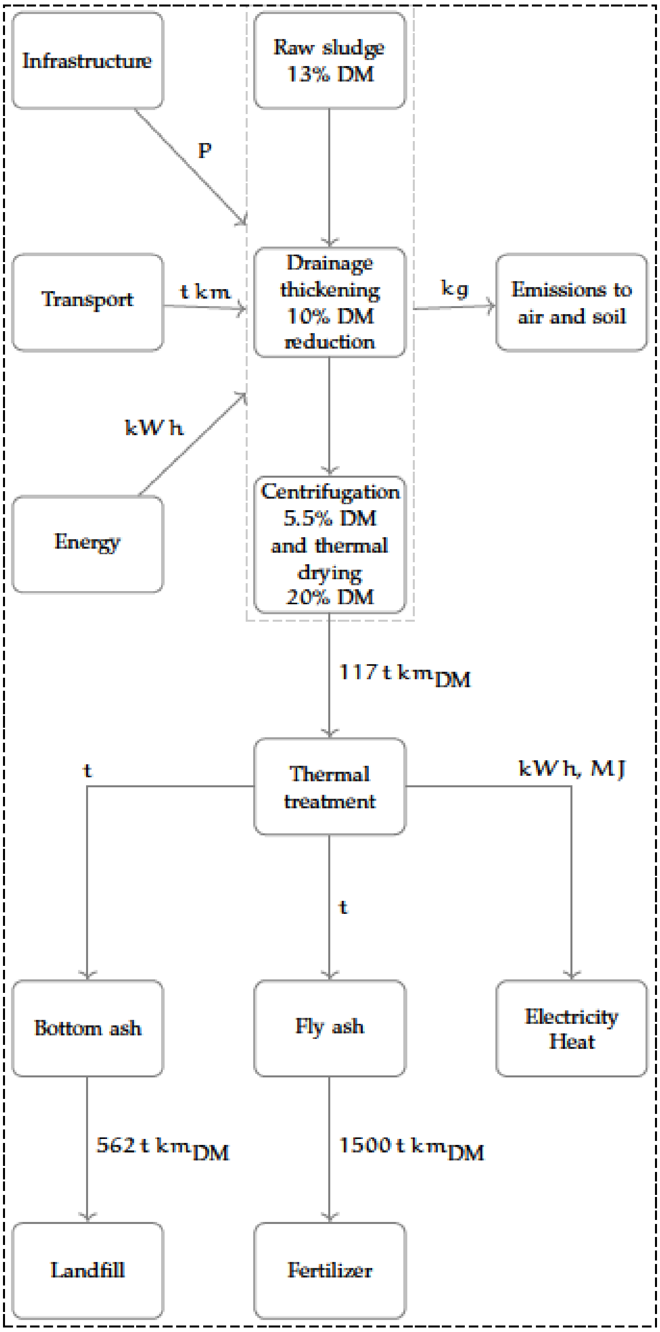

Figure 26: Process tree for incineration scenario, centralized option

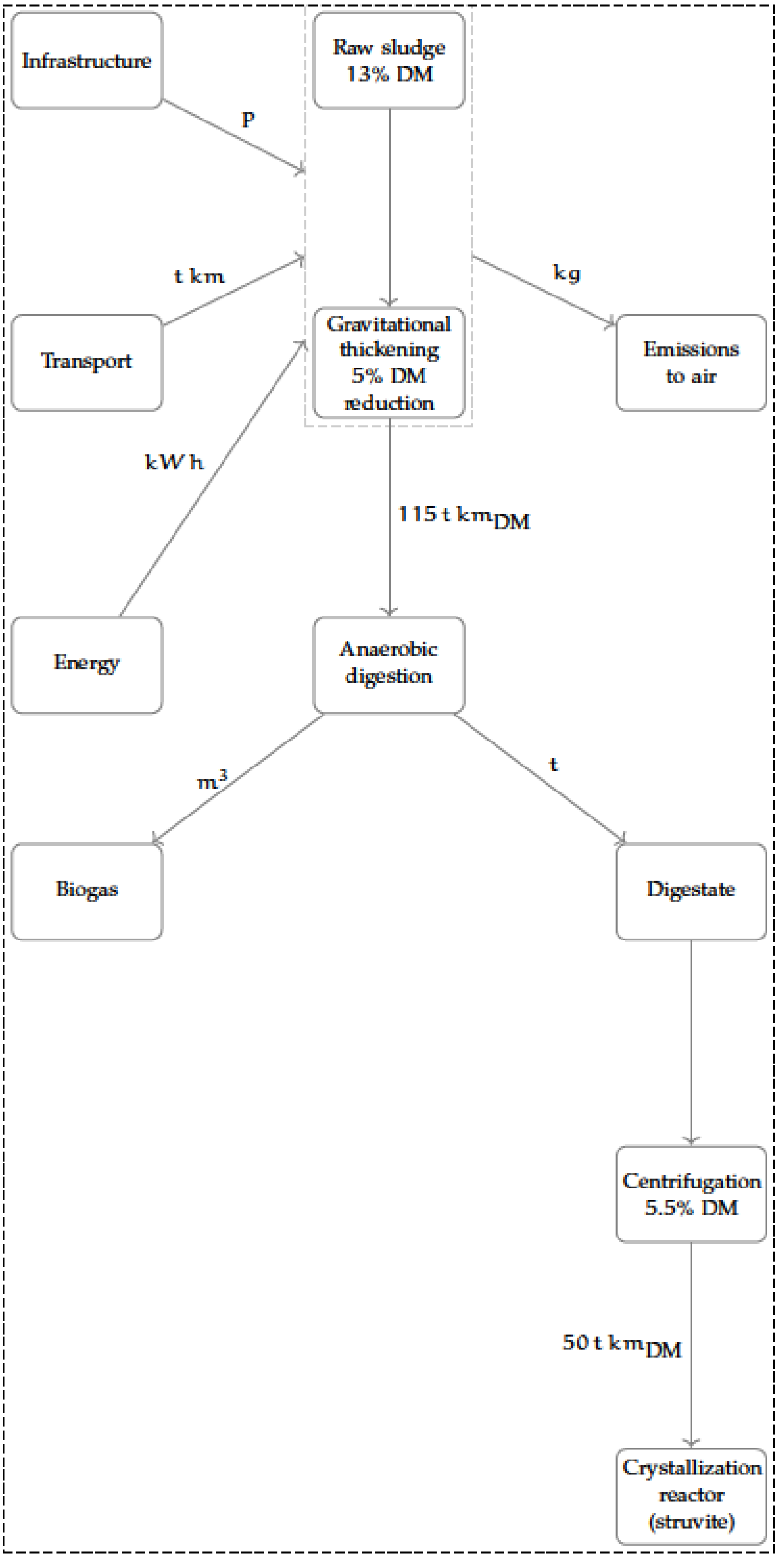

Figure 27: Process tree for biological P removal scenario, local option

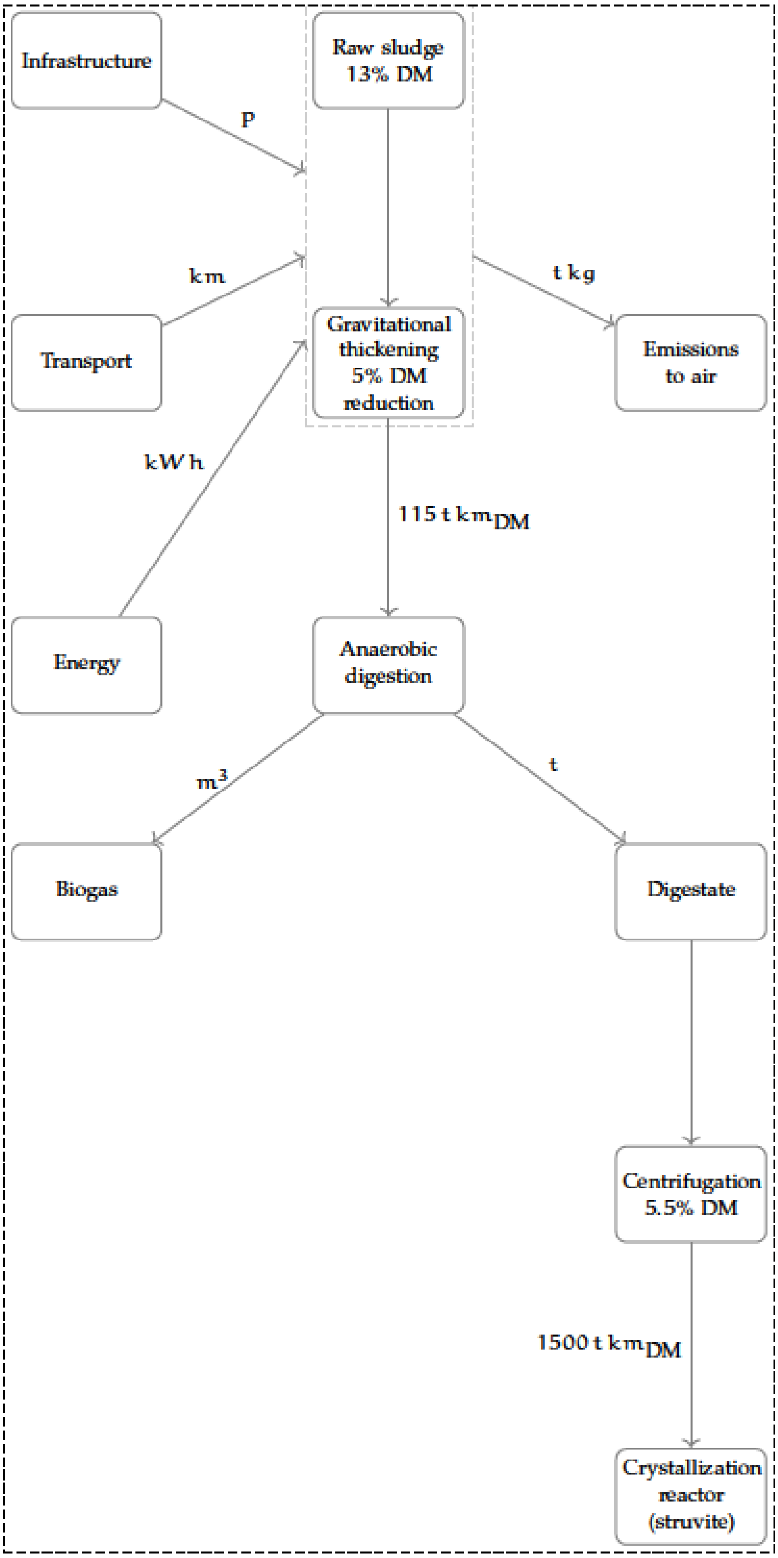

Figure 28: Process tree for biological P removal scenario, centralized option

D

LIFE CYCLE INVENTORY (LCI)

Appendix D collects the inventory of the life cycle of the different processes. In the first part, the LCI of the different treatment processes are reported. The tables are ordered by scenarios, without discriminating between local or centralized alternative. The different specifications for the local and centralized option are listed in the table (e. g. "transport truck, 10-20, 80% LF, empty return/GLO" and " transport, freight, sea, transoceanic ship, GLO | market for | Alloc Def, U"). The data reported are retrieved from the literature, or derived from own calculations (e. g. "emissions to air related to storage of substrate", see Appendix B). They refer to the FU of 1 t of raw sludge 13% DM that undergoes the related treatment (e. g. kWh necessary to treat with anaerobic digestion 1 t of raw sludge in the biogas plant). It is specify in the tables the recipient for the emissions, i. e. whether they are directed to air or to soil.

The second part of the appendix reports the LCI of the different dewatering methods, namely:

gravitational thickening;

centrifugation;

drainage thickening;

thermal drying.

Data are retrieved from the report tiled „Analyses du cycle de vie des filières de traitement et de valorisation des boues issues du traitement des eaux usées," (2013) from Marilys, Marion, and Reverdy and own calculations.

Table 15: Parameters used in SimaPro, reference scenario

	Input	Grow-out
Input from technosphere: materials/fuels	Transport, truck, 10-20, 80% LF, empty return/GLO	5 t_{FU} km (local), 250 t_{FU} km (centralized) from fish farm to land spreading
	dew sludge, grav thickening, std sludge	1 t
Input from technosphere: electricity/heat	Electricity, medium voltage NO | market for | Alloc Def, U	58.5 kWh t_{FU}^{-1}
Emissions to air, related to spreading	Methane, biogenic, CH_4	3.18 kg_{CH_4} t_{FU}^{-1}
	Dinitrogen monoxide, N_2O	1.88 g_{N_2O} t_{FU}^{-1}
Output to technosphere: avoided products	Triple superphosphate, as P_2O_5, RER | monoammonium phosphate production | Alloc Def, U	950 kg t_{FU}^{-1}

Table 16: Parameters used in SimaPro, biogas scenario

	Input	Smolt	Grow-out
Input from technosphere: materials/fuels	Anaerobic digestion plant, agriculture, with methane recovery GLO | market for | Alloc Def, U	$6.057\,335\,344\,037\,63 \times 10^{-8}$ $\mathrm{pt}_{\mathrm{FU}}^{-1}$	$6.057\,335\,344\,037\,63 \times 10^{-8}$ $\mathrm{pt}_{\mathrm{FU}}^{-1}$
	Transport, truck, 10-20, 80% LF, empty return/GLO	$50\,\mathrm{t_{FU}\,km}$ (local), $215\,\mathrm{t_{FU}\,km}$ (centralized) from fish farm to biogas plant	
	Transport, freight, sea, transoceanic ship, GLO | market for | Alloc Def, U	$1500\,\mathrm{t_{FU}\,km}$ (export) from biogas plant to agricultural application	
	dew sludge, centrifugation, digested sludge	1 t	
Input from technosphere: electricity/heat	Heat, central or small scale, other than natural gas, CH | treatment of biogas, CH | market for | Alloc Def	$1110.15\,\mathrm{MJ\,t_{FU}^{-1}}$	$1110.15\,\mathrm{MJ}$
	Electricity, medium voltage NO | market for | Alloc Def, U	$1029.22\,\mathrm{kW\,h\,t_{FU}^{-1}}$	$1029.22\,\mathrm{kW\,h\,t_{FU}^{-1}}$
Emissions to air, related to storage of substrate	Hydrogen sulfide	not considered, missing data	
	Ammonia, NH_3	$1.117\,992\,9\,\mathrm{kg_{NH_3}\,t_{FU}^{-1}}$	$1.321\,264\,286\,\mathrm{kg_{NH_3}\,t_{FU}^{-1}}$
	Dinitrogen monoxide, N_2O	$0.000\,791\,9\,\mathrm{kg_{NO_2}\,t_{FU}^{-1}}$	$0.000\,778\,792\,\mathrm{kg_{NO_2}\,t_{FU}^{-1}}$
	Carbon dioxide, CO_2	$5.903\,333\,3\,\mathrm{kg_{CO_2}\,t_{FU}^{-1}}$	$2.104\,666\,667\,\mathrm{kg_{CO_2}\,t_{FU}^{-1}}$
	Methane, biogenic, CH_4	$1.595\,310\,2\,\mathrm{kg_{CH_4}\,t_{FU}^{-1}}$	$1.595\,310\,2\,\mathrm{kg_{CH_4}\,t_{FU}^{-1}}$
Emissions to air, related to storage of digestate prior further treatment	Hydrogen sulfide	not considered, missing data	
	Ammonia, NH_3	$0.126\,225\,\mathrm{kg_{NH_3}\,t_{FU}^{-1}}$	$0.149\,175\,\mathrm{kg_{NH_3}\,t_{FU}^{-1}}$
	Dinitrogen monoxide, N_2O	-	-
	Carbon dioxide, CO_2	$117.173\,79\,\mathrm{kg_{CO_2}\,t_{FU}^{-1}}$	$117.173\,787\,5\,\mathrm{kg_{CO_2}\,t_{FU}^{-1}}$
	Methane, biogenic, CH_4	$18.260\,85\,\mathrm{kg_{CH_4}\,t_{FU}^{-1}}$	$18.260\,85\,\mathrm{kg_{CH_4}\,t_{FU}^{-1}}$
Output to technosphere: avoided products	Triple superphosphate, as P_2O_5, RER | monoammonium phosphate production | Alloc Def, U	$807.97\,\mathrm{kg\,t_{FU}^{-1}}$	$807.97\,\mathrm{kg\,t_{FU}^{-1}}$
	Electricity, medium voltage NO | market for | Alloc Def, U	$6076.8\,\mathrm{MJ\,t_{FU}^{-1}}$	$6076.8\,\mathrm{kW\,h\,t_{FU}^{-1}}$
	Heat, central or small scale, other than natural gas, CH | treatment of biogas, CH | market for | Alloc Def	$6836.4\,\mathrm{MJ\,t_{FU}^{-1}}$	$6836.4\,\mathrm{MJ}$

Table 17: Parameters used in SimaPro, incineration scenario

	Input	Grow-out
Input from technosphere: materials/fuels	Transport, truck, 10-20, 80% LF, empty return/GLO	117 t_{FU} km from fish farm to incineration plant
	Transport, truck, 10-20, 80% LF, empty return/GLO	50 t_{FU} km (local)
	Transport, truck, 10-20, 80% LF, empty return/GLO	562 t_{FU} km from incineration plant to landfill
	Transport, freight, sea, transoceanic ship, GLO | market for | Alloc Def, U	1500 t_{FU} km (export) from incineration plant to agricultural application
	Ammonia	3.72 kg t_{FU}^{-1}
	Lime GLO | market for | Alloc, Def, U	4.96 kg t_{FU}^{-1}
	Sodium hydroxide (50% NaOH), production mix/RER Economic	12.2 kg t_{FU}^{-1}
	Heavy fuel oil, burned in refinery furnace CH | processing | Alloc Def, U	41.868 MJ t_{FU}^{-1}
	dew sludge, grav thickening, std sludge	1 t
Output to techosphere: avoided products	Electricity, low voltage NO | market for | Alloc Def, U	610.25 kW h t_{FU}^{-1}
	Heat, for reuse in municipal waste incineration only, NO | treatment of municipal solid waste, incineration | Alloc Def, U	563.6 MJ t_{FU}^{-1}
Emissions related to agricultural application	Air emissions of CH_4	3.18 kg_{CH_4} t_{FU}^{-1}
	Soil emissions of Cr	0.08 kg_{Cr} t_{FU}^{-1}
	Soil emissions of Cu	0.19 kg_{Cu} t_{FU}^{-1}
	Soil emissions of Pb	0.33 kg_{Pb} t_{FU}^{-1}
	Soil emissions of Zn	1.51 kg_{Zn} t_{FU}^{-1}
Input from technosphere: electricity/heat	Electricity, medium voltage NO | market for | Alloc Def, U	58.5 kW h t_{FU}^{-1}
Output to technosphere: waste treatment	Average incineration residue CH | treatment of, residual material landfill | Alloc Def, U	250 kg t_{FU}^{-1}
Output to technosphere: co-products	Triple superphosphate, as P_2O_5, RER | monoammonium phosphate production | Alloc Def, U	30 kg t_{FU}^{-1}

Table 18: Parameters used in SimaPro, biological P removal scenario

	Input	Grow-out
Input from technosphere: materials/fuels	Wastewater treatment facility, capacity 1.1E10L yr^{-1}, CH, construction | Alloc Def, U	$6.057\,335\,344\,037\,63 \times 10^{-8}$ pt_{FU}^{-1}
	Transport, truck, 10-20, 80% LF, empty return/GLO	115 t_{FU} km from fish farm to wastewater treatment plant
	Transport, truck, 10-20, 80% LF, empty return/GLO	50 t_{FU} km (local)
	Transport, freight, sea, transoceanic ship, GLO | market for | Alloc Def, U	1500 t_{FU} km (export) from wastewater treatment plant to agricultural application
Input from technosphere: electricity/heat	Electricity, medium voltage NO | market for | Alloc Def, U	0.012 96 kWh t_{FU}^{-1}
	Calcium chloride, GLO | market for | Alloc Def, U	0.017 28 t t_{FU}^{-1}
	Sodium hydroxide (50% NaOH), production mix, RER Economic	0.002 16 t t_{FU}^{-1}
Emissions to air, related to storage of substrate	Hydrogen sulfide	not considered, missing data
	Ammonia, NH_3	1.321 264 286 kg_{NH_3} t_{FU}^{-1}
	Dinitrogen monoxide, N_2O	0.000 778 792 kg_{NO_2} t_{FU}^{-1}
	Carbon dioxide, CO_2	2.104 666 667 kg_{CO_2} t_{FU}^{-1}
	Methane, biogenic, CH_4	1.595 310 2 kg_{CH_4} t_{FU}^{-1}
Emissions to air, related to storage of digestate prior further treatment	Hydrogen sulfide	not considered, missing data
	Ammonia, NH_3	0.149 175 kg_{NH_3} t_{FU}^{-1}
	Dinitrogen monoxide, N_2O	-
	Carbon dioxide, CO_2	117.173 787 5 kg_{CO_2} t_{FU}^{-1}
	Methane, biogenic, CH_4	18.26085 kg_{CH_4} t_{FU}^{-1}
Output to technosphere: co-products	Triple superphosphate, as P_2O_5, RER | monoammonium phosphate production | Alloc Def, U	21.6 kg t_{FU}^{-1}

Table 19: Input data SimaPro, gravitational thickening

Input	Value
Electricity, medium voltage NO | market for | Alloc Def,U	10 kW h $\mathrm{t}_{\mathrm{FU}}^{-1}$
Methyl methacrylate, RER | production | Alloc Def, U	0 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
Infrastructure	0.081 5467 pt $\mathrm{t}_{\mathrm{FU}}^{-1}$
Methane, biogenic, CH_4	3.5 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
Dinitrogen monoxide, N_2O	0.7 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$

Table 20: Input data SimaPro, centrifugation

Input	Value	
	Standard sludge	Digested sludge
Electricity, medium voltage NO | market for | Alloc Def,U	65.8 kW h $\mathrm{t}_{\mathrm{FU}}^{-1}$	50.33 kW h $\mathrm{t}_{\mathrm{FU}}^{-1}$
Methyl methacrylate, RER | production | Alloc Def, U	5.78 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$	6.65 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
Infrastructure	0.000 149 $\mathrm{pt}_{\mathrm{FU}}$	0.000 149 $\mathrm{pt}_{\mathrm{FU}}$
Methane, biogenic, CH_4	12.33 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$	12.33 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
Dinitrogen monoxide, N_2O	0.77 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$	0.77 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$

Table 21: Input data SimaPro, drainage thickening

Input	Value
Electricity, medium voltage NO | market for | Alloc Def,U	33 kW h $\mathrm{t}_{\mathrm{FU}}^{-1}$
Methyl methacrylate, RER | production | Alloc Def, U	2.71 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
Infrastructure	0.000 001 63 p $\mathrm{t}_{\mathrm{FU}}^{-1}$
Methane, biogenic, CH_4	-
Dinitrogen monoxide, N_2O	-

Table 22: Parameters used in SimaPro, thermal drying

Input	Value
Electricity, medium voltage NO | market for | Alloc Def,U	201.59 kW h $\mathrm{t}_{\mathrm{FU}}^{-1}$
Heat natural gas, at boiler condensing modulating > 100 kW/RER U	9426.36 MJ $\mathrm{t}_{\mathrm{FU}}^{-1}$
Infrastructure	0.000 059 4 p $\mathrm{t}_{\mathrm{FU}}^{-1}$
Water	2.8 t $\mathrm{t}_{\mathrm{FU}}^{-1}$
Carbon dioxide, biogenic	8.10 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
Ammonia	3.42 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
Methane, biogenic, CH_4	0.18 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
VOC	0.04 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
Propanoic acid	0.63 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
Acetic acid	0.18 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
Formic acid	1.18 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$
n-heptane	0.63 kg $\mathrm{t}_{\mathrm{FU}}^{-1}$

MAPS

(a) Map of Norway

(b) Map of Trøndelag

Figure 29: Maps of locations in Norway (a) and Trøndelag (b) considered for the calculation of the transport routes in the modelled scenarios

F

WEIGHTING RESULTS OF THE LCIA

Appendix F shows, in Table 30, the result from the Life Cycle Impact Assessment (LCIA), for all categories computed by SimaPro. From this general result, the more relevant environmental categories have been chosen and discussed in Chapter 9.

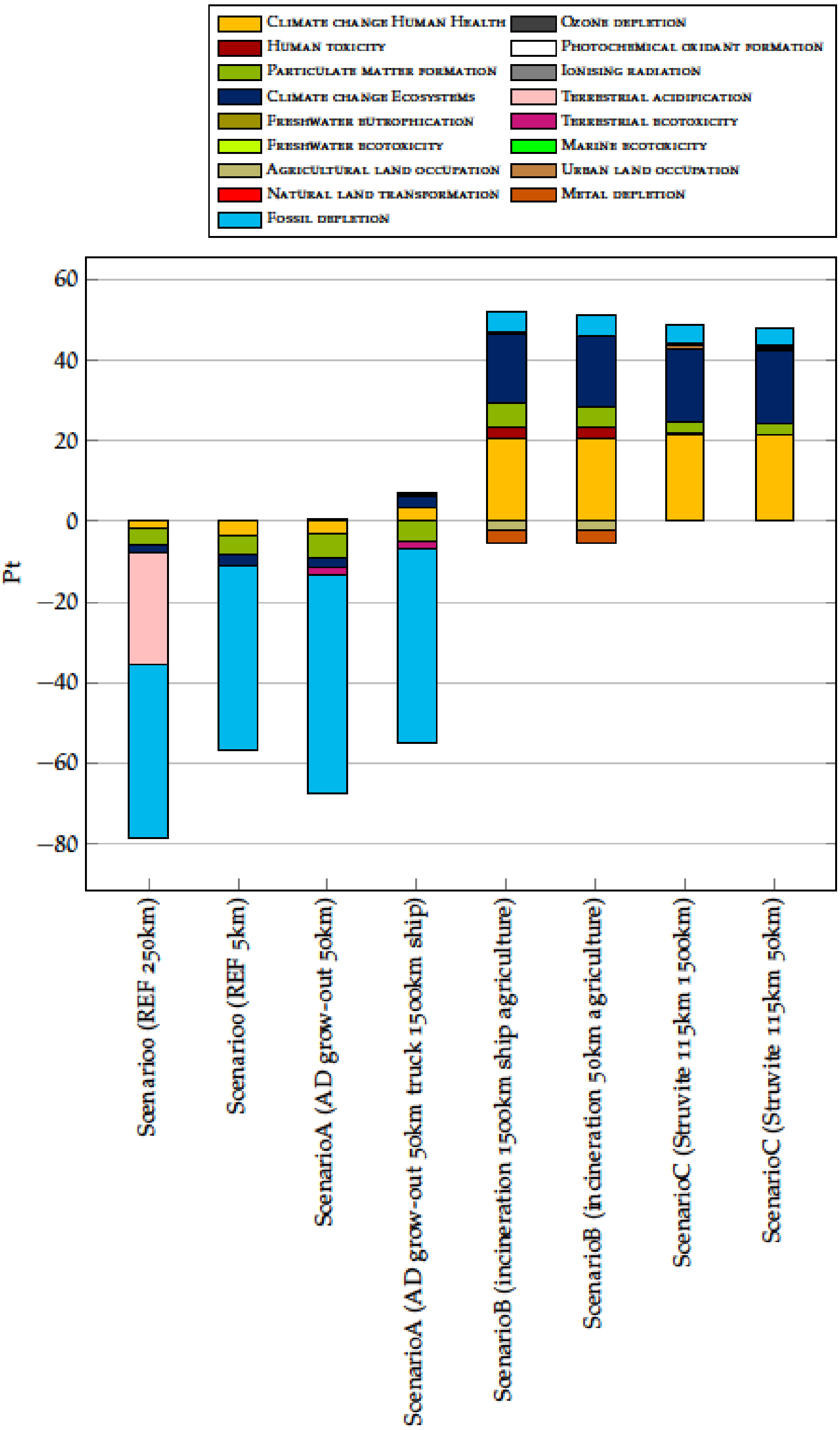

Figure 30: Weighting comparison for all scenarios, single score, default midpoint categories

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DECLARATION

Ich erkläre ehrenwörtlich, dass ich die vorliegende Arbeit selbstständig und ohne fremde Hilfe verfasst, andere als die angegebenen Quellen nicht benutzt und die den Quellen wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe. Die Arbeit wurde bisher in gleicher oder ähnlicher Form keiner anderen inländischen oder ausländischen Prüfungsbehörde vorgelegt und auch noch nicht veröffentlicht. Die vorliegende Fassung entspricht der eingereichten elektronischen Version.

Graz,
July 2018

YASMINE ZAKI ABDELAZIZ