MSc Program
Environmental Technology & International Affairs

# Phosphorus Management and Recovery from Sewage Sludge on an International Scale - Potentials and Limitations

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 06.06.2021

# Affidavit

I, **DIPL.-ING. MARIA CLARA RASINGER, BSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "PHOSPHORUS MANAGEMENT AND RECOVERY FROM SEWAGE SLUDGE ON AN INTERNATIONAL SCALE - POTENTIALS AND LIMITATIONS", 92 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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## Abstract

Phosphorus (P) is an important nutrient and essential for life. It is being mainly applied in agriculture as mineral fertiliser for food and feed production. The agricultural products which contain phosphorus are being consumed and eventually end up in waste such as sewage sludge. Since phosphorus is a non-renewable resource phosphate mines are getting depleted and thus imposing a serious challenge on future food security. One way of moving towards a more sustainable management of phosphorus is through recycling it from sewage sludge.

Many countries have recognised the importance of managing and using phosphorus on a sustainable way. However, they differ in their patterns of phosphorus consumption, in their political approaches on recovering phosphorus from sewage sludge and their state of development in the implementation of P recovery technologies.

This thesis analyses endeavours concerning P recovery from sewage sludge in Austria, Germany, the Netherlands, Sweden and Switzerland. The analysis consists of an examination of current legal frameworks and national strategies on P recovery in those five countries. Further, the thesis looks at the national P balances of the five countries to discern the main phosphorus flows in a country and consequently make statements on current P management at the national level. Based on the P balances current and potential P recycling rates are being identified. In addition to that, this thesis includes investigations on whether technologies for P recovery from sewage sludge have been already implemented in those five countries. Since four of the five countries are members of the European Union regulations and strategies on P recovery on the EU level are being examined as well. The results of the analysis of the domestic regulations and the national P balances are being compared and differences among the countries regarding P recovery and P management are listed.

The results from the comparison show that Austria, Germany, the Netherlands, Sweden and Switzerland have similar approaches concerning P management, but they slightly differ in their state of development in the implementation of technologies for P recovery from sewage sludge. However, none of the five countries is currently recovering phosphorus from sewage sludge on a large scale. Thus there is still work need to be done to attain the goal of sustainable P management and circular economy.

# Contents

## Acknowledgements

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Finally, I would like to thank all my friends for their support in the various phases of my studies.

# 1 Introduction

## 1.1 Phosphorus

Phosphorus (P) is a non-metallic chemical element with atomic number 15 and it belongs to the nitrogen family. At room temperature it is solid but soft and it glows in the dark. Phosphorus has a high chemical reactivity and thus occurs very rarely in its raw chemical state. It is the 12$^{th}$ most abundant element in the Earth's crust and it is found in form of different minerals such as apatites, vivianite and wavellite (Encyclopaedia Britannica, n.d.).

Phosphorus is important for life and therefore is an essential nutrient. The element occurs rather scarcely in the biosphere. Even though most of Earth's biomass is stored in forests they accumulate rather little phosphorus. Compared to the fact that phosphorus is rather scarce in the biosphere the element can be found in relative abundance in vertebrate species. Especially bones and teeth are rich in phosphorus (Smil 2000, 54-55).

## 1.2 Phosphorus Cycle

### The natural phosphorus cycle

Comprehending the phosphorus cycle is important to understand why phosphorus is considered as a non-renewable resource and hence recognising the importance of a sustainable phosphorus management. The natural phosphorus cycle includes many complex processes and sub-processes. In the following a brief overview of the main components in the cycle are being described for a general understanding.

The natural phosphorus cycle describes the migration of phosphorus through rocks, soil, organisms, water and sediments (University of Waikato 2013). Phosphorus is present in the soil in form of certain minerals (Filippelli 2008, 90). Through the exposure to weathering processes P minerals are being dissolved and released from rocks. Subsequently the dissolved phosphorus is distributed in the soil and thus available for uptake by plants. Plants absorb and incorporate the phosphorus in their tissues. Animals eventually eat the P containing plants and incorporate the phosphorus compounds in their organic matter. Phosphorus returns to the soil either through animal excretions or through the decay of plants and animals. In the soil bacteria break down organic phosphorus compounds to inorganic compounds and as a result making phosphorus available again to plants (Ruttenberg 2003, 585-587; Smil 2000, 63; University of Waikato 2013).

Through erosion of soil phosphorus is eventually transported to rivers and subsequently ends up in oceans. In the oceans phosphorus is deposited on the seabed as sediment. Uplifting processes of the oceanic lithosphere bring back P containing rocks to the land surface where it is exposed to weathering and erosion and thus the natural P cycle is being closed (Filippelli 2008, 90-91). Since uplifting processes occur very slowly the P cycle is estimated to take $10^7$ to $10^8$ years (Smil 2000, 56). The illustration in figure 1.1 depicts the natural P cycle.

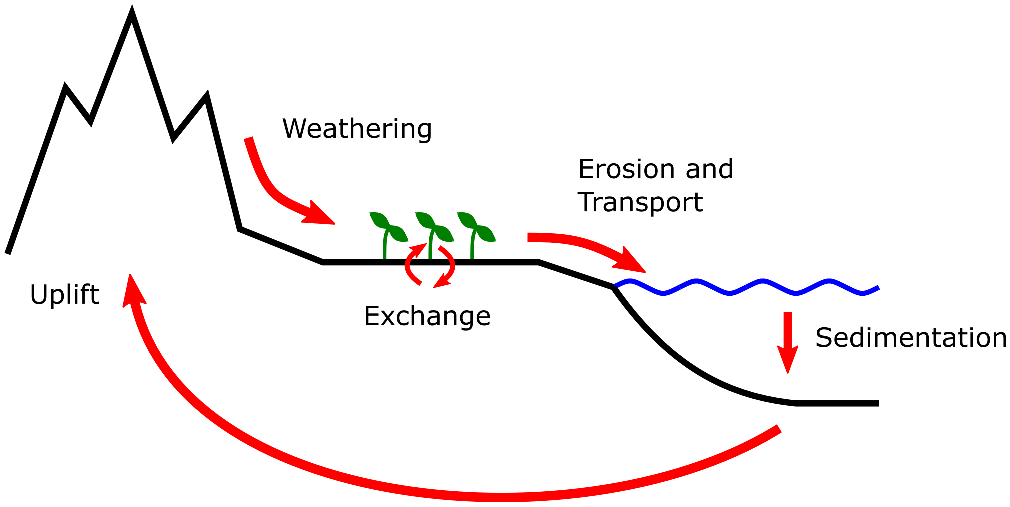


**Figure 1.1:** Natural P cycle (modified after Ruttenberg 2003, 586)

### The role of humans in the phosphorus cycle

The use of P containing fertilisers has enhanced the mobilisation of phosphorus in the cycle. The first time that P fertilisers were applied in agriculture was in the 19th century. Back then sedimentary rocks rich in phosphates were mined in Europe and in the United States and applied on agricultural fields. The use of P fertilisers was improved over time. After the Second World War population grew rapidly due to increased food production caused by the use of fertilisers. It is estimated that through the human interference into the natural P cycle input fluxes of dissolved phosphorus into oceans have doubled (Filippelli 2002, 396-398). Increased P levels in water bodies also accelerate the growth of phytomass. The eutrophication of water through phosphorus may also support the growth of potentially toxic algae which deteriorate the quality of drinking water and consequently leads to serious health problems. Further, eutrophication in water also leads to serious harm of coastal ecosystems (Smil 2000, 74-76).

Another problem of the growing population and hence increasing demand for fertilisers is that global P reserves are being depleted (Smil 2000, 81). Since the duration of the phosphorus cycle is very long compared to durations of anthropogenic activities it is seen as a non-renewable resource. As mentioned before P fertilisers are responsible for increased yields in agriculture and therefore allow to feed more people. Thus, the depletion of phosphate rock mines and further population growth may cause serious stress on future food security (Cordell et al. 2009, 294).

Due to anthropogenic activities resulting in increased P fluxes caused by excessive mining and enhanced use of P fertilisers phosphorus flows are rather linear than circular in the short run. Phosphorus that is being mined in form of phosphate rock enters the anthroposphere where it is being applied as fertiliser in agriculture and it is eventually lost either to the oceans or to waste (Cordell et al. 2009, 293-294). Figure 1.2 illustrates the main P pathway in the short run due to human intervention in the P cycle.

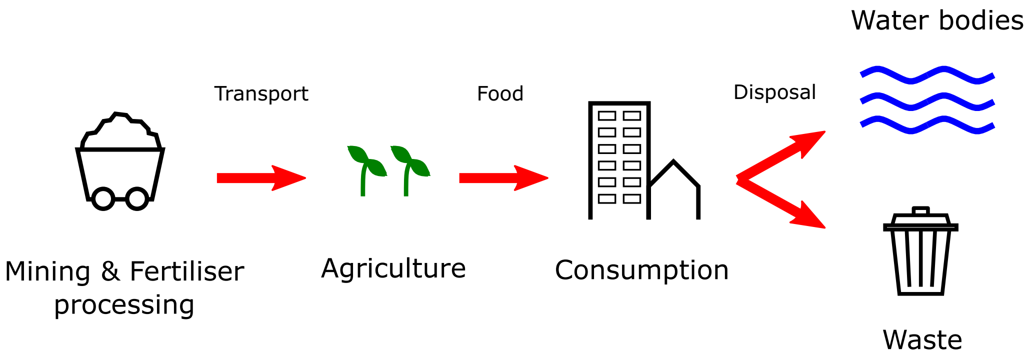


**Figure 1.2:** Main phosphorus pathway in the short-term due to anthropogenic activities

### Phosphorus Recovery from Sewage Sludge

There are various technologies available that recover phosphorus either directly from raw or digested sewage sludge, or from ashes after sewage sludge incineration.

Sewage sludge is a residue from the wastewater treatment process. Depending on how the phosphorus has been removed from the wastewater, sewage sludge contains biologically or chemically bound phosphorus. As a result, different methods have been developed to recover phosphorus from raw or digested sewage sludge such as wet-chemical treatments, thermal treatments or metallurgical smelt-gasification processes. The disadvantage of P recovery from raw and digested sewage sludge is that these processes produce additional waste streams that need to be treated. Further, the applied processes are known to be complex and resource-intensive. The P recovery rate ranges between 10 and 25% compared to P content in the WWTP influent (Egle et al. 2015).

When sewage sludge is being incinerated organic matter is being oxidised leading to a volume reduction of the waste stream. Further, pathogens and persistent organic pollutants (POPs) are being destroyed. However, phosphorus stays in the ashes in a low-soluble form. Methods of extracting phosphorus from sewage sludge ashes comprise for example various leaching, thermo-electric or thermo-chemical processes. The P recovery rate ranges between 60 to 85% compared to P content in the WWTP influent. However, the ash quality concerning the content of phosphorus and heavy metals depends on the quality of the sewage sludge. An advantage of the approach of recovering phosphorus from incinerated sewage sludge is that these processes do not have to be performed on-site at the wastewater treatment plant where the sewage sludge is being produced. Sewage sludge incineration and P recovery plants (for sewage sludge ashes) can be centralised and supplied with sewage sludge by several wastewater treatment plants. Thus, larger installations for P recovery from sewage sludge ashes can be built which treat sewage sludge ashes from multiple WWTPs (Egle et al. 2015).

## 1.3 Motivation

Given the fact that phosphorus is an essential nutrient but a scarce and naturally non-renewable resource in the short-term possibilities of maintaining or recycling it in the system need to be considered. As mentioned before, throughout the linear P pathway incurred by human activities phosphorus eventually ends up in waste that is being deposited. One type of waste where phosphorus ends up is sewage sludge which is a residual product from the wastewater treatment process. Therefore, sewage sludge is a potential source for phosphorus that can be recycled and reintroduced into the anthropogenic metabolism.

Various countries follow different approaches on how to recycle phosphorus from sewage sludge and thus moving away from a linear economy towards a circular economy. However, they differ in their state of development regarding the implementation of P recovery technologies.

## 1.4 Research Questions

The subject of this thesis is to examine potentials and eventual limitations of phosphorus management and recovery from sewage sludge on an international scale using the examples of Austria, Germany, the Netherlands, Sweden and Switzerland. Hence, in the course of this work, the following questions will be addressed:

- Which strategies do those countries pursue to recover phosphorus from sewage sludge?
- How far developed are the endeavours from those countries to recover and recycle phosphorus from sewage sludge?
- To what extent do the strategies and implementation efforts of those countries differ from each other?
- Can we draw further conclusions from comparing different national strategies to recover phosphorus out of sewage sludge?

# 2 Materials and Methods

In the course of this work, endeavours of Austria, Germany, the Netherlands, Sweden and Switzerland on phosphorus recovery from sewage sludge will be examined. Those countries are being known for exercising a pioneering role in this field. For each of these countries a literature review on phosphorus management is being conducted. Since all five countries are located in Europe and four of them are members to the European Union (EU) literature dealing with phosphorus management on the European and on the EU level will be reviewed as well. However, the example of Europe shall serve more as a reference to the five countries rather than being an object of study. The next step consists of an analysis of national P balances. The P balances will serve as a foundation for own examinations and calculations concerning P recovery and P recycling. Last but not least, the results of the preceding literature review and P balance studies of each country will be compared.

## 2.1 Literature Review

The aim of the literature review is to give an overview of the current state of development regarding the recovery of phosphorus from sewage sludge in each of the examined countries.

The literature review will encompass foremost the study of national legislation concerning phosphorus management. The study of national law will be conducted in three steps. Firstly, general regulations will be studied in order to give an overview of whether there are limits given regarding P levels in discharges to natural water bodies. Further, it will be examined whether there are specific regulations in place concerning the treatment of wastewater in WWTPs. Secondly, laws on the management of sewage sludge as waste will be analysed. It will be investigated if there are any regulations dealing with the treatment and disposal of sewage sludge. Thirdly, it will be examined whether there are any regulations explicitly addressing the recovery of phosphorus from sewage sludge.

In addition to examining legal bases for phosphorus management, national commitment or strategy papers on this issue will be analysed. The purpose is to see whether there are official governmental endeavours to recycle phosphorus. Further, if available, projects implementing P recovery technologies will be examined.

## 2.2 Material Flow Analysis

The method of Material Flow Analysis (MFA) allows to quantify within a system flows and stocks of materials. The system is defined within a boundary of space and time. MFAs are based on the law of conservation of mass meaning that inputs, outputs and stocks of a process are balanced. The material that is being examined can be either a good or a substance. Materials are being either transported, transformed or stored in processes. Material reservoirs within a process are called *stocks* which can stay either constant, increase or decrease depending on the material flows into and out of the process. Material flows link the processes with each other. A system encompasses a number of flows, stocks and processes and has a system boundary which delimits the system in space and time. Material flows which trespass the system boundary and enter or exit the system are also called import and export flows. When putting together an MFA and determining material flows and stocks one may be have to deal with incomplete data which is mirrored in an MFA as quantitative uncertainties (given in percent or in absolute mass) (Brunner and Rechberger 2004, 3-5 and 234).

Figure 2.1 gives an example of an MFA created with the freeware programme STAN. The system contains processes, flows, imports and exports. The encircled caption on the arrows indicate the size of the flow (x1 to x5) and their uncertainties (u1 to u5). The system is enclosed by a system boundary which is illustrated by the dashed line.

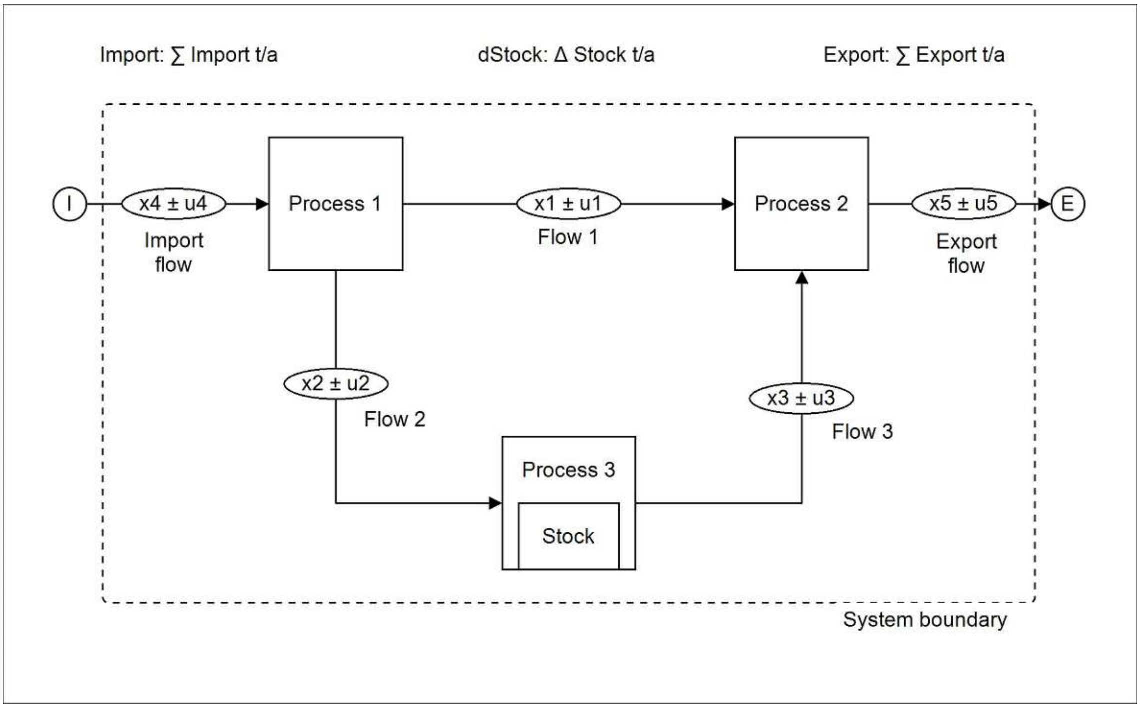


**Figure 2.1:** Example of an MFA system (after Brunner and Rechberger 2004)

For each of the five countries and for Europe P balances were determined in the past years and presented in different studies and publications. The P balances serve in this master thesis as a foundation for studying P flows in each country. Further, calculations and examinations based on the given MFAs will be conducted. However, the national MFAs vary in their scope of processes and flows included in their system meaning that those differences need to be considered when comparing the balances. Some MFAs include uncertainties in their flows and stocks. However, those uncertainties will not be taken into consideration in the course of this thesis. In order to allow a reliable comparison between the countries the P balances will be put into relation to the country's respective size of population (hereafter called population-specific MFA or population-specific P balance).

Flows and changes in stocks in the MFA will be divided by the country's population and thus indicated in mass per capita and time.

## 2.3 Determination of Recycling Rates

Based on the given data in the MFAs current and potential P recycling rates of phosphorus from sewage sludge will be determined. The national P balances were set up for different years in time lying in the past. Hence, the term *current* does not mean at present but in context of the P balance whenever the MFA was elaborated. When the term *potential* is used in this thesis in reference to recycling rates, it means that it is a theoretical value rather than a practical feasible value. It serves to give an indication on how much phosphorus could be theoretical recycled from sewage sludge disregarding technological or economic feasibility. The consideration of theoretical recycling rates without taking into account technological or economic restrictions suffices the purpose of this thesis.

However, in this thesis a differentiation between *recycled phosphorus* and *recovered phosphorus* is being made. *Recycled phosphorus* is being defined as all the phosphorus that is either reused in an extracted form from sewage sludge or reapplied in agriculture together with the sewage sludge. In contrary, *recovered phosphorus* refers to the phosphorus that is being actually extracted from sewage sludge. Hence, the term *recycling* can be seen as a generic term for any form of phosphorus reuse from sewage sludge while *recovery* describes a particular form of P recycling encompassing some kind of phosphorus extraction process from sewage sludge before the phosphorus is being reintroduced into the economy. The national P balances propose that none of the countries actually recovers phosphorus from sewage sludge on a large scale. Thus, during the examination of the national P balances in this thesis the emphasis will lie on *recycled phosphorus* from sewage sludge. When looking at national strategies on sustainable P management the emphasis will lie on *recovery* since countries increasingly refrain from applying sewage sludge directly on arable land and instead pursue approaches where phosphorus is being extracted from sewage sludge for further use.

In the following the terms *P recycling rate from sewage sludge* and *P recycling rate in agriculture* are being described in more detail.

The **P recycling rate from sewage sludge** is calculated as the ratio between the amount of phosphorus recycled from sewage sludge to the total amount of phosphorus found in sewage sludge.

The **P recycling rate in agriculture** puts into relation the amount of phosphorus recycled from sewage sludge to P input in agriculture. The P recycling rate in agriculture is being referred to two different P input flows into agriculture. The first flow to which the recycled phosphorus is being related to is P flow through mineral fertilisers. It is used to assess how the size of recycled P flows and P flows in mineral fertilisers relate to each other. The second flow to which recycled phosphorus is being related to is total P input into agriculture. It serves to determine what share recycled phosphorus make up for total P input in agriculture.

In the case when all the phosphorus is being recycled from sewage sludge (i.e. potential P recycling rate) it is not only of interest how much phosphorus can be recycled compared to the P amount applied in agriculture through mineral fertilisers. It is also of interest to know to what degree recycled phosphorus could substitute mineral fertilisers. With the assumption that P demand in agriculture does not change and neither does the size of different P inputs the **potential P substitution** of mineral fertilisers through recycled phosphorus is being calculated as the ratio of total amount of phosphorus recycled minus amount of recycled phosphorus currently applied in agriculture to total P demand in agriculture through mineral fertilisers.

The recycling rates will be determined for each country and listed in tables for a better overview for the following comparison.

## 2.4 Comparison of Results

After reviewing the national regulations and strategies, examining the national P balances and determining the recycling rates their results will be compared. The aim of comparing the countries is to present their level of development and progress of P recycling and P recovery. In addition to that, eventual limitations or development deficits in the countries concerning P recycling will be discussed.

# 3 Case Studies

## 3.1 European Union

### 3.1.1 EU Policy

**EU Urban Waste Water Treatment Directive**

On May 1991 the Council Directive 91/271/EEC concerning urban wastewater treatment (also referred to as the Urban Waste Water Treatment Directive, UWWTD) was adopted. The objective of this directive is the protection of the environment from negative impacts from poorly or untreated wastewater (European Commission, n.d.(c)). The introduction in the directive lists problems caused by untreated wastewater. One of the opening statements in the introduction reads that it is necessary to "monitor treatment plants, receiving waters and the disposal of sludge to ensure that the environment is protected from the adverse effects of the discharge of waste waters" (Council Directive 91/271/EEC 1991). This statement hints at the importance of sewage sludge as potential polluter that has to be dealt with. Article 4 of the Urban Waste Water Treatment Directive rules that wastewater shall undergo secondary treatment (i.e. biological treatment according to Art. 2, § 8) before being discharged to the environment. However, the Urban Waste Water Treatment Directive differs between discharges to sensitive areas and to less sensitive areas. According to Article 5 § 2 of the directive wastewater that is being discharged to sensitive areas is "subject to more stringent treatment". The directive sets specific requirements concerning the P removal from discharges to sensitive areas (Annex I, table 2). However, it does not feature any requirements on P removal from discharges to less sensitive areas. Annex II of the directive sets criteria for the identification of sensitive and of less sensitive areas. Additionally, Article 14 § 1 in the Urban Waste Water Treatment Directive says that "sewage sludge arising from waste water treatment shall be reused whenever appropriate". This article suggests the importance of sewage sludge as nutrient source. However, the directive does not explicitly mention whether phosphorus shall be recycled or recovered (Council Directive 91/271/EEC 1991).

The emphasis of Urban Waste Water Treatment Directive lies foremost on the protection of water. It sets threshold values for phosphorus (in discharges to sensitive areas) in order to prevent negative impacts from its introduction into water bodies but not because phosphorus shall be retained and subsequently recycled. Even though the directive does not feature explicit rules on P recycling and recovery from sewage sludge there is a connection to be discerned between water protection and P recycling. Since phosphorus has to be removed from discharges through cleaning and removal processes it ends up in sewage sludge which may serve as potential P source. In the following case studies national water protection laws will be briefly mentioned and eventual links between water protection and P recycling will be underlined.

### EU Sewage Sludge Directive

The Council Directive 86/278/EEC on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (also referred to as the Sewage Sludge Directive, SSD) was adopted in June 1986. The directive suggests that sewage sludge needs to be treated or disposed of after it underwent the wastewater treatment process (European Commission, n.d.(b)). In its introduction the Sewage Sludge Directive admits the value of sewage sludge as a source of nutrients such as phosphorus and nitrogen for agricultural use (Council Directive 86/278/EEC 1986, European Commission, n.d.(b)). According to Article 1 the aim of the Sewage Sludge Directive "is to regulate the use of sewage sludge in agriculture in such a way as to prevent harmful effects on soil, vegetation, animals and man" and subsequently encourage the correct handling and application of sewage sludge. The directive sets limit values for heavy metals in soils and in sewage sludge. If the concentrations of those heavy metals in soil is higher than the limit values then sewage sludge shall not be applied (Art. 5, § 1). Further, the use of sewage sludge shall not lead to such an accumulation of heavy metals in the soil that the limit values are exceeded (Art. 5, § 2). The threshold values for heavy metals in soils and sewage sludge are listed in the annex of the directive (Council Directive 86/278/EEC 1986).

### Critical Raw Materials

Certain raw materials are essential to the European economy for the production of everyday goods and modern technologies. Therefore, unhindered and reliable access to those raw materials is of high interest and concern to the EU. As a response to this challenge to supply the European industry with raw materials the European Commission has issued a list of critical raw materials (CRMs) for the European Union which features those raw materials of special economic importance and high supply risk. The aim of the CRMs list is not only to provide an inventory of raw materials important to EU economy but also to incentivise the production and development of recycling technologies of raw materials in the EU. The first list issued in 2011 comprised 14 critical raw materials and has been updated and replenished with additional CRMs over time. The current list encompasses 30 CRMs. (European Commission, n.d.(a); European Commission 2020a, 12-17)

One material that features in the CMRs list is phosphate rock. The EU recognises its importance in agriculture. Most of the phosphorus is imported to the EU. The EU sees a possibility of recycling phosphorus from secondary sources (i.e. sewage sludge, manure and food waste) in order to substitute phosphorus from primary sources (i.e. phosphate rocks) and thus becoming more independent from P imports. (European Commission 2020b, 525-542)

Even though the European Union acknowledges the significance of phosphorus as nutrient and the importance of sewage sludge as potential source for P there is no EU regulation dealing with the recovery of phosphorus from sewage sludge.

### 3.1.2 Phosphorus Balance

The illustration in figure 3.1 depicts the P balance of Europe elaborated by Ott and Rechberger (2012) excluding the uncertainties of flows and stocks. The spatial boundary of this MFA is set on the former 15 member states of the European Community (EU15) them being: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the United Kingdom. All examined countries except for Switzerland were members of the EU15 zone. The time boundary for the P balance is set for one year. However, the data collected for the MFA is from the years 2006-2008 and is averaged. Within the system boundaries there are five processes: *Industry Trade Commerce*, *Consumption*, *Wastewater Treatment*, *Agriculture* and *Waste Management*. *Atmosphere* and *Hydrosphere* lie outside the system and represent processes to which phosphorus is lost.

Total P import into the system amounts to 5.30 kg/cap.yr whereas 1.43 kg/cap.yr of phosphorus is transported out of the EU15 zone. Because of this difference between import and export phosphorus accumulates in the system's stocks by +3.97 kg/cap.yr (subject to uncertainties). Most of the phosphorus is imported through phosphate ore and fertilisers (4.1 kg/cap.yr) followed by food and feed (0.88 kg/cap.yr) and other goods (0.21 kg/cap.yr). Contrary to the import flows there is no prevalent export flow in terms of quantity of phosphorus transported. About 0.43 kg/cap.yr of phosphorus leave the system through fertiliser exports, 0.33 kg/cap.yr of P are transported outside the EU15 zone through food and feed and 0.13 kg/cap.yr of P are exported through other goods. The main P flows within the system are *Plant products* (2.3 kg/cap.yr), *Fertiliser* (2.7 kg/cap.yr) and *Feed* (2.6 kg/cap.yr). They transport phosphorus between the industry process and the agriculture process indicating a frequent P exchange between them. However, more phosphorus is being introduced into agriculture than it is being taken from agriculture thus leading to a P accumulation in agricultural soils of +2.9 kg/cap.yr.

Phosphorus is also accumulated in the waste management process. The main P input flows are *Industrial waste* (0.74 kg/cap.yr), *Waste* (0.45 kg/cap.yr) and *Sewage sludge* (0.44 kg/cap.yr). The main P output flow from waste management is through compost (0.33 kg/cap.yr). Further, minimal amounts of phosphorus are being carried out of the waste management system through leaching processes in landfills ($1.3 \cdot 10^{-5}$ kg/cap.yr). Hence, +1.4 kg/cap.yr of phosphorus accumulate in the waste management process.

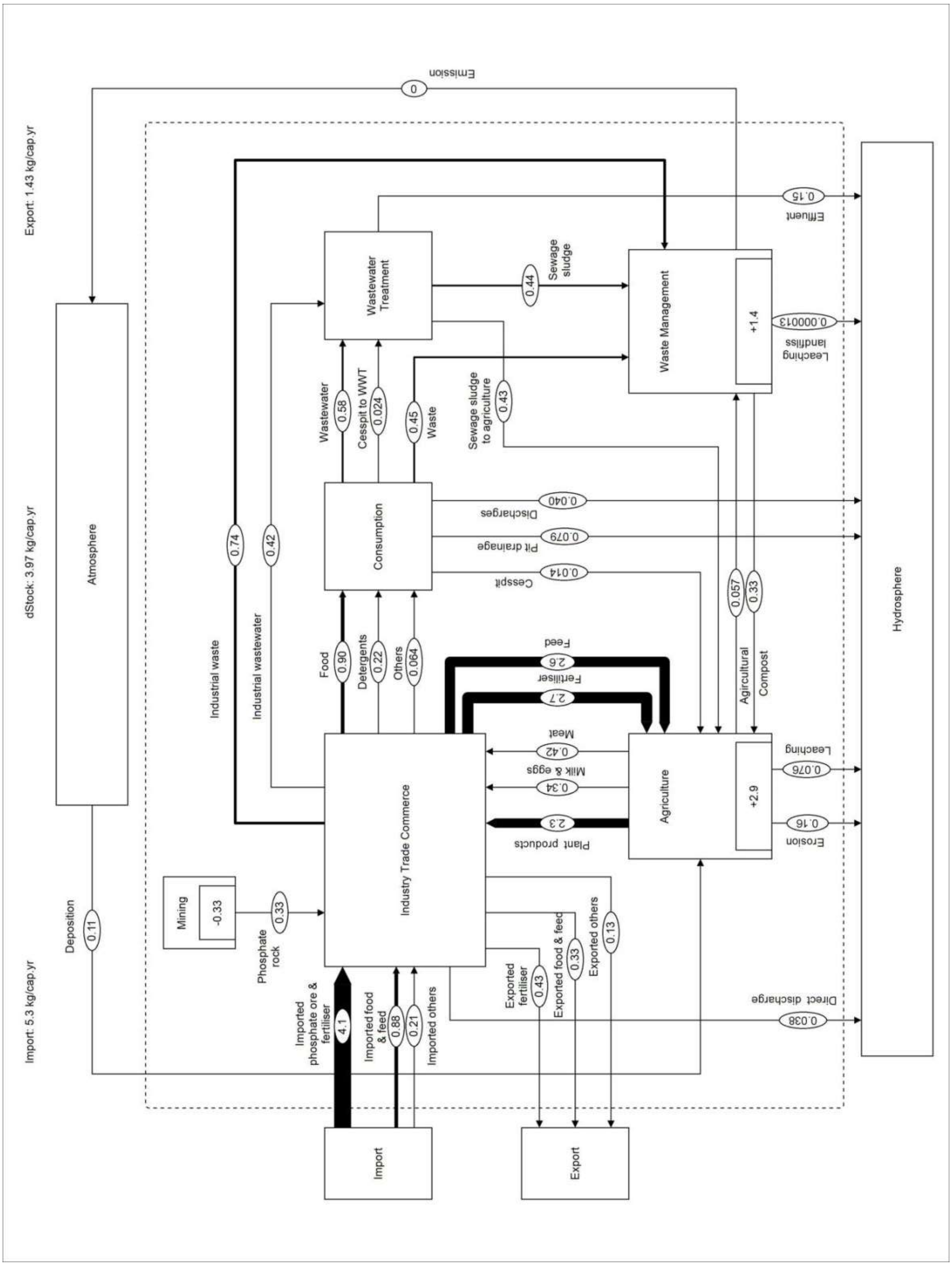


**Figure 3.1:** P balance in Europe (modified after Ott and Rechberger 2012)

Figure 3.2 shows in more detail the input and output flows of the wastewater treatment process. Phosphorus is mainly carried into WWTPs through wastewater from the process *Consumption* (0.58 kg/cap.yr) and through industrial wastewater (0.42 kg/cap.yr). Most of the phosphorus then ends up in sewage sludge that is either recycled and applied in agriculture (0.43 kg/cap.yr) or carried to the waste management process (0.44 kg/cap.yr). Some of the phosphorus is lost to the hydrosphere through effluents (0.15 kg/cap.yr).

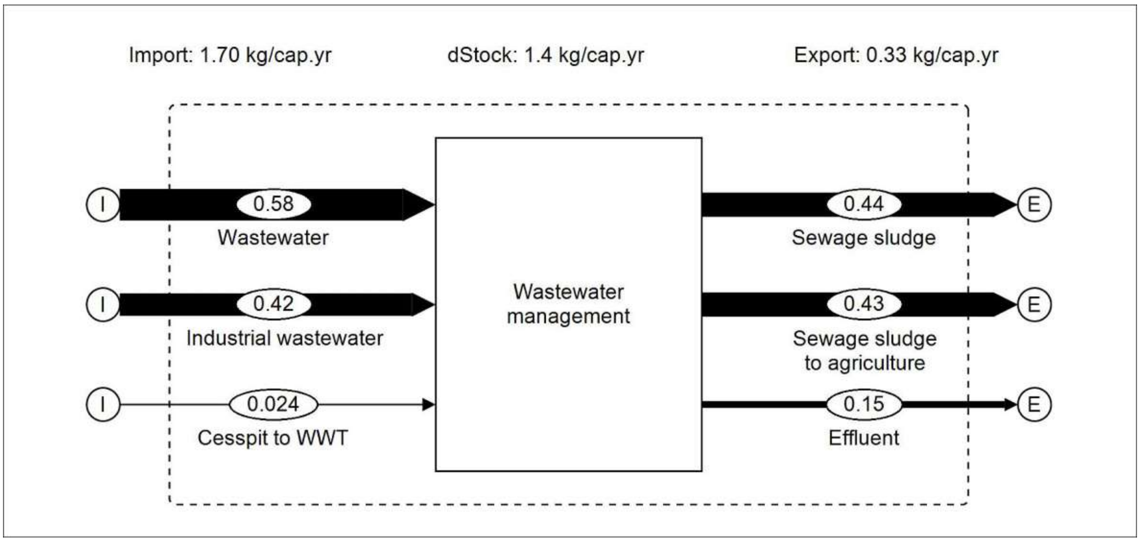


**Figure 3.2:** P balance in Europe, Wastewater management process (modified after Ott and Rechberger 2012)

### 3.1.3 Phosphorus Recycling

Table 3.2 lists the phosphorus loads in sewage sludge and the current and potential P recycling rates. The P balance by Ott and Rechberger (2012) does not distinguish between P loads in municipal and industrial sewage sludge thus the P loads from those streams are not given separately. The phosphorus found in sewage sludge amounts to 0.87 kg/cap.yr. However, 0.43 kg/cap.yr of phosphorus is being recycled through sewage sludge application in agriculture while the rest is being introduced into the waste management process. The P input through mineral fertilisers into agriculture amounts to 2.7 kg/cap.yr. The total P input into agriculture is 6.18 kg/cap.yr.

Around 49.4% of the phosphorus in sewage sludge is currently being recycled. Putting the recycled phosphorus into relation to the amount of phosphorus applied through mineral fertilisers in agriculture it yields a ratio of 15.9%. Around 7% of total P input in agriculture comes from recycled sewage sludge. Relating the total amount of phosphorus in sewage sludge to P input into agriculture through mineral fertilisers (potential recycling rate) it yields a ratio of 32.2%. If all of the phosphorus were recycled from sewage sludge (0.87 kg/cap.yr) it could cover 16.3% of mineral fertiliser demand and 14.1% of total P input demand in agriculture.

**Table 3.1:** P recycling rates from sewage sludge in Europe

| **P recovery from sewage sludge** | |
|---|---|
| **P in sewage sludge** | |
| municipal sewage sludge | N/A |
| industrial sewage sludge | N/A |
| total sewage sludge | 0.87 kg/cap.yr |
| **P recycled from sewage sludge** | |
| municipal sewage sludge | N/A |
| industrial sewage sludge | N/A |
| total sewage sludge | 0.43 kg/cap.yr |
| **P input into agriculture** | |
| through (mineral) fertilisers | 2.7 kg/cap.yr |
| total P input | 6.18 kg/cap.yr |
| **Current P recycling rate from sewage sludge** | |
| municipal WWTP | N/A |
| industrial WWTP | N/A |
| total | 49.4% |
| **Current P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 15.9% |
| in relation to total P input | 7.0% |
| **Potential P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 32.2% |
| in relation to total P input | 14.1% |
| **Potential P substitution** | |
| of (mineral) fertiliser | 16.3% |

## 3.2 Austria

### 3.2.1 Legal Framework

Since Austria is a member of the European Union it has to comply with EU regulations. The EU Urban Waste Water Directive (91/271/EEC) is implemented through the Waste Water Emission Ordinance ("Allgemeine Abwasseremissionsverordnung", AAEV) into national Austrian law.

The Austrian Waste Water Emission Ordinance deals with emissions of wastewater and their introduction into natural water bodies. It determines under which circumstances wastewater has to be treated. Further, the regulation sets out what kind of treatment shall be applied depending on the origin of the sewage. According to the Austrian Water Emission Ordinance urban wastewater shall undergo a biological treatment (BMLFUW 1996, § 3 Sec. 1). The regulation also demands a state-of-the-art equipment for wastewater treatment plants (BMLFUW 1996, § 3 Sec. 13). Concerning the quality of the effluent from WWTPs the ordinance lists threshold values for pollutants. Among them it features a limiting value for phosphorus. However, the ordinance does not mention how phosphorus shall be removed from the sewage nor whether it shall be recovered. Currently, there is no law in force in Austria that regulates P recovery from sewage sludge.

Nevertheless, the application of sewage sludge in agriculture is regulated at Land[1] level. The regulations on the spreading of sewage sludge differ between the Länder. While in some Länder it is forbidden to apply sewage sludge on agricultural land (e.g. Tyrol, Vienna) others allow the use of sewage sludge on soil under certain conditions such as compliance with limit values for heavy metal concentrations and analysis of sewage sludge and soil (e.g. Lower Austria, Upper Austria) (Tyrolean Regional Government 2000, Vienna State Parliament 2000, Regional Government of Lower Austria 2005, Regional Government of Upper Austria 1991, Regional Government of Upper Austria 2006).

The diagram in figure 3.3 shows how sewage sludge has been disposed of in the past years. Due to incomplete datasets between the years 2009 to 2015 the values on sewage sludge disposal for these years are not given in order to avoid a distorted representation. It can be seen that the prevalent form of disposal is incineration with values ranging between 35 and 53% followed by composting and agricultural use. From 2000 to 2008 sewage sludge has been landfilled. However, the diagram shows that from 2016 onwards sewage sludge has not been deposited on landfills (Eurostat 2021a).

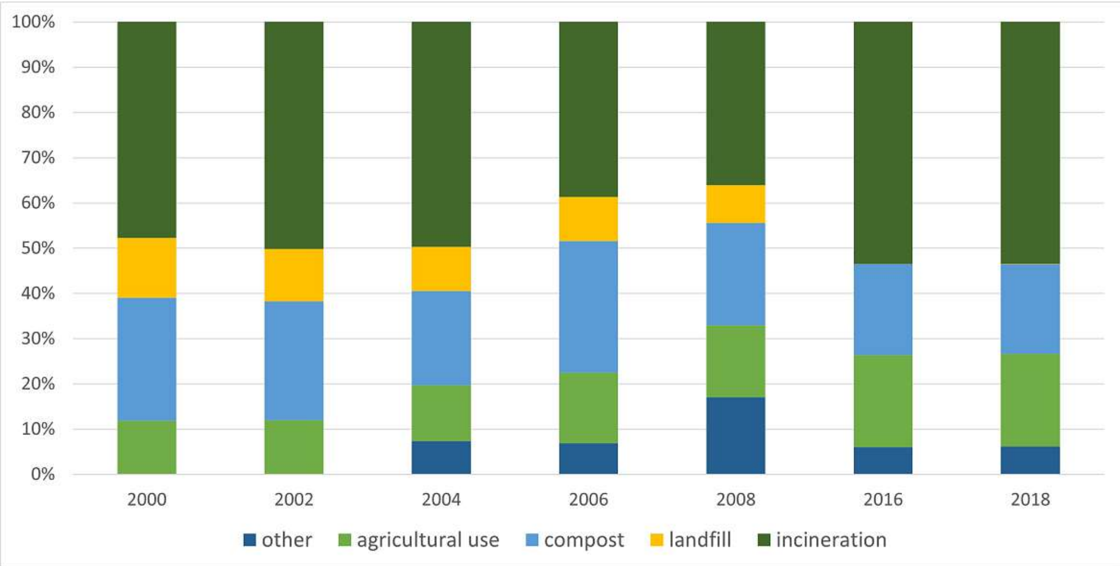


**Figure 3.3:** Sewage sludge disposal in Austria (modified after Eurostat 2021a)

### 3.2.2 Phosphorus Balance

The P balance for Austria examined in this master thesis is taken from Egle et al. (2014) and put into relation to the population size in Austria.

The Austrian territory is set as spatial boundary. The temporal boundary is one year. The MFA is based on averaged data from the time period from 2004 to 2008 (Egle et al. 2014). Between 2004 and 2008 Austria had around 8.2 million inhabitants (Statistik Austria 2015). This number is applied for the calculation of the population-specific P balance in Austria.

[1] Austria is made up of nine states which are called *Länder* (sg. *Land*) in German.

The MFA by Egle et al. (2014) with the original stock and flow values can be found in Annex I. The size of the flows and the stocks are fraught with uncertainties. In the context of this thesis, the uncertainties will not be further discussed.

### Population-Specific Phosphorus Balance

The population-specific P balance in Austria elaborated by Egle et al. (2014) is illustrated in figure 3.4. The MFA contains nine processes them being: *Animal husbandry*, *Crop farming*, *Forestry and miscellaneous soils*, *Chemical industry*, *Industry (food, feed, fertiliser)*, *Consumption*, *Wastewater management*, *Waste management* and *Water bodies*. The processes *Animal husbandry* and *Crop farming* form together the agricultural industry.

Most of the phosphorus is imported to Austria in form of P ore and P raw materials (5.58 kg/cap.yr) which are being introduced into the industry process. Some smaller amounts of phosphorus are being imported through food (0.38 kg/cap.yr) and feed (0.57 kg/cap.yr). Large quantities of phosphorus leave the Austrian system via fertilisers (3.9 kg/cap.yr) followed by food (0.3 kg/cap.yr) and feed (0.26 kg/cap.yr) exports. Within the system, most of the phosphorus is being transported by manure (3.29 kg/cap.yr) and non-marketable feed (2.56 kg/cap.yr) between the processes *Animal husbandry* and *Crop farming*. Manure is being applied on arable land as fertiliser while feed is being fed to animals. Notable amounts of phosphorus are also being transported between the industry process and the crop farming process. Phosphorus is being carried through plant products (2.44 kg/cap.yr) to industry while at the same time P flows from industry are being transported to *Crop farming* through mineral fertilisers (1.95 kg/cap.yr). Further, noteworthy P flows are *Animal products* (1.09 kg/cap.yr) and *Marketable feed* (1.83 kg/cap.yr) which link the processes *Animal husbandry* and *Industry (food, feed, fertiliser)* together. Regarding the just described flows a high P exchange between the animal husbandry, crop farming and industry process can be discerned.

The largest amounts of phosphorus which end up in stocks within a year are being accumulated in the stocks of the waste management process (+1.06 kg/cap.yr) and in *Crop farming* (+0.54 kg/cap.yr). Smaller amounts of phosphorus accumulate in *Forestry and miscellaneous soils* (+0.18 kg/cap.yr), in *Water bodies* (+0.16 kg/cap.yr) and in *Consumption* (+0.28 kg/cap.yr)

Figure 3.5 shows in more detail the sub-processes in the wastewater management process and the incoming and outgoing P flows. Most of the phosphorus enters the wastewater management sub-system through municipal wastewater (0.71 kg/cap.yr). The quantity of phosphorus transported by different industrial wastewater flows is notably smaller. Phosphorus entering the sewage collecting system through wastewater is introduced almost entirely into WWTPs (0.89 kg/cap.yr). Only a small share is lost through direct storm water discharges into water bodies (0.06 kg/cap.yr). After the treatment process in WWTPs most of the phosphorus ends up in sewage sludge (0.8 kg/cap.yr) while a small amount of the phosphorus ends up in the effluent (0.09 kg/cap.yr). The P flows of both municipal (0.8 kg/cap.yr) and industrial sewage sludge (0.05 kg/cap.yr) exit the wastewater management sub-system and are being introduced into the waste management process (cf. figure 3.4).

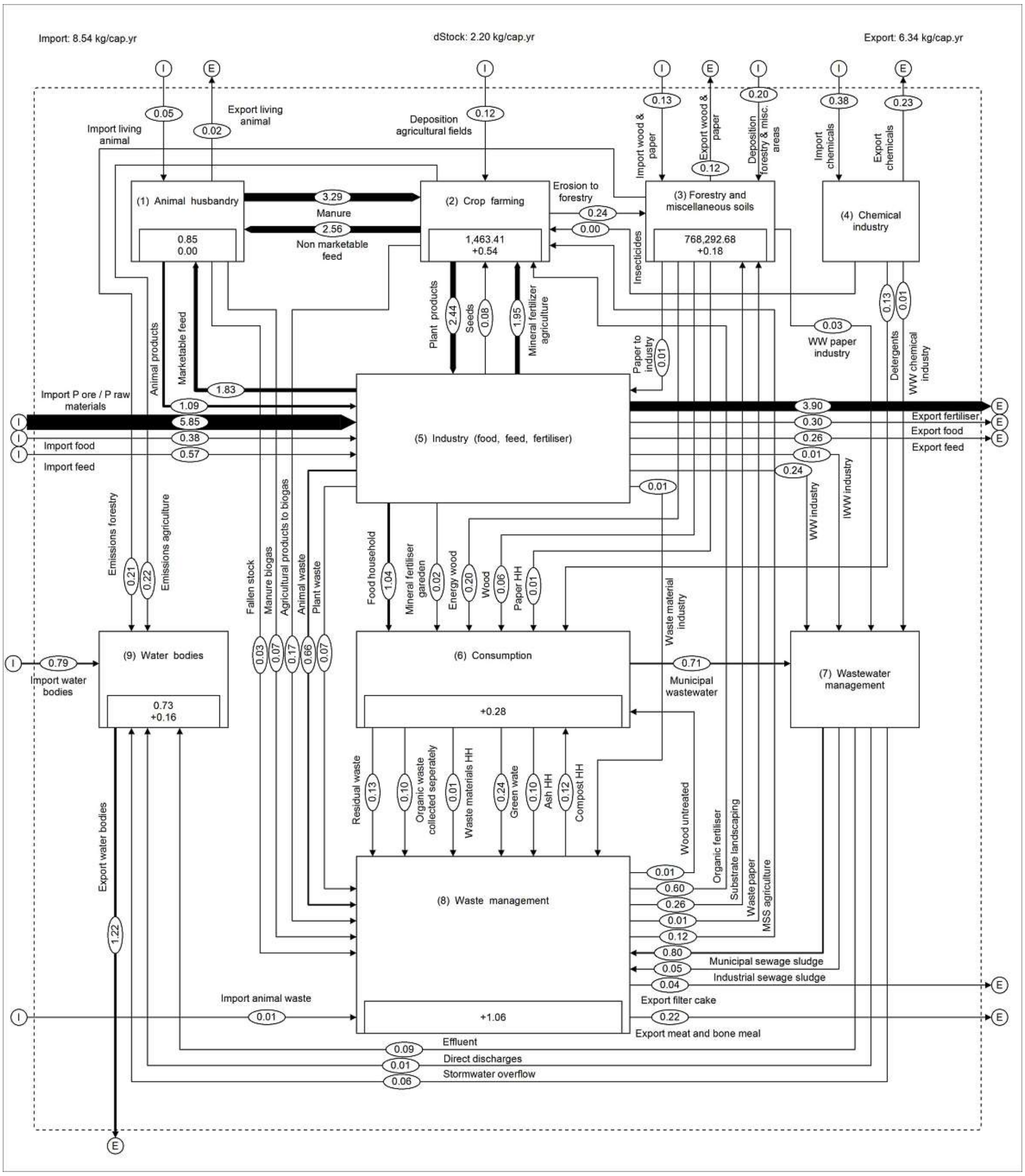


**Figure 3.4:** P balance in Austria (modified after Egle et al. 2014)

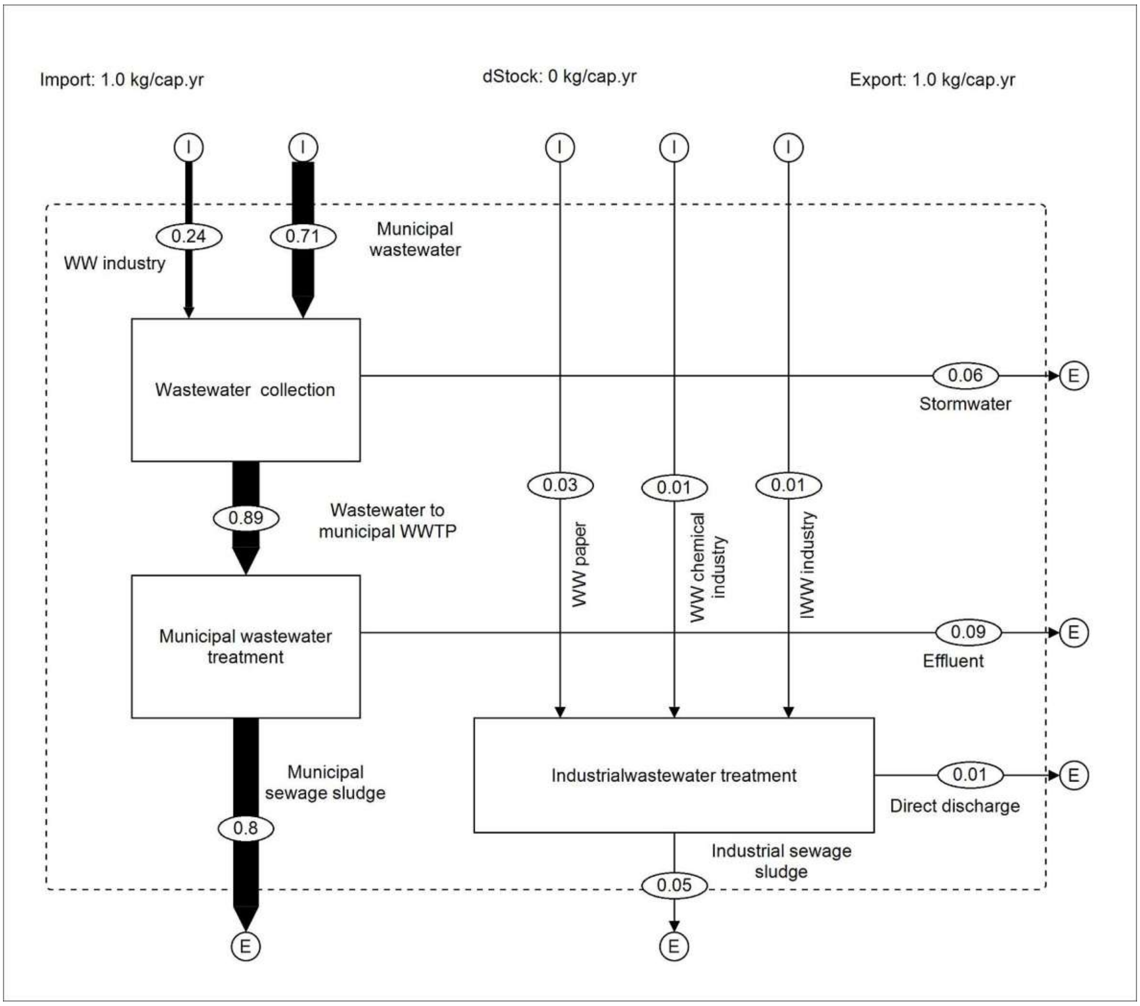


**Figure 3.5:** P balance in Austria, Wastewater management process (modified after Egle et al. 2014)

### 3.2.3 Phosphorus Recovery

#### Potential Phosphorus Recovery

Table 3.2 lists current and potential P recycling rates from sewage sludge in Austria. Around 0.85 kg/cap.yr of phosphorus end up in sewage sludge in Austria. However, larger phosphorus amounts are transported by municipal sewage sludge (0.8 kg/cap.yr) than by industrial sewage sludge (0.05 kg/cap.yr). According to the conducted MFA by Egle et al. (2014) 0.12 kg/cap.yr out of 0.80 kg/cap.yr of phosphorus are being recycled from sewage sludge (i.e. directly applied to agriculture, cf. figure 3.4) while the rest is being incinerated. Thus, the P recycling rate from municipal sewage sludge amounts to 15%. Industrial sewage sludge is being incinerated and landfilled in its entirety consequently leading to an P recycling rate of 0%. Therefore, the total P recycling rate from both municipal and industrial sewage sludge amount to 14.1%.

The MFA by Egle et al. (2014) splits the agricultural activities into the processes *Animal husbandry* and *Crop farming*. Since in some MFAs from other countries presented in this thesis do not make this distinction, the two processes *Animal husbandry* and *Crop* *farming* in the Austrian P balance will be merged for determining the P input into Austrian agriculture and hence making it comparable to other countries. P flows between *Animal husbandry* and *Crop farming* will not be considered because they represent P exchanges within agriculture. Further, the phosphorus carried by the flow *Marketable feed* is not being taken either into consideration in the calculation of total P input in agriculture since part of the marketable feed is a product from the flow *Plant products* coming from the crop farming process. An integration of the phosphorus carried by marketable feed into the calculation of total P input in agriculture would lead to a double counting of phosphorus. However, phosphorus imported through feed (0.38 kg/cap.yr, cf. figure 3.4) will be considered in the calculation of total P input in agriculture since it can be assumed that the imported feed is being used in agriculture. Thus, the total P input into both *Animal husbandry* and *Crop farming* (i.e. agriculture) amounts to 3.49 kg/cap.yr. P input into agriculture through mineral fertilisers amounts to 1.95 kg/cap.yr.

When putting in to relation the amount of phosphorus currently being recycled from sewage sludge (0.12 kg/cap.yr) to the amount of phosphorus applied in agriculture it yields a ratio of 6.2%. Recycled phosphorus from sewage sludge makes up 3.4% of total P input into agriculture.

If the all of the phosphorus were recovered from both industrial and municipal sewage sludge it could cover 24.4% of total P input into agriculture. The ratio between total P recycling from sewage sludge to P input into agriculture through mineral fertilisers yields a value of 43.6%. However, recovered phosphorus could substitute 37.4% of P input in agriculture through mineral fertilisers assuming all the other P input flows are unchanged.

**Table 3.2:** P recycling rates from sewage sludge in Austria

| **P recovery from sewage sludge** | |
|---|---|
| **P in sewage sludge** | |
| municipal sewage sludge | 0.80 kg/cap.yr |
| industrial sewage sludge | 0.05 kg/cap.yr |
| total sewage sludge | 0.85 kg/cap.yr |
| **P recycled from sewage sludge** | |
| municipal sewage sludge | 0.12 kg/cap.yr |
| industrial sewage sludge | 0.0 kg/cap.yr |
| total sewage sludge | 0.12 kg/cap.yr |
| **P input into agriculture** | |
| through (mineral) fertilisers | 1.95 kg/cap.yr |
| total P input | 3.49 kg/cap.yr |
| **Current P recycling rate from sewage sludge** | |
| municipal WWTP | 15.0% |
| industrial WWTP | 0.0% |
| total | 14.1% |
| **Current P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 6.2% |
| in relation to total P input | 3.4% |
| **Potential P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 43.6% |
| in relation to total P input | 24.4% |
| **Potential P substitution** | |
| of (mineral) fertiliser | 37.4% |

### 3.2.4 Strategies

#### Federal Waste Management Plan

Even though there are no legally binding regulations concerning P recovery from sewage sludge in force in Austria, there is a state and commitment report ("Federal Waste Management Plan") issued by the Austrian Ministry for Environment every six years describing the state of the Austrian waste management and addressing current problems in that sector (BMK, n.d.).

The Federal Waste Management Plan ("Bundes-Abfallwirtschaftsplan") acknowledges the importance of phosphorus as a nutrient and scarce resource and recognises the dependence of Austria on phosphorus imports. Therefore it underlines the necessity to take action and recycle phosphorus from waste streams. The waste management plan sets the ambition to recover phosphorus from sewage sludge while at the same time safely removing and discarding pollutants from sludge. The document sees the technology of mono-incineration of sewage sludge and the subsequent recovery of phosphorus from the ashes as the most promising method for recycling phosphorus sustainably. However, the Federal Waste Management Plan does not exclude the application of other P recovery technologies in order to pursue the ambitions of P recycling. The waste management report also sets a target on the P recovery rate from sewage sludge. It sets the goal that by 2030 65 to 85% of phosphorus in sewage sludge shall be recovered (BMNT 2017, 259-261).

However, within the framework of the literature research on P recovery strategies in Austria no information could be found concerning present implementations of P recovery technologies in wastewater treatment plants or similar facilities.

#### Austrian Governmental Agreement on P Recycling

At the beginning of its legislative period the Austrian Government concludes a so called "Regierungsprogramm" (Governmental Agreement) which sets political goals for the following legislative period of four years. The Austrian Governmental Agreement for the legislative period from 2020 to 2024 features in the light of promoting a circular economy the ambition to establish a P management strategy which includes P recovery from sewage sludge in wastewater treatment plants (Austrian Government 2020, 142-144).

The Governmental Agreement only makes political statements and in the case of P management it only sets out a common goal without mentioning specific targets. Nevertheless, the aspiration towards a circular economy and thus including a P management strategy underlines the importance of this topic on the political level.

## 3.3 Germany

### 3.3.1 Legal Framework

Germany is a member of the European Union and consequently has to comply with EU law. The EU directive on the treatment of urban wastewater is implemented by the German Federal Water Act ("Wasserhaushaltsgesetz", WHG) in German national law. The Water Act sets the foundation for water protection against polluted discharges. According to § 57 Sec. 1 of the regulation effluents may only be discharged into water bodies if the pollutant loads are kept as low as possible in compliance with current state-of-the-art technology (BMU 2009). The specific threshold values for the pollutants in effluents are laid down in the Wastewater Ordinance ("Abwasserverordnung", AbwV) (BMU 1997). However, a demand for recovering phosphorus from sewage sludge does neither feature in the Water Act nor in the Wastewater Ordinance.

The German Sewage Sludge Ordinance ("Klärschlammverordnung", KlärV) regulates the recycling of sewage sludge and the monitoring of its application. It does not only determine how sewage sludge shall be examined when applying it on soils but it also contains a demand that sewage sludge producers (i.e. operators of WWTPs) shall recycle the sewage sludge to the highest possible quality as far as this is technically possible and economically reasonable (§ 3 Sec. 1) (BMU 2017a). The German Ordinance on the Reorganisation of Sewage Sludge Utilisation ("Verordnung zur Neuordnung der Klärschlammverwertung") gives further indications on how much phosphorus shall be recovered from sewage sludge (or from sewage sludge ashes) depending on the initial P concentrations to be found in the sewage sludge. However, it does not set an overall target of how much phosphorus shall be recovered in Germany (Art. 3) (BMU 2017b). Both ordinances thus supplement the German law on circular economy (“Kreislaufwirtschaftsgesetz”, KrWG) which aims to conserve resources by introducing a circular economy system (BMU 2012, BMU 2020).

The diagram in figure 3.6 illustrates the sewage sludge disposal in Germany between 2006 and 2016. It shows a gradual shift towards the incineration of sewage sludge. However, the share of sewage sludge being composted or used in agriculture decreased over time. This suggests that Germany is moving away from applying sewage sludge directly on agricultural soil but has to find other ways of recycling phosphorus from sewage sludge in order to comply with national legislation (Eurostat 2021b).

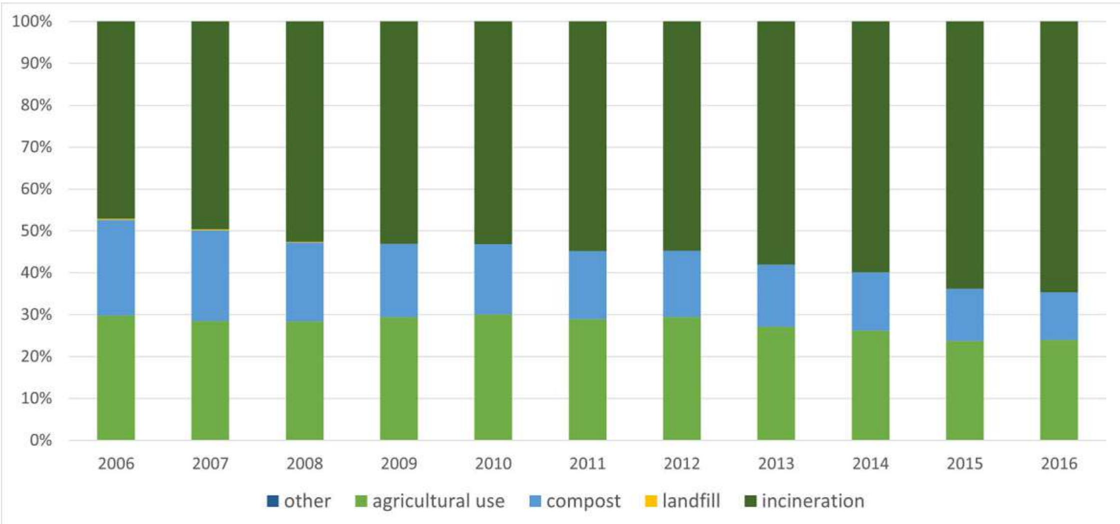


**Figure 3.6:** Sewage sludge disposal in Germany (modified after Eurostat 2021b)

### 3.3.2 Phosphorus Balance

The P balance for Germany presented in this thesis is by Gethke-Albinus (2012). The spatial boundary is set for German territory and the temporal boundary is set for the duration of one year. Gethke-Albinus (2012) does not explicitly mention for which year the P balance has been set up or from which years data has been retrieved.

In the following the German P balance in relation to the German population size will be examined. Since Gethke-Albinus (2012) does not mention for which period the MFA has been conducted it will be assumed that the P balance has been elaborated for the period between 2008 and 2010. For the calculation of the population-specific P balance the mean population size between 2008 and 2010 in Germany will be taken into account. Between 2008 and 2010 Germany had a mean population of 81,852,072 inhabitants (Statistisches Bundesamt 2021).

The German P balance by Gethke-Albinus (2012) with the original values is included in Annex II.

#### Population-Specific Phosphorus Balance

Figure 3.7 shows the German P balance in relation to the German population. It comprises in total 18 processes. For a better overview the processes can be classified into five categories: industry, waste disposal, sink, agriculture and consumption. The industry category encompasses all the industry processes: *Phosphorus industry*, *Fertiliser industry*, *Food industry*, *Detergent industry*, *Feed industry* and *Miscellaneous industry*. The processes in the waste disposal category are *Wastewater management*, *Waste management* and *Biogas production*. The category *sinks* comprises the processes *Stockpiles*, *Durable products*, *Human*, *Soil*, *Landfill, Incineration* and *Hydrosphere*. Agriculture includes the processes *Crop farming* and *Animal husbandry*. In the consumption category there is only one process it being *Household*.

The largest P import flows to the German system are through *P imports* (2.28 kg/cap.yr), food imports (1.6 kg/cap.yr), feed imports (1.45 kg/cap.yr) and through fertiliser imports (0.87 kg/cap.yr). The total phosphorus import amounts to 6.55 kg/cap.yr. Most of the phosphorus is being exported from Germany through food (1.94 kg/cap.yr) followed by P exports from the phosphorus industry (0.39 kg/cap.yr). In total 3.26 kg/cap.yr of phosphorus are being exported from Germany. Due to the difference between imports and exports phosphorus is being accumulated in the system (+3.2 kg/cap.yr). According to Gethke-Albinus (2012) the P balance contains uncertainties which explain the deviation of the given stock accumulation value from the difference of import and export when calculating the imported phosphorus minus the exported phosphorus. The sink that accumulates the largest amounts of phosphorus is *Landfill/Incineration* with +1.34 kg/cap.yr.

The largest flows within the system are to be found between the processes *Crop farming* and *Animal husbandry*. About 3.52 kg/cap.yr of phosphorus are transported through feed from the crop farming process and to the animal husbandry process. In the other direction 2.77 kg/cap.yr of phosphorus are being transported by fertiliser in form of manure. Another notable P flow originates from the biogas production process and ends up in crop farming carrying 1.96 kg/cap.yr of phosphorus through fermentation residues.

The illustration in figure 3.8 shows the wastewater management process in isolation and its input and output flows. Most of the phosphorus is being carried to the wastewater management process through municipal waste water (0.69 kg/cap.yr) followed by wastewater from the fertiliser industry (0.12 kg/cap.yr) and miscellaneous industry (0.05 kg/cap.yr). After the wastewater treatment phosphorus mostly ends up in sewage sludge while one part of the sewage sludge is being introduced into the crop farming process (0.19 kg/cap.yr) and another part is transported to the waste management process (0.48 kg/cap.yr) where it is being subsequently incinerated or landfilled. Small amounts of phosphorus are carried by effluents to the hydrosphere (0.01 kg/cap.yr). Different to the Austrian MFA by Egle et al.

(2014) presented in chapter 3.2.2 Gethke-Albinus (2012) does not describe in her MFA the sub-processes within the wastewater management process.

As mentioned before, the German P balance is subject to uncertainties concerning the data collected which explains the inconsistency between input and output flows in absence of stock accumulation.

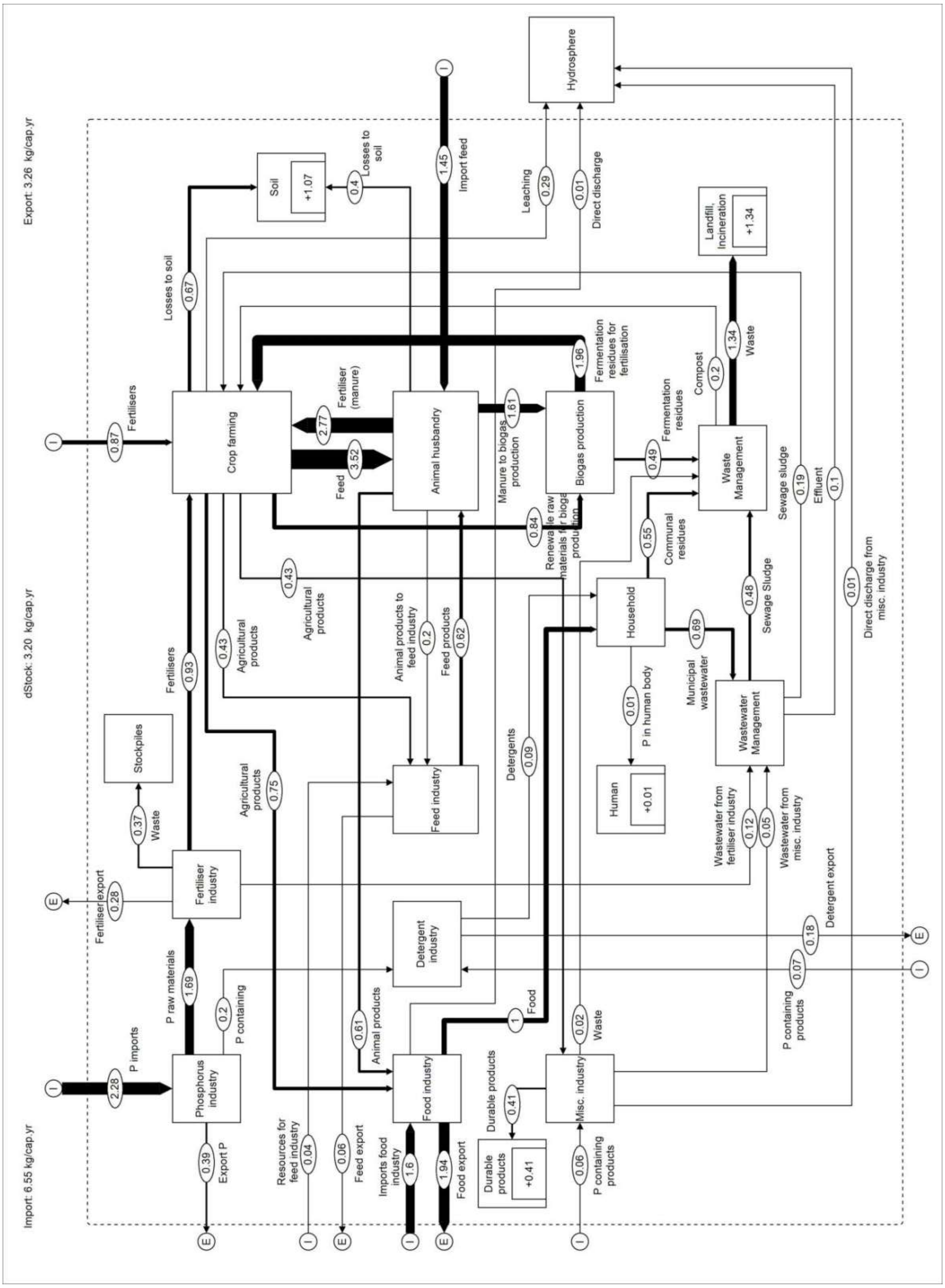


**Figure 3.7:** P balance in Germany (modified after Gethke-Albinus 2012)

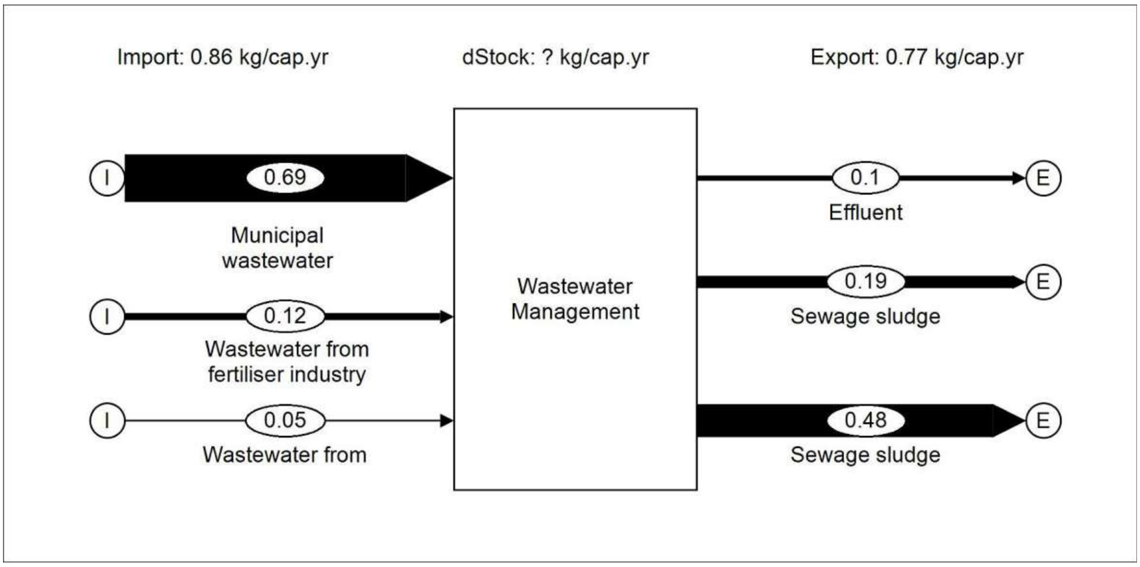


**Figure 3.8:** P balance in Germany, Wastewater management process (modified after Gethke-Albinus 2012)

### 3.3.3 Phosphorus Recovery

#### Potential Phosphorus Recovery

The current and potential P recycling rates are listed in table 3.3. The P balance by Gethke-Albinus (2012) does not subdivide the sewage sludge into municipal and industrial streams. Therefore table 3.3 does not feature separate P recovery rates from municipal and industrial sewage sludge. Currently the phosphorus load in sewage sludge amounts to 0.67 kg/cap.yr. According to the figures in table 3.6 in chapter 3.3.1 part of the sewage sludge is being composted. However, the German P balance by Gethke-Albinus (2012) does not clearly show how much phosphorus carried to the waste management process through sewage sludge is actually being composted. In this case the waste management process acts as a block box and it does not demonstrate what happens to the flows within this black box.

At this point it is assumed that sewage sludge entering the waste management sub-system is being incinerated and landfilled and thus none of its phosphorus is being recycled back to agriculture. The amount of phosphorus leaving wastewater treatment plants through sewage sludge and being applied to agriculture (*Crop farming*) is 0.19 kg/cap.yr.

Similar to the Austrian P balance by Egle et al. (2014) in the German P balance by Gethke-Albinus (2012) agriculture is divided between the processes *Crop farming* and *Animal husbandry*. For the following analysis those processes will be put together and treated as one process and generally denominated as agriculture. Since the phosphorus in the flows *Manure to biogas production* and *Renewable raw materials for biogas production* which exit one of the agricultural processes contributes to the phosphorus flow carried by *Fermentation residues for fertilisation* into the crop farming process the latter P flow will

**Table 3.3:** P recycling rates from sewage sludge in Germany

| P recovery from sewage sludge | |
|---|---|
| **P in sewage sludge** | |
| municipal sewage sludge | N/A |
| industrial sewage sludge | N/A |
| total sewage sludge | 0.67 kg/cap.yr |
| **P recycled from sewage sludge** | |
| municipal sewage sludge | N/A |
| industrial sewage sludge | N/A |
| total sewage sludge | 0.19 kg/cap.yr |
| **P input into agriculture** | |
| through (mineral) fertilisers | 1.80 kg/cap.yr |
| total P input | 4.26 kg/cap.yr |
| **Current P recycling rate from sewage sludge** | |
| municipal WWTP | N/A |
| industrial WWTP | N/A |
| total | 28.4% |
| **Current P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 10.6% |
| in relation to total P input | 4.5% |
| **Potential P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 37.2% |
| in relation to total P input | 15.7% |
| **Potential P substitution** | |
| of (mineral) fertiliser | 26.7% |

not be included in the calculation of total P input into agriculture because it would lead to a double counting of P flows. Hence, the total P input flow into agriculture amounts to 4.26 kg/cap.yr while 1.8 kg/cap.yr of phosphorus are being introduced through mineral fertilisers.

Currently 28.4% of phosphorus in sewage sludge is being recycled and used in agriculture. Putting the recycled P from sewage sludge into relation with the P input in agriculture through fertilisers it yields a ratio of 10.6%. Recycled phosphorus from sewage sludge makes up 4.5% of total P input into agriculture. If all of the phosphorus in sewage sludge were recovered (0.67 kg/cap.yr) it could cover 15,7% of total P input in agriculture. Relating the total amount of phosphorus in sewage sludge to current P input into agriculture through mineral fertilisers it yields a ratio of 37.2%. If the entire phosphorus recycled from sewage sludge were to substitute mineral fertiliser it could cover 26.7% of mineral fertiliser demand.

### 3.3.4 Strategies

#### German Environment Agency

The German Environment Agency ("Umweltbundesamt", UBA) is the main environmental protection agency in Germany who's target it is to promote a clean and healthy environment. The main tasks of the agency is to gather data on the state of the environment, investigate important interrelationships and make projections. Those findings shall serve as foundation for policy advice to federal bodies (UBA, n.d.). The German Environment Agency has published several reports (Roskosch and Heidecke 2018, Montag et al. 2015, Wiechman et al. 2013 and UBA 2017) dealing with the topic of the use and disposal of sewage sludge and the recovery of phosphorus from sewage sludge. All of them underline the importance of sewage sludge as a potential phosphorus source.

In the context of this thesis, the reports "Evaluation of concrete measures for further phosphorus recovery from relevant material flows and for efficient phosphorus use" (Montag et al. 2015) and "Sewage sludge disposal in the Federal Republic of Germany" (Roskosch and Heidecke 2018) will be looked at as they give a detailed assessment of P recovery in Germany and are the most recent reports on this topic.

The report "Evaluation of concrete measures for further phosphorus recovery from relevant material flows and for efficient phosphorus use" was issued in 2015 and as the title suggests it assesses P management methods in Germany and draws conclusions on those findings. It gives a general overview on the application of phosphorus in different sectors and how it can be managed sustainably in those sectors. Concerning P recovery from sewage sludge the UBA report gives several recommendations on how to proceed in this area. For example, it suggests phosphorus to be recovered in wastewater treatment plants which have a certain size (> 10,000 population equivalent) due to too small quantities of phosphorus that can be potentially recovered in small-scale WWTPs but high technical requirements. Further, the UBA acknowledges that there does not yet exist a best available technology for P recovery to be preferably applied. Thus the UBA suggests not to conclude legal requirements that would later possibly exclude a P recovery process. Since the implementation of P recovery technologies and their operations involves high costs, the UBA proposes to establish political incentives or governmental financing aids to promote the development of P recovery processes (Montag et al. 2015, 193-195).

The report "Sewage sludge disposal in the Federal Republic of Germany" was published in 2018 and similar to the aforementioned report from 2015 it also deals with P management in Germany. However, the emphasis of the 2018 report lies, as the title suggests, on sewage sludge disposal instead of a holistic approach towards a sustainable P management. The main findings and recommendations of this report are to refrain from the direct use of sewage sludge as fertiliser on agricultural land and further develop the implementation of P recovery technologies in wastewater treatment plants. Nevertheless, the implementation of P recovery processes should obtain financial support if necessary. Further, the access to the market for fertilisers obtained through P recovery shall be facilitated by revoking their status as waste. Similar to the 2015 report the UBA states in the 2018 report that there is no P recovery technology that is to be preferred over others. The UBA makes no statements which is the most promising technology that shall be implemented in future (Roskosch and Heidecke 2018, 68-71).

In Germany there are 14 large-scale plants already implemented or planned for P recovery as of 2018 (Roskosch and Heidecke 2018).

#### German Phosphorus-Platform

The German Phosphorus-Platform ("Deutsche Phosphor-Plattform", DPP) is a network comprising stakeholders in science, industry and the public sector. The network aims at establishing sustainable P management in Germany by using phosphorus more efficiently and promoting the recycling of phosphorus. Hence, the DPP network develops numerous strategies focusing on a more efficient use of phosphorus, optimising P recycling rates and searching for P substitutes. The main activities of the Phosphorus-Platform is to bring together representatives from science, agriculture, industry and politics for exchange of information. Further, it develops regulation proposals and recommendations for policy makers. The DPP network also organises events, workshops and seminars on topics related to P management and initiates projects. It seeks to bring stakeholders together in order to work jointly on solutions for sustainable P management (Deutsche Phosphor-Plattform, n.d.).

## 3.4 Netherlands

### 3.4.1 Legal Framework

The Netherlands is a member of the European Union and thus is obliged to comply with the EU Urban Waste Water Treatment Directive. The management of water in the Netherlands is ruled by the Dutch Water Act. Before 2009, the Dutch legislation on water was very fragmented. Different segments of water management were separated in different laws and legal instruments. The Dutch Government combined the water governance laws which resulted in the Dutch Water Act in 2009 (Dutch Water Authorities 2017, 20).

The Dutch Water Act rules that the State and the so-called water boards (i.e. regional water authorities) are the responsible authorities for water management in the Netherlands (Dutch Water Act, Art 3.1). It further states that "urban waste water discharged into a public sewer shall be treated in an establishment destined for this purpose" and that the water boards are responsible for managing wastewater treatment (Dutch Water Act, Art 3.4). However, the Water Act does not mention which quality standards shall be applied for wastewater treatment or whether phosphorus shall be recovered. As the management of wastewater treatment in the Netherlands lies within the responsibility of the water boards they are the ones to determine discharge requirements form wastewater treatment plants (Government of the Netherlands 2010).

The Dutch Decree on the Use of Fertilisers (“Besluit gebruik meststoffen”) regulates, as the name suggests, the use of fertilisers in agriculture since 1998. This decree has been amended several times over the years. Since 2008 the following provisions are in force within the framework of the Decree on the Use of Fertilisers. Article 1b § 1 states a general prohibition of applying sewage sludge as fertilisers to agricultural soils. This is followed by several paragraphs and articles laying out exceptions to this ban and conditions under which sewage sludge may be used in agriculture. One of those exceptions is that restricted quantities of sewage sludge may be applied if heavy metal concentrations in the receiving soil do not exceed certain threshold values (Art. 1b § 3, Annex III). Thus Article 1c § 1 demands that the agricultural soil shall be sampled and analysed before sewage sludge is being applied. These statues concerning the application of sewage sludge on land and their conditions of determining heavy metals in in soil are reminiscent of the EU Sewage Sludge Directive which sets out similar regulations (Rijksoverheid 2008, Rijksoverheid 2021).

Data on sewage sludge disposal show that actually no municipal sewage sludge is being directly applied in agriculture (Eurostat 2021c). The diagram in figure 3.9 illustrates how municipal sewage sludge is being disposed of in the Netherlands between 2005 and 2016. The prevalent form of sewage sludge disposal has been incineration. The fact, that no sewage sludge is being used on agricultural land suggests that the regulations concerning their application in agriculture might be so stringent that sewage sludge has to be disposed of in other ways.

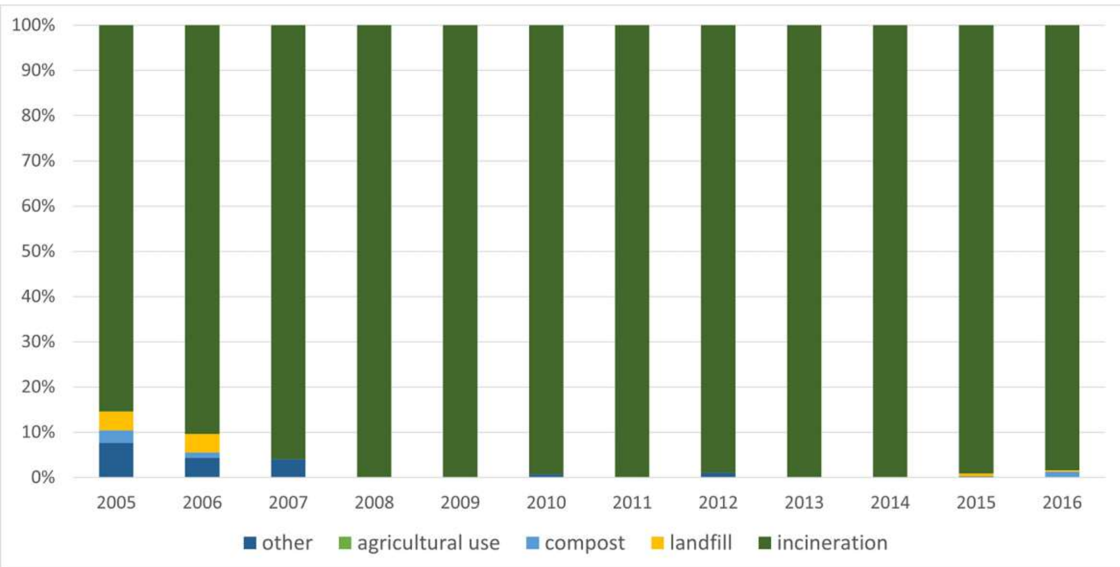


**Figure 3.9:** Sewage sludge disposal in the Netherlands (modified after Eurostat 2021c)

### 3.4.2 Phosphorus Balance

The following P balance was elaborated by Smit et al. (2015). The geographical boundary of the MFA by Smit et al. (2015) is limited to Dutch territory and the time boundary is set for the course of one year. The reference year is 2011. Their MFA does only consider net national P flows meaning that imported materials that are being processed in the Netherlands and then exported as feed or food products (transit products) are not included. Phosphate rock that is imported, processed and again exported is not considered either (Smit et al. 2015).

The MFA with the original absolute values (i.e. not related to the Dutch population size) and the uncertainties by Smit et al. (2015) can be found in Annex III.

### Population-Specific Phosphorus Balance

Figure 3.10 illustrates the MFA for phosphorus in the Netherlands in relation to the population in 2011. In 2011 the Netherlands had a population of 16,655,799 inhabitants (Statistics Netherlands 2014).

The system comprises six processes them being: *Industry*, *Agriculture*, *Household/Retail*, *Waste*, *Surface water* and *Lost P*. Smit et al. (2015) further break down the processes *Agriculture*, *Industry* and *Waste* into sub-processes. The sub-processes describe in more detail the umbrella-processes of agriculture, industry and waste management. Some flows and stocks in the MFA are subject to uncertainties in their quantities. For the sake of this thesis the uncertainties will be neglected.

The MFA in figure 3.10 shows that most of the phosphorus is imported through food (1.89 kg/cap.yr) and feed (3.52 kg/cap.yr) into the Netherlands and are inserted into the industrial process. Compared to those major import flows the P import to the Netherlands through fertilisers (0.42 kg/cap.yr) which is introduced into the agricultural process is rather small. The total P import flows amount to 6.6 kg/cap.yr, whereas 2.5 kg/cap.yr of phosphorus are exported from the Netherlands. This difference between import and export leads to a P accumulation of +4.1 kg/cap.yr in the Netherlands. Most of the phosphorus is being accumulated in the process *Lost P* with +1.39 kg/cap.yr. However, all of the phosphorus ending up in *Lost P* originates from the waste management process (cf. figure 3.10) or rather from the *Landfill, Incineration, Cement industry* sub-process (cf. figure 3.11) implying that phosphorus is lost to landfills and to concrete constructions. In the agricultural sector around +0.71 kg/cap.yr of phosphorus are being accumulated. Due to intensive agricultural activities in the Netherlands the phosphorus input into arable and grazing land is bigger than the phosphorus output through harvest and leaching leading to an accumulation of phosphorus in the soils (Smit et al. 2015).

Within the system large amounts of phosphorus are transported between industry and agriculture. About 3.21 kg/cap.yr of phosphorus are transported through agricultural products from agriculture to industry, whereas a P amount of 4.57 kg/cap.yr is introduced from industry to agriculture through feed. Most of the phosphorus is exported from industry through food (2.95 kg/cap.yr) followed by manure export (0.96 kg/cap.yr) from agriculture. Other notable P flows are *F15, Food, Detergents* which amounts to 1.24 kg/cap.yr of phosphorus from industry to households and *F16, Household Waste* with a phosphorus transport of 1.24 kg/cap.yr from households to waste management. Around 1.39 kg/cap.yr of phosphorus are lost from the waste management process and not recycled or introduced into the agricultural or industrial processes.

Figure 3.11 illustrates the flows and the sub-processes in the waste management process in more detail. Most of the phosphorus enters the waste management sub-system either through household waste (1.24 kg/cap.yr) or industrial waste (0.58 kg/cap.yr). P flows originating from household waste are either introduced into municipal wastewater treatment plants (0.73 kg/cap.yr) or incinerated and landfilled (0.45 kg/cap.yr). Most of the phosphorus introduced into municipal wastewater treatment plants ends up in sewage sludge (0.65 kg/cap.yr) whereas a small portion is discharged in the effluent (0.14 kg/cap.yr). The phosphorus in sewage sludge from municipal WWTPs is not being recovered or recycled and ends up in its entirety in the process of incineration and landfilling and is thus lost. This condition matches with the data on sewage sludge disposal by Eurostat (2021) illustrated in figure 3.9.

Phosphorus that enters the waste management system with industrial waste (0.58 kg/cap.yr) is either introduced as wastewater into industrial or municipal wastewater treatment plants (0.3 kg/cap.yr and 0.06 kg/cap.yr) or directly incinerated and landfilled (0.22 kg/cap.yr). The P input flow into industrial WWTPs is split into output flows of the same order of magnitude. The sewage sludge from industrial WWTPs is either directly exported from the Netherlands (0.01 kg/cap.yr), incinerated and landfilled (0.08 kg/cap.yr) or recycled into agriculture (0.03 kg/cap.yr). About 0.06 kg/cap.yr of phosphorus are lost to the effluent.

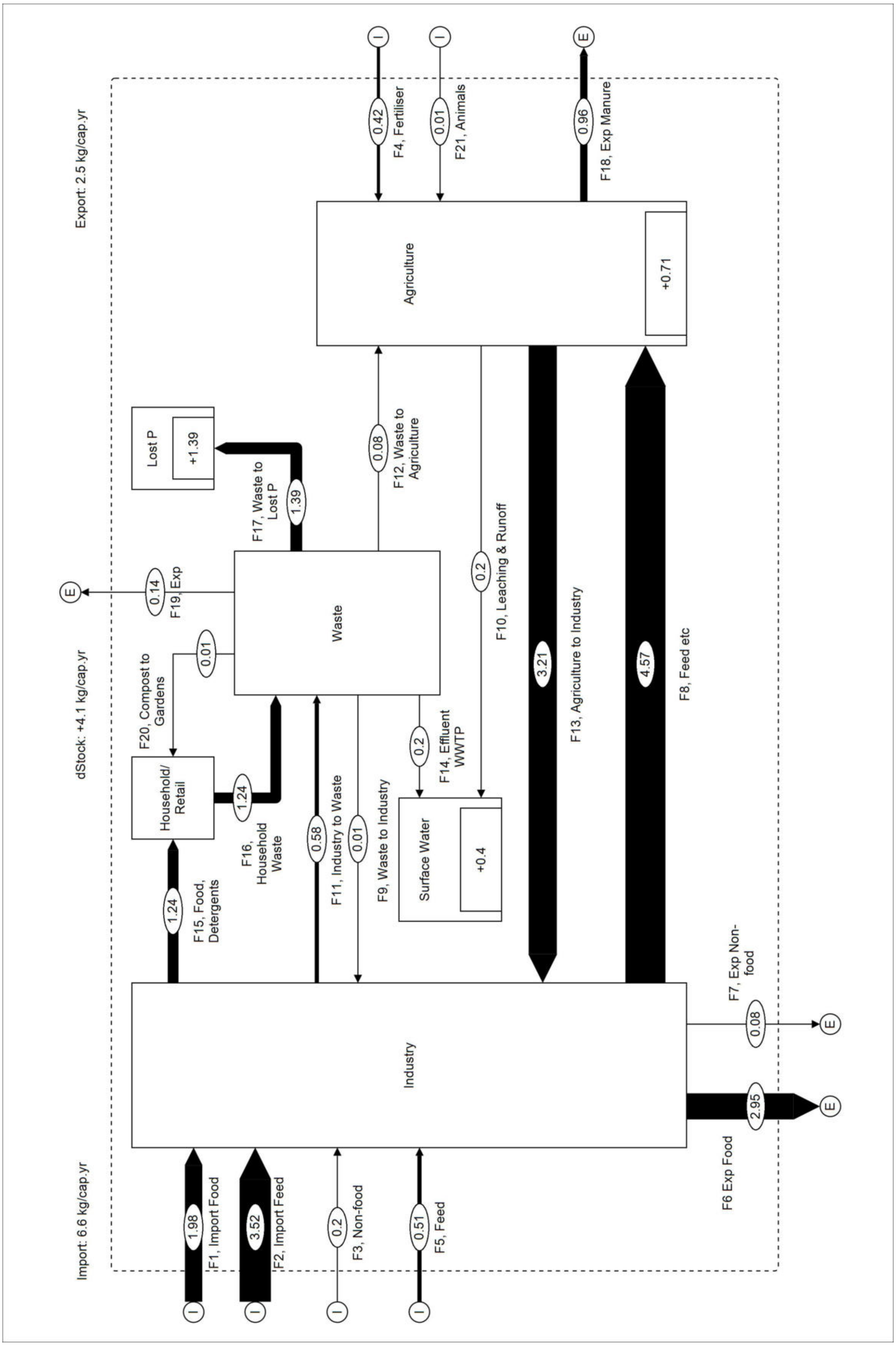


**Figure 3.10:** P balance in the Netherlands (modified after Smit et al. 2015)

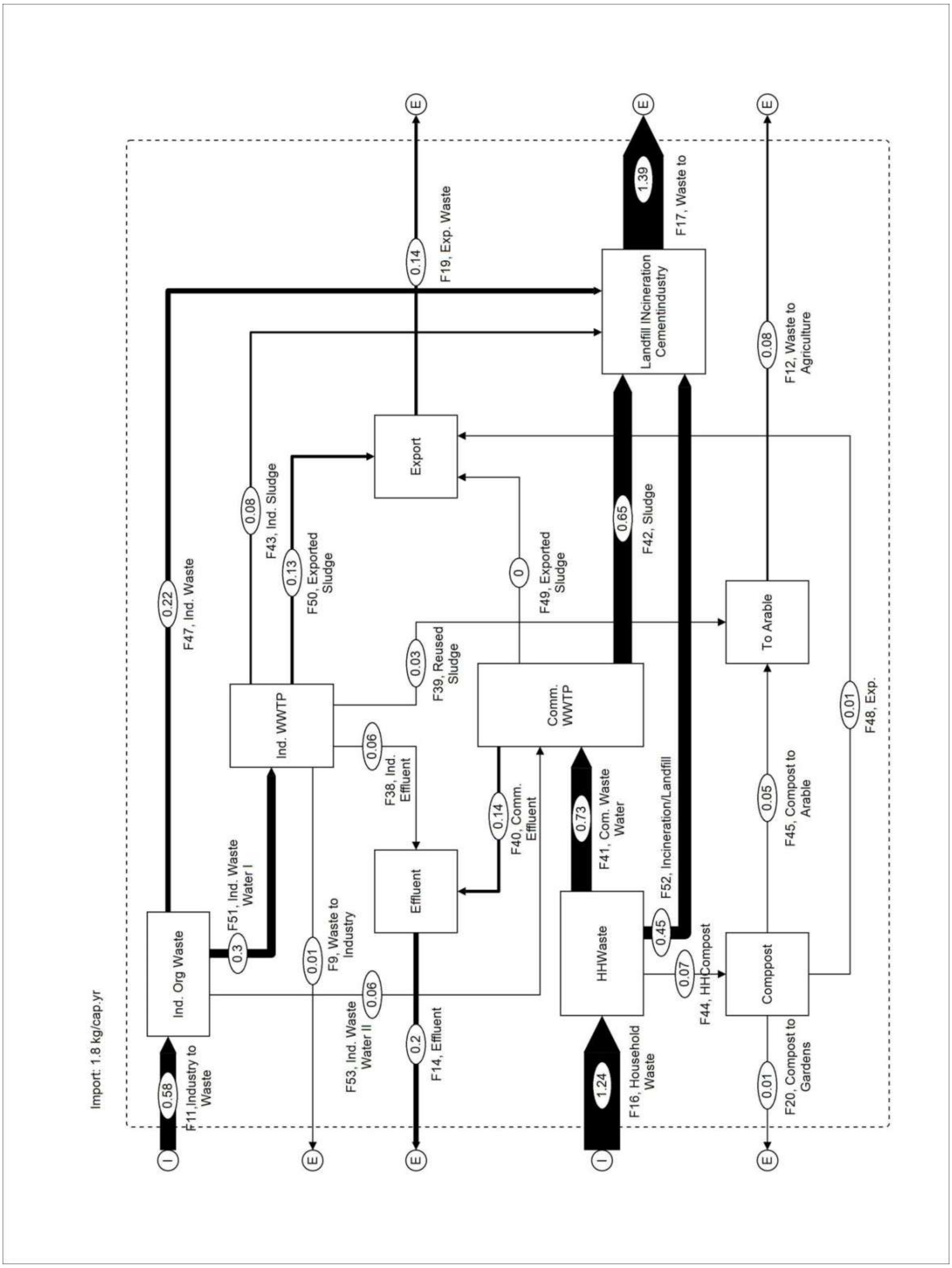


**Figure 3.11:** P balance in the Netherlands, Waste management process (modified after Smit et al. 2015)

### 3.4.3 Phosphorus Recovery

#### Potential Phosphorus Recovery

Analysing the P flows in the Netherlands the following recovery rates listed in table 3.4 can be determined.

In the Netherlands 0.65 kg/cap.yr of phosphorus end up in municipal sewage sludge and 0.24 kg/cap.yr in industrial sewage sludge thus leading to a total amount of 0.89 kg/cap.yr of phosphorus in sewage sludge. Looking at the P flows in 2011 in the Netherlands no phosphorus is recovered from sewage sludge coming from municipal WWTPs. All of the sewage sludge from municipal wastewater treatment plants is being introduced into the process of incineration and land-filling. Sewage sludge from industrial WWTPs is either directly used in agriculture, exported or incinerated and landfilled. From the P balance by Smit et al. (2015) it is not clear what happens with the exported sewage sludge, whether it is being recycled or landfilled beyond the system boundaries. As the exported sewage sludge is not being processed within the MFA system it will be considered as if it was not recycled. Hence the P recycling rate from industrial sewage sludge is calculated as the ratio of the P in reused sludge to the total P amount of all industrial sludge streams resulting to a value of 12.5%. When also considering in the calculation the phosphorus in municipal sewage sludge the recovery rate gives a value of 3.4%.

About 0.42 kg/cap.yr of phosphorus are applied on agricultural land through fertilisers. According to Smit et al. (2015) the flow *F13, Agriculture to Industry* is processed to food meaning that there is no recirculation of P from agriculture to industry and back to agriculture in the form of processed feed. Imported feed to the Netherlands actually ends up in agriculture. Thus, the total amount of P input into agriculture amounts to 5.08 kg/cap.yr. The ratio of the current amount of P recycled from sewage sludge to the P input into agriculture through fertilisers is 7.1%. However, when looking at how much of the recycled phosphorus contributes to the total P input into agriculture it only accounts for 0.6%.

If the phosphorus were recycled entirely both from municipal and industrial sewage sludge the ratio of recycled phosphorus to P input through mineral fertilisers in agriculture would yield a value of 211.9%. However, if recycled phosphorus were to substitute mineral fertilisers it could cover twice the amount of mineral fertiliser demand in agriculture (204.8%). When putting into relation the total P amount in sewage sludge to the total P input into agriculture, recycled phosphorus would cover 17.5% of the total P application in agriculture. These figures show that P fertilisers could be easily replaced by recycled P from sewage sludge. However, a total recycling of phosphorus from sludge would not suffice to cover the demanded of total P input into agriculture.

**Table 3.4:** P recycling rates from sewage sludge in the Netherlands

| P recovery from sewage sludge | |
|---|---|
| **P in sewage sludge** | |
| municipal sewage sludge | 0.65 kg/cap.yr |
| industrial sewage sludge | 0.24 kg/cap.yr |
| total sewage sludge | 0.89 kg/cap.yr |
| **P recycled from sewage sludge** | |
| municipal sewage sludge | 0.0 kg/cap.yr |
| industrial sewage sludge | 0.03 kg/cap.yr |
| total sewage sludge | 0.03 kg/cap.yr |
| **P input into agriculture** | |
| through (mineral) fertilisers | 0.42 kg/cap.yr |
| total P input | 5.08 kg/cap.yr |
| **Current P recycling rate from sewage sludge** | |
| municipal WWTP | 0.0% |
| industrial WWTP | 12.5% |
| total | 3.4% |
| **Current P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 7.1% |
| in relation to total P input | 0.6% |
| **Potential P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 211.9% |
| in relation to total P input | 17.5% |
| **Potential P substitution** | |
| of (mineral) fertiliser | 204.8% |

### 3.4.4 Strategies

**"Circular Economy in the Netherlands by 2050"**

In 2016 the Dutch government issued a programme aiming at the development of a circular economy in the Netherlands. The objective of this programme is to reduce by 50% the use of primary raw materials by 2030 and further, use and reuse those raw materials without negative impacts on the environment by 2050. For the effort towards a circular economy the government wants to include different parties such as local governments, social partners and citizens (Government of the Netherlands 2016, 7).

The programme on circular economy sets among other ambitions the priority on closing the nutrient cycle by optimising nutrient recovery from residues. In this context, the programme underlines the importance of phosphates being a scarce resource that needs to be managed sustainably and therefore recycled. However, it does not explicitly mention how phosphorus or phosphates shall be recovered. It only gives a general objective of using and reusing the nutrient on a sustainable way (Government of the Netherlands 2016, 48).

#### The Dutch Nutrient Platform

The Dutch Nutrient Platform is a network of Dutch organisations aspiring a sustainable management of phosphorus as nutrient. The members of this network are the Dutch government, NGOs, the chemical industry and organizations from the agriculture, water and waste sector. They aim at establishing a circular economy by recovering nutrients from waste streams (e.g. sewage sludge) and recycle them into new valuable products (e.g. fertilisers). Further, they want to contribute to food security abroad in case of an excess supply of recovered nutrients within the Netherlands. Those ambitious goals shall be achieved through knowledge exchange between the different parties of the platform, raising awareness about sustainable management of nutrients and adapting legislation regarding recovery of nutrients from waste (Nutrient Platform, n.d.(a)).

The Nutrient Platform gives examples of where success in the area of phosphorus recovery from sewage sludge has been achieved. For instance, the wastewater treatment plants in Amersfoort and Rotterdam have implemented P recovery technology (Nutrient Platform, n.d.(c), Nutrient Platform, n.d.(b)).

#### P recovery in wastewater treatment plants

According to Kabbe (2017) there are ten wastewater treatment plants in the Netherlands that recover phosphorus from sewage sludge on-site. They apply different technologies in order to obtain phosphorus in the form of struvite [2].

## 3.5 Sweden

### 3.5.1 Legal Framework

Being a member of the European Union Sweden has implemented the Urban Waste Water Treatment Directive into domestic law within the framework of the Swedish Environmental Code (Naturvårdsverket 2018, 30-31).

The Swedish Environmental Code is a framework legislation that lays down the principles of environmental protection (Naturvårdsverket 2020). Concerning the treatment of wastewater the Environmental Code only states that "wastewater shall be diverted and purified or treated in some other way in order to avoid detriment to human health or the environment" (Swedish Environmental Code, Chpt. 9, Sec. 7). However, the code does not mention how the wastewater shall be treated or whether phosphorus shall be recovered from sewage sludge (Swedish Ministry of the Environment 1999).

Specific requirements on the wastewater treatment are laid down in supplementary regulations to the Environmental Code (Naturvårdsverket 2018, 30-31). The main regulation dealing with standards of wastewater treatment is the "Naturvårdsverkets föreskrifter om rening och kontroll av utsläpp av avloppsvatten från tätbebyggelse" (Swedish Environmental Protection Agency's regulations on treatment and control of discharges of wastewater

[2] magnesium ammonium phosphate, $Mg(NH_4)(PO)_4$ (Smil 2000)

from urban areas, NFS 2016:6) (Naturvårdsverket 2016). The regulations contain concentration levels for nitrogen and organic matter in discharge water coming from wastewater treatment plants. However, standards on phosphor concentrations in wastewater treatment plant discharges or requirements on recovering phosphorus from sewage sludge do not feature in the regulations on treatment and control of discharges of wastewater from urban areas. Requirements for phosphorus concentrations in discharges from wastewater treatment plants are set in the permits for wastewater treatment plants. The Environmental Assessment Ordinance (2013:251) ("Miljöprövningsförordning" Government of Sweden 2013) regulates which wastewater treatment plants need a permit. The requirements laid down in the permits are in general more stringent than the requirements set out in the Urban Wastewater Treatment Directive (Naturvårdsverket 2018).

The SNFS ("Statens naturvårdsverks författningssamling", Constitutional Collection of the National Environmental Protection Agency) Act 1994:2 regulates the use of sewage sludge in agriculture in Sweden (Wiśniowska et al. 2019). According to § 1 of this regulation application of sewage sludge on agricultural land shall be carried out in such a way that it does not have an harmful impact on soil, plants, animals and humans. Further, this paragraph states that the use of sewage sludge shall be encouraged (Government of Sweden 1994). The wording of this paragraph is very reminiscent of the EU Sewage Sludge Directive. Thus, Sweden does not prohibit the application of sewage sludge on agricultural land. However, it may only be used in agriculture under specific conditions. For instance, the soil on which sewage sludge will be applied shall not have too high concentrations of heavy metals which exceed the limit values laid down in the SNFS Act 1994:2. Further, heavy metal concentrations in sewage sludge shall not exceed certain threshold values either. According to § 10 and § 11 of the regulation both soil and sewage sludge need to be sampled and analysed regularly (Government of Sweden 1994).

The diagram in figure 3.9 shows how municipal sewage sludge is being disposed of in Sweden based on data by Eurostat. (Eurostat 2021d). It shows that over the years between 20 and 40% of the municipal sewage sludge has been applied on agricultural land. Besides the application in agriculture sewage sludge has been also composted (30 to 35%) or has been disposed of in an other form (around 30 to 40%). However, other forms of sewage sludge disposal are not defined in more detail by Eurostat. Only a very small percentage of the sewage sludge is being either incinerated or landfilled (Eurostat 2021d).

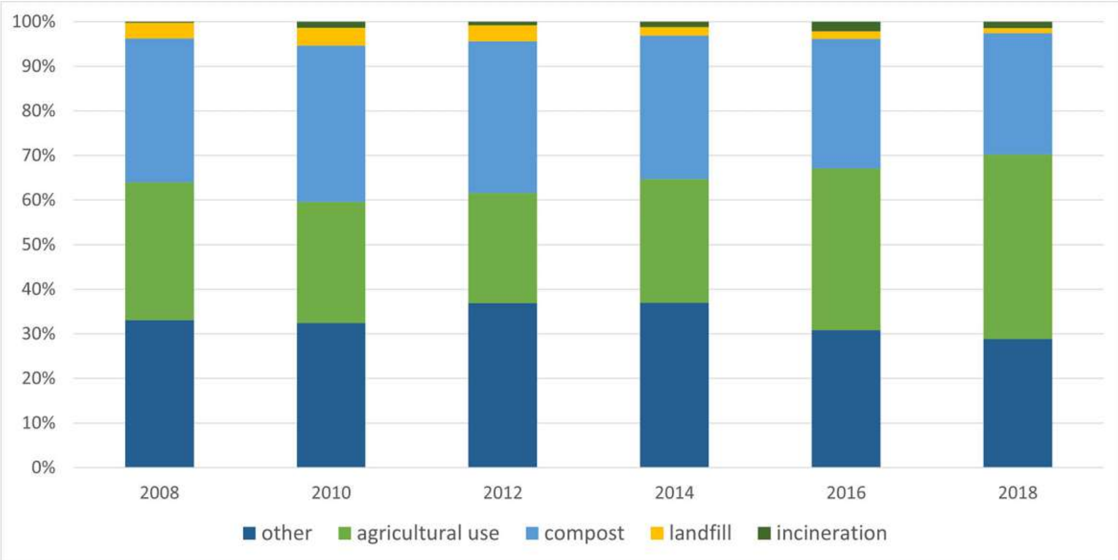


**Figure 3.12:** Sewage sludge disposal in Sweden (modified after Eurostat 2021d)

### 3.5.2 Phosphorus Balance

Several MFAs for phosphorus were conducted for the purpose of determining the P balance in Sweden. However, the MFAs differ in their structure regarding the processes they include in their analysis and in the number of flows entering and exiting these processes. In addition to that, they vary in the magnitudes of the processes and flows. Linderholm (2012), Wikberg (2019) and Lorick (2019) each have created different P balances for Sweden. The MFA by Linderholm (2012) is the oldest depicting the average Swedish P balance in the period between 2008 and 2010. Lorick (2019) does not indicate for which period his MFA has been elaborated. However, he has used data from Linderholm (2012) for his P balance. The MFA created by Wikberg (2019) represents the P balance in Sweden in the year 2016 and is mainly based on official statistical data issued by Swedish authorities.

In the course of this thesis the P balance by Wikberg (2019) will be used for further investigation as it is the most recent one and does not base on data from the MFA conducted by Linderholm (2012).

In the following the population-specific P balance of Sweden based on the MFA by Wikberg (2019) is being further examined. The MFA with the original absolute values (i.e. not related to the population of Sweden) by Wikberg (2019) is included in Annex IV.

#### Population-Specific Phosphorus Balance

Figure 3.13 shows the P balance in Sweden in relation to the Swedish population in 2016 with 9,995,153 inhabitants (Statistics Sweden 2020). Wikberg (2019) has defined the territory of Sweden as geographical boundary for the MFA. The time boundary is set for one year. The system also considers P import and export flows into and out of the system. The MFA encompasses in total five processes within the system them being: *Import/Export*, *Agriculture*, *Industry*, *Waste Management* and *Consumption/Retail/Domestic*. All the processes except from *Import/Export* are further broken down into sub-processes.

Total P input into the system including P depositions from the atmosphere and the environment amounts to 2.91 kg/cap.yr of phosphorus. The output P flows out of the system including P emissions into the hydrosphere total up to 1.53 kg/cap.yr. The difference between the import and export flows amounts to 1.38 kg/cap.yr of phosphorus. Hence, the P stocks in Sweden are increasing. When only looking at imports and exports without considering natural P depositions or P losses into the hydrosphere the P input into the system is 2.31 kg/cap.yr and P output is 1.29 kg/cap.yr thus leading to a P surplus of +1.02 kg/cap.yr. Most of the phosphorus is being accumulated in the waste management process (+1.0 kg/cap.yr) followed by the process *Consumption/Retail/Domestic* with a P stock accumulation of +0.33 kg/cap.yr.

The largest P import to Sweden is through mineral fertilisers (1.25 kg/cap.yr) which are then entirely applied in agriculture. Other flows through which phosphorus is being imported to Sweden are *Food Products* (0.55 kg/cap.yr), *Animal Products* (0.25 kg/cap.yr), *Other Products & Chemicals* (0.27 kg/cap.yr) and imports from the atmosphere through deposition (0.18 kg/cap.yr) and the environment (0.41 kg/cap.yr). Phosphorus is being exported from Sweden mainly through food (0.61 kg/cap.yr) and products (0.56 kg/cap.yr). Some of the phosphorus is being lost to the hydrosphere (0.12 kg/cap.yr).

Within the system the largest flows are *Agricultural Waste* (1.87 kg/cap.yr) and *Fertiliser recycled* (1.69 kg/cap.yr) which are responsible for a high P exchange between the agriculture and the waste management process. Another notable flow transports phosphorus from agriculture to the industry (1.04 kg/cap.yr) through food products.

As aforementioned, each of the processes except from *Import/Export* in the MFA's system is divided into sub-systems. For the purpose of this thesis the sub-processes in the process *Waste Management* will be examined in more detail. Figure 3.14 illustrates the sub-processes of *Waste Management*.

The process of waste management encompasses five sub-processes: *Wastewater Treatment*, *Organic Waste Processing/Biogas/Compost*, *Sorting*, *Incineration* and *Landfill*. The main P flows enter the waste management system (i.e. process) through agricultural waste (1.87 kg/cap.yr) leading into the sub-process *Sorting* and through wastewater (0.55 kg/cap.yr) leading to the wastewater treatment sub-process. Looking at the latter sub-process it can be seen that most of the phosphorus entering wastewater treatment plants ends up in sludge (0.5 kg/cap.yr) while only a small fraction ends up in the treatment plants' effluents (0.02 kg/cap.yr).

In the MFA by Wikberg (2019) the phosphorus containing sludge originating from the wastewater treatment sub-process leads to the sub-process *Organic Waste Processing/Biogas/Compost*. Besides the P input flow through sewage sludge phosphorus enters the latter sub-process through organic waste (1.65 kg/cap.yr). Phosphorus leaves the sub-process *Organic Waste Processing/Biogas/Compost* through fertilisers (1.69 kg/cap.yr) which is being reintroduced into agriculture (cf. figure 3.13) and through sewage sludge (0.5 kg/cap.yr) which ends up in landfills that subsequently accumulate phosphorus (+1.0 kg/cap.yr).

In the depiction of the sub-process of waste processing within the waste management process (cf. figure 3.14) it is not apparent whether the phosphorus in organic waste is recycled to it's entirety to fertilisers and a fraction of the phosphorus in the inflowing sludge is recovered and also used as fertiliser or whether the P input flows are being split differently among the output flows. Wikberg (2019) does not give any indications on how the input flows in the sub-process of waste processing are split among the output flows. For further investigation regarding phosphorus recycling from sewage sludge in Sweden it will be assumed that the P input flow from sludge (0.53 kg/cap.yr) is split according to the data on sewage sludge disposal in Sweden given in figure 3.12. According to figure 3.12 30% of the sewage sludge is composted and 35% is directly applied in agriculture. Assuming that the composted sewage sludge is also being applied as fertiliser in agriculture the total amount of phosphorus recycled from sewage sludge amounts to 0.34 kg/cap.yr.

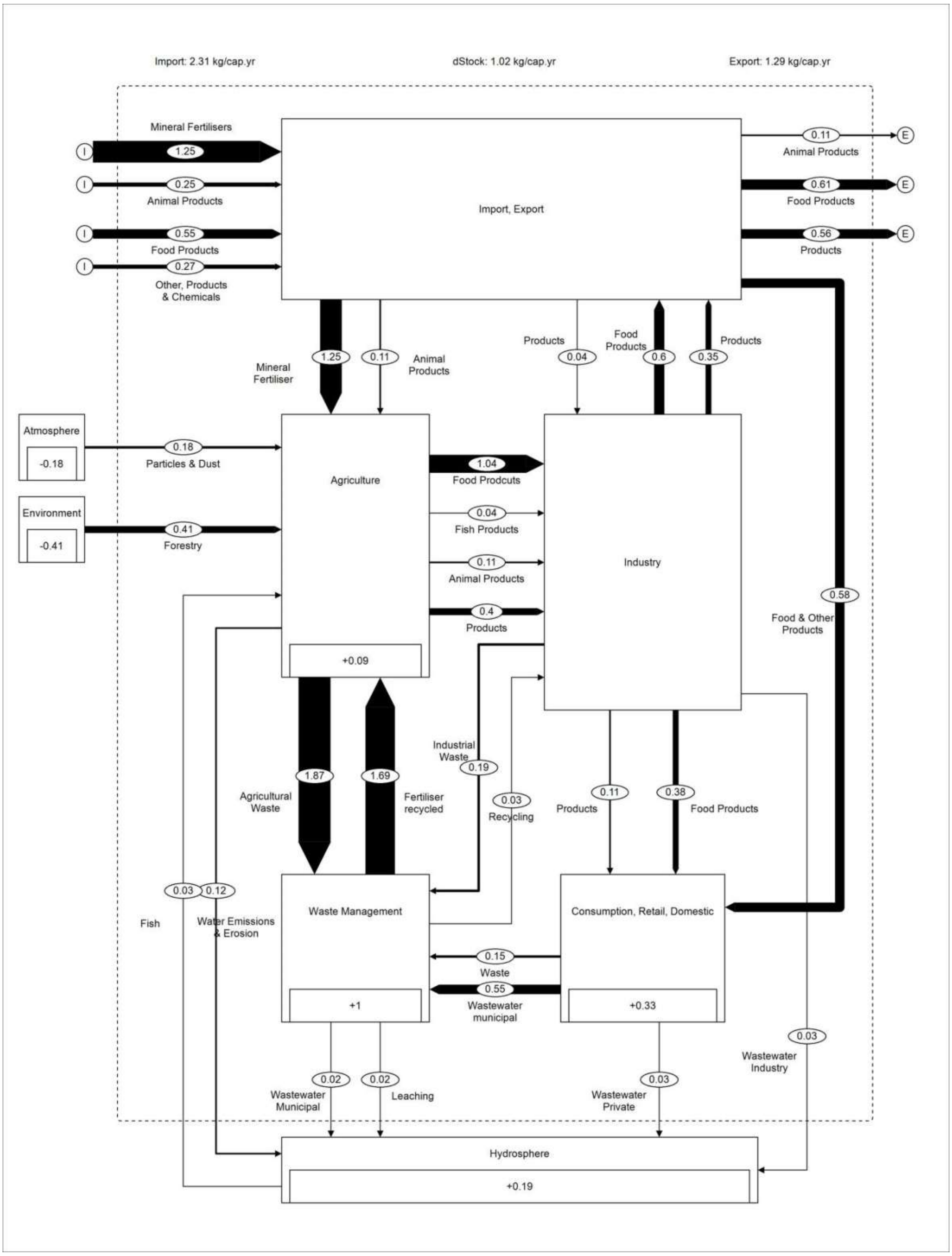


**Figure 3.13:** P balance in Sweden (modified after Wikberg 2019)

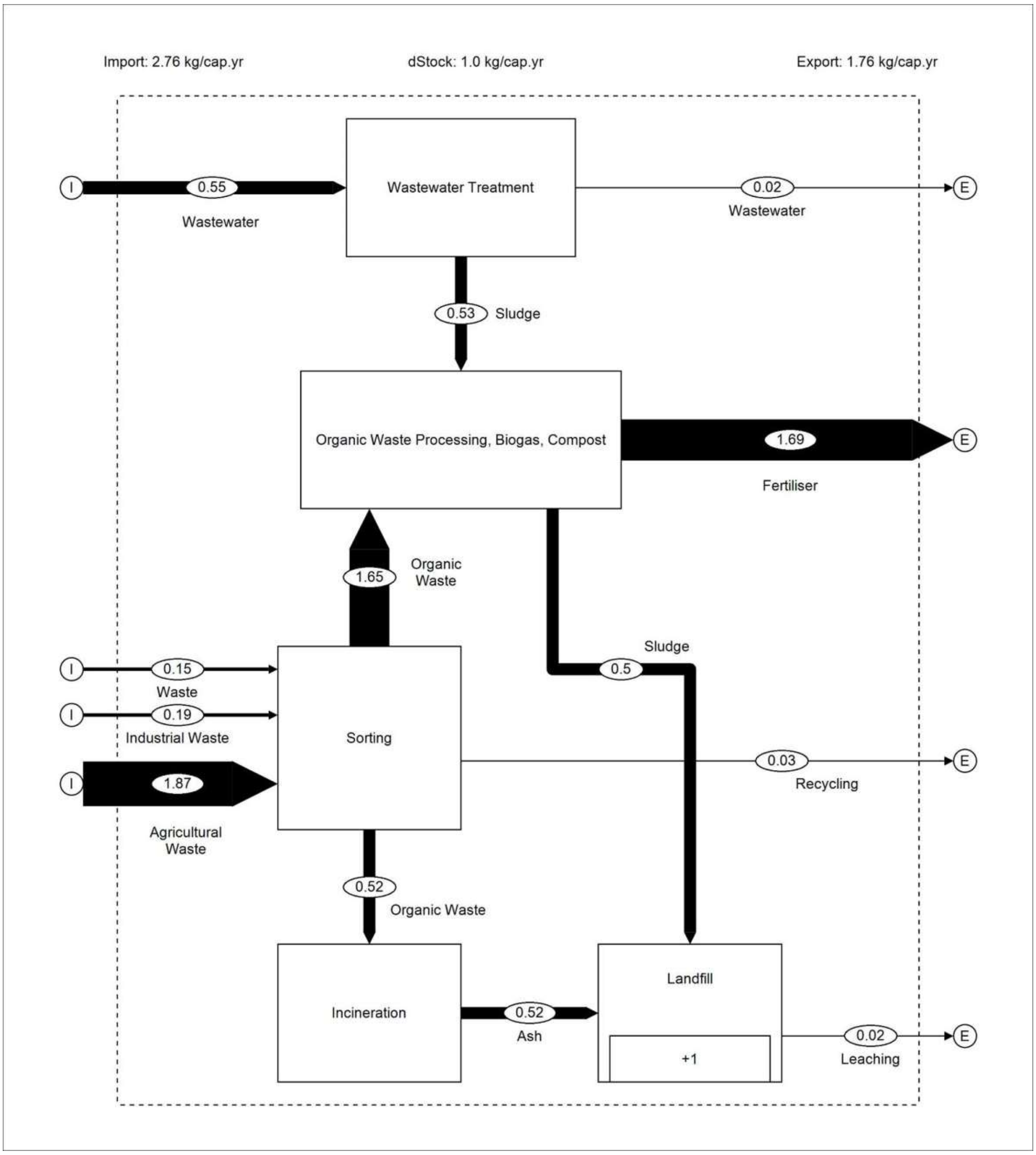


**Figure 3.14:** P balance in Sweden, Waste management process (modified after Wikberg 2019)

### 3.5.3 Phosphorus Recovery

**Potential Phosphorus Recovery**

Given the P flows from the MFA by Wikberg (2019) in Sweden the following recycling rates in table 3.5 can be derived (cf. figure 3.13 and 3.14). Wikberg (2019) does not differ between sewage sludge generated in municipal or industrial wastewater treatment plants. Thus, 0.53 kg/cap.yr of phosphorus ends up in sewage sludge while 0.34 kg/cap.yr is being recycled from sewage sludge. Mineral fertilisers carry 1.25 kg/cap.yr of phosphorus to the agriculture process. The total P input into agriculture amounts to 3.67 kg/cap.yr.

According to the Swedish P balance around 65% (0.34 kg/cap.yr out of 0.53 kg/cap.yr, cf. figure 3.12) of phosphorus are being recycled from sewage sludge. Comparing the amount of recycled phosphorus from sewage sludge (0.34 kg/cap.yr) with the amount of phosphorus introduced into agriculture through mineral fertilisers (1.25 kg/cap.yr) gives a ratio of 27.2%. The quantity of phosphorus recycled from sewage sludge makes up for 9.3% of total P input into agriculture.

**Table 3.5:** P recycling rates from sewage sludge in Sweden

| **P recovery from sewage sludge** | |
|---|---|
| **P in sewage sludge** | |
| municipal sewage sludge | N/A |
| industrial sewage sludge | N/A |
| total sewage sludge | 0.53 kg/cap.yr |
| **P recycled from sewage sludge** | |
| municipal sewage sludge | N/A |
| industrial sewage sludge | N/A |
| total sewage sludge | 0.34 kg/cap.yr |
| **P input into agriculture** | |
| through (mineral) fertilisers | 1.25 kg/cap.yr |
| total P input | 3.67 kg/cap.yr |
| **Current P recycling rate from sewage sludge** | |
| municipal WWTP | N/A |
| industrial WWTP | N/A |
| total | 64.2% |
| **Current P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 27.2% |
| in relation to total P input | 9.3% |
| **Potential P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 42.4% |
| in relation to total P input | 14.4% |
| **Potential P substitution** | |
| of (mineral) fertiliser | 40.0% |

If all of the phosphorus were recycled from sewage sludge (0.53 kg/cap.yr) it could substitute 14.4% of total P input into agriculture. Relating the total amount of phosphorus in sewage sludge to current P input into agriculture through mineral fertilisers it yields a ratio of 42.4%. In case recycled phosphorus should substitute P input into agriculture through mineral fertilisers it could cover 40% of mineral fertiliser demand.

### 3.5.4 Strategies

**Report by the Swedish Environmental Protection Agency on Sustainable Recycling of Phosphorus**

The government in Sweden assigned the Swedish Environmental Protection Agency ("Naturvårdsverket") to investigate on the topic of sustainable phosphorus recycling. The idea behind sustainable P management is to establish a circular and resource-efficient economy absent from undesirable and hazardous materials. In 2013 the SEPA issued a survey presenting potentials in sustainable P recycling and undesirable materials in different P sources, proposing legal requirements for P recycling and introducing possible milestone targets for P recycling (Naturvårdsverket 2013, 11-18).

The SEPA acknowledges the importance of phosphorus in the agricultural sector and thus recognises the major linkage between food production and food consumption through P flows. Among the different P sources the SEPA looks at sewage sludge of WWTPs and its role in P management. According to the presented report by the SEPA 25% of the sewage sludge is being recycled and applied on agricultural fields. The SEPA claims that if all of the phosphorus in sewage sludge should be used as fertiliser in agriculture it would need the consent of farmers since increasing application of sewage sludge in agriculture as fertiliser would highly depend on their acceptance. Further, it proposes on-site recovery of phosphorus from sewage sludge through struvite precipitation methods or P recovery from incinerated sewage sludge (mono-incineration). However, there do not exist mono-incineration plants in Sweden (Naturvårdsverket 2013, 11-18).

In its report the SEPA suggests restricting concentrations of undesirable material in sewage sludge when applying it in agriculture. In order to allow those affected by the measures to adapt to these restrictions they shall be implemented gradually over time. Regulations with stricter limit values for undesirable material contribute in the first way to the goal of a safe application of sewage sludge in agriculture. However, these measures might not serve the goal of increasing the quantity of sewage sludge application on agricultural land but rather the opposite. A lowering of limit values might ask for alternative ways of sewage sludge disposal such as sewage sludge incineration with subsequent P recovery from the ashes (Naturvårdsverket 2013, 11-18).

The SEPA proposes the introduction of milestones targets in order to encourage a sustainable use of resources and increasing the recycling of nutrients while at the same time avoiding harmful impacts on the environment. In the case of phosphorus the SEPA sets the milestones target of recovering at least 40% of phosphorus from waste for agricultural use (Naturvårdsverket 2013, 11-18).

**Government Inquiry on Sustainable Sewage Sludge Management**

In 2018 a government inquiry was launched in order to submit a proposal on a prohibition of applying sewage sludge on agricultural land. In addition to that, the inquiry shall present a requirement for phosphorus recycling from sewage sludge. The aim of the Swedish government is to move towards self-sufficiency and thus a circular economy, where waste is seen as a potential source for resources. Applied to the sphere of sewage sludge that means that phosphorus shall be recovered from sewage sludge and reused in agriculture in such a way that it does not impose harm to the environment through hazardous material (Government Offices of Sweden 2018).

The government inquiry presented its final report on *Sustainable Sludge Management* ("Hållbar slamhantering", Regeringskansliet 2020) in January 2020 (Research Institutes of Sweden 2020). Dagerskog and Olsson (2020) give a summary of the submitted report and its key statements. It presents two possible options regarding future sewage sludge management in Sweden. The first approach brought forth is a prohibition on spreading sewage sludge on agricultural land. The second option proposes that the application in agriculture shall be further on allowed, however under stricter conditions than the ones currently in place. Nevertheless, both proposals set the target to recover 60% of the phosphorus from sewage sludge in the following 12 to 15 years. (Dagerskog and Olsson 2020)

When the first wastewater treatment plants were built in Sweden the prevalent idea was to reuse sewage sludge in agriculture. It was considered as a cheap solution concerning the problem of how sewage sludge shall be disposed of and at the same time farmers also profited from this practice. In the 1970s and 1980s discussions on potential dangers caused by containments such as heavy metals arouse (Dagerskog and Olsson 2020).

Dagerskog and Olsson (2020) mention that regarding current developments refraining more and more from using sewage sludge directly in agriculture, the incineration of sewage sludge with subsequent P recovery from the ashes might become more common practice. However, a ban on application of sewage sludge on agricultural land would oblige to implement P recovery technologies in WWTPs.

According to Kabbe (2017) there is no wastewater treatment plant in Sweden that recovers phosphorus from sewage sludge on-site as of 2017.

## 3.6 Switzerland

### 3.6.1 Legal Framework

Switzerland is not a member of the European Union and thus is not compelled to comply with EU law. However, environmental and water protection in Switzerland are founded in the *Federal Act on the Protection of the Environment* ("Bundesgesetz über den Umweltschutz") and the *Federal Act on the Protection of Waters* ("Bundesgesetz über den Schutz der

Gewässer") (Federal Assembly of the Swiss Confederation 1983, Federal Assembly of the Swiss Confederation 1991a).

The *Waters Protection Ordinance* ("Gewässerschutzverordnung") is based on the water protection act and regulates the quality of effluents before their discharge in natural water bodies. It sets threshold values for pollutants in discharges from wastewater treatment plants. The general quality requirements do not include limiting values for phosphorus. Threshold values for phosphorus are laid down for discharges under special conditions them being WTTP discharges into sensitive water. However, the ordinance for water protection does not mention how phosphorus shall be removed from polluted water or whether it shall be recovered from sewage sludge (Federal Assembly of the Swiss Confederation 1991b).

The demand to recover phosphorus from sewage sludge features in the *Ordinance on the Avoidance and the Disposal of Waste* ("Verordnung über die Vermeidung und die Entsorgung von Abfällen"). Art. 10 rules that sewage sludge shall be incinerated. Consequently, this statute implies that sewage sludge may not be directly applied on agricultural soil. According to Art. 15 Sec. 1 "phosphorus must be recovered from municipal waste water, from sewage sludge from central waste water treatment plants or from the ash produced by the incineration of such sewage sludge and then recycled" (Federal Assembly of the Swiss Confederation 2015). For the recovery of phosphorus state-of-the-art technology shall be applied (Ordinance on the Avoidance and the Disposal of Waste, Art. 15 Sec. 2). However, "the duty to recover phosphorus in accordance with Article 15 applies from 1 January 2026" (Ordinance on the Avoidance and the Disposal of Waste, Art. 51). In other words the ordinance sets a transitional period for the recovery of phosphorus from sewage sludge (Federal Assembly of the Swiss Confederation 2015).

The digram in figure 3.15 illustrates the development of sewage sludge disposal in Switzerland over the years. At the end of the 1990s and in the beginning of the 2000s sewage sludge has been used as fertiliser in agriculture. However, the application of sewage sludge on agricultural land has decreased and its incineration has increased in the past two decades resulting in a complete incineration of all the sewage sludge produced.

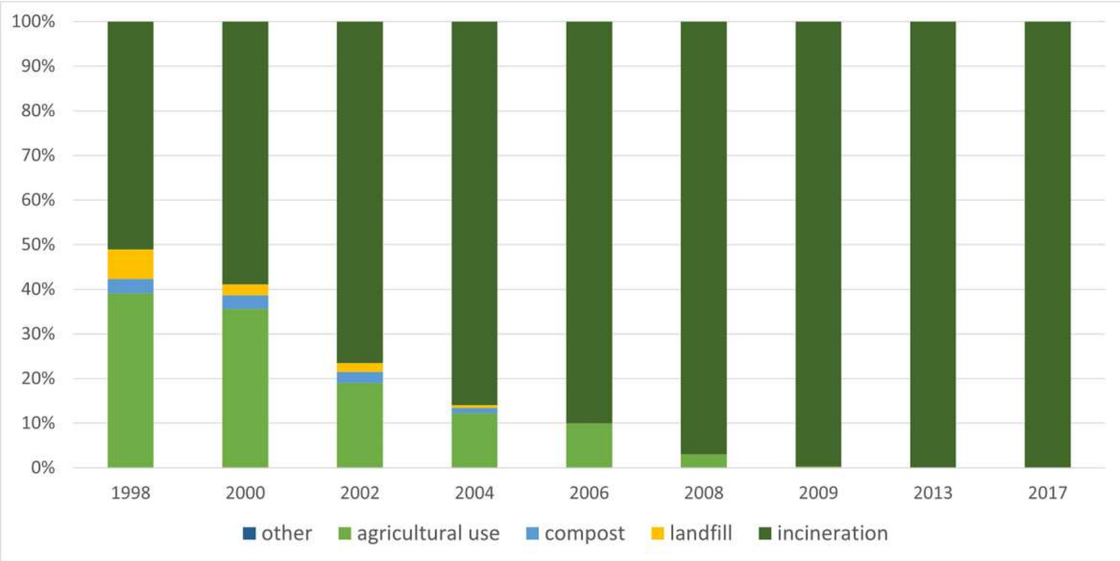


**Figure 3.15:** Sewage sludge disposal in Switzerland (modified after Eurostat 2021e)

### 3.6.2 Phosphorus Balance

The Swiss P balance presented in this thesis is retrieved from Binder et al. (2009). The spatial boundary of the MFA comprises Swiss territory. The temporal boundary is set for the duration of one year. Binder et al. (2009) have conducted the MFA for the year 2006.

In the following chapter the population-specific P balance in Switzerland based on the MFA by Binder et al. (2009) will be analysed. The Swiss P balance with the original values (i.e. not related to the size of the Swiss population) and uncertainties is listed in Annex V.

#### Population-Specific Phosphorus Balance

Figure 3.16 illustrates the P balance of Switzerland related to the Swiss population in 2006. In 2006 Switzerland had 7,508,739 inhabitants (Bundesamt für Statistik 2020). The MFA encompasses six processes them being: *Animal husbandry*, *Crop farming*, *Chemical Industry*, *Household & business*, *Hydrosphere* and *Waste management*. For each of this processes Binder et al. (2009) have also determined sub-systems with sub-processes. In the course of this thesis only the waste management sub-system will be further examined.

Total P import to Switzerland amounts to 2.20 kg/cap.yr. Most of the phosphorus is imported to Switzerland through feed (0.75 kg/cap.yr) which is being introduced into the animal husbandry process and through mineral fertilisers (0.78 kg/cap.yr) which are applied in crop farming. Around 0.52 kg/cap.yr of phosphorus are exported from Switzerland mainly through out-flowing water bodies (0.29 kg/cap.yr) and animal waste exports (0.2 kg/cap.yr). Since more phosphorus is being imported than exported phosphorus is being accumulated in the stocks of the system (+1.68 kg/cap.yr). Most of the phosphorus is being collected in the waste management process (+1.2 kg/cap.yr) followed by P accumulations in *Crop farming* (+0.47 kg/cap.yr).

Within in the system the main carriers of phosphorus are the flows *Manure* (3.9 kg/cap.yr) and *Feed* (3.9 kg,cap.yr). Both of the flows link the processes *Animal husbandry* and *Crop farming* together leading to a high P exchange between those two processes. Other notable P carriers are plant (0.53 kg/cap.yr) and animal products (0.46 kg/cap.yr) which transport phosphorus to households and businesses. Most of the phosphorus from the process *Household & business* ends up in municipal wastewater which is being introduced into the waste management process (0.81 kg/cap.yr).

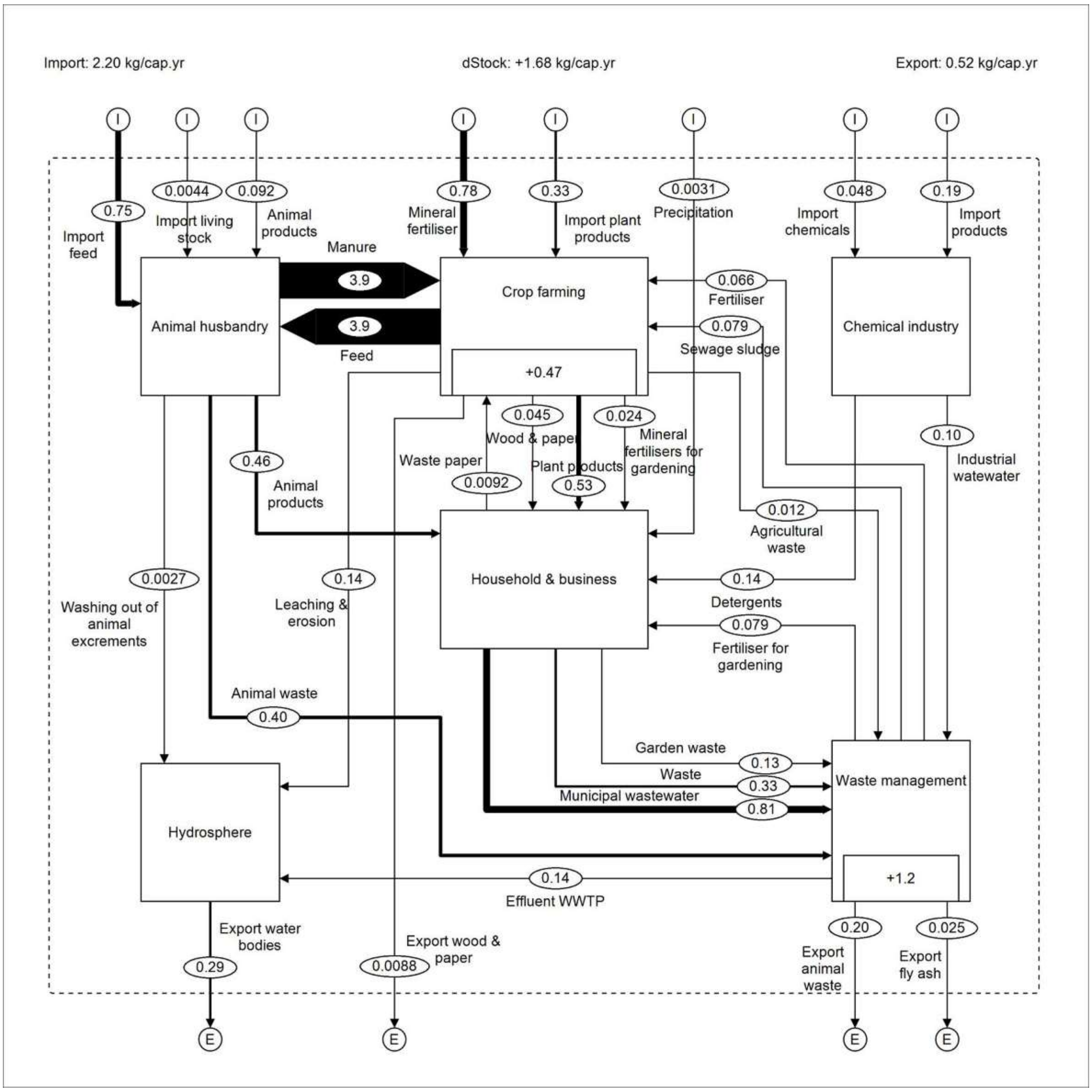


**Figure 3.16:** P balance in Switzerland (modified after Binder et al. 2009)

The illustration in figure 3.17 depicts the waste management sub-system and its sub-processes. It shows that the main P input flows into waste management are carried by municipal and industrial waste water (0.81 kg/cap.yr and 0.1 kg/cap.yr), animal waste

(0.4 kg/cap.yr) and general waste (0.33 kg/cap.yr). Wastewater both from industry and from households are being collected together in the sewerage system and transported to wastewater treatment plants. Most of the phosphorus ends up in some kind of incineration process: 0.33 kg/cap.yr in mono-incineration plants, 0.19 kg/cap.yr in waste incineration plants and 0.17 kg/cap.yr in cement plants. P containing residues from waste and mono-incineration are being subsequently landfilled. Only 0.08 kg/cap.yr of phosphorus are being recycled and applied in agriculture.

Comparing the data given in the figure 3.17 and the data in the diagram in figure 3.15 a discrepancy can be discerned. While the data in figure 3.17 implies that sewage sludge is still being applied in agriculture the data in figure 3.15 suggests that sewage sludge is being incinerated without exception for the last couple of years. However, the investigation period for the MFA by Binder et al. (2009) is set for 2006 where some P recycling to agriculture through sewage sludge still took place (cf. figure 3.15).

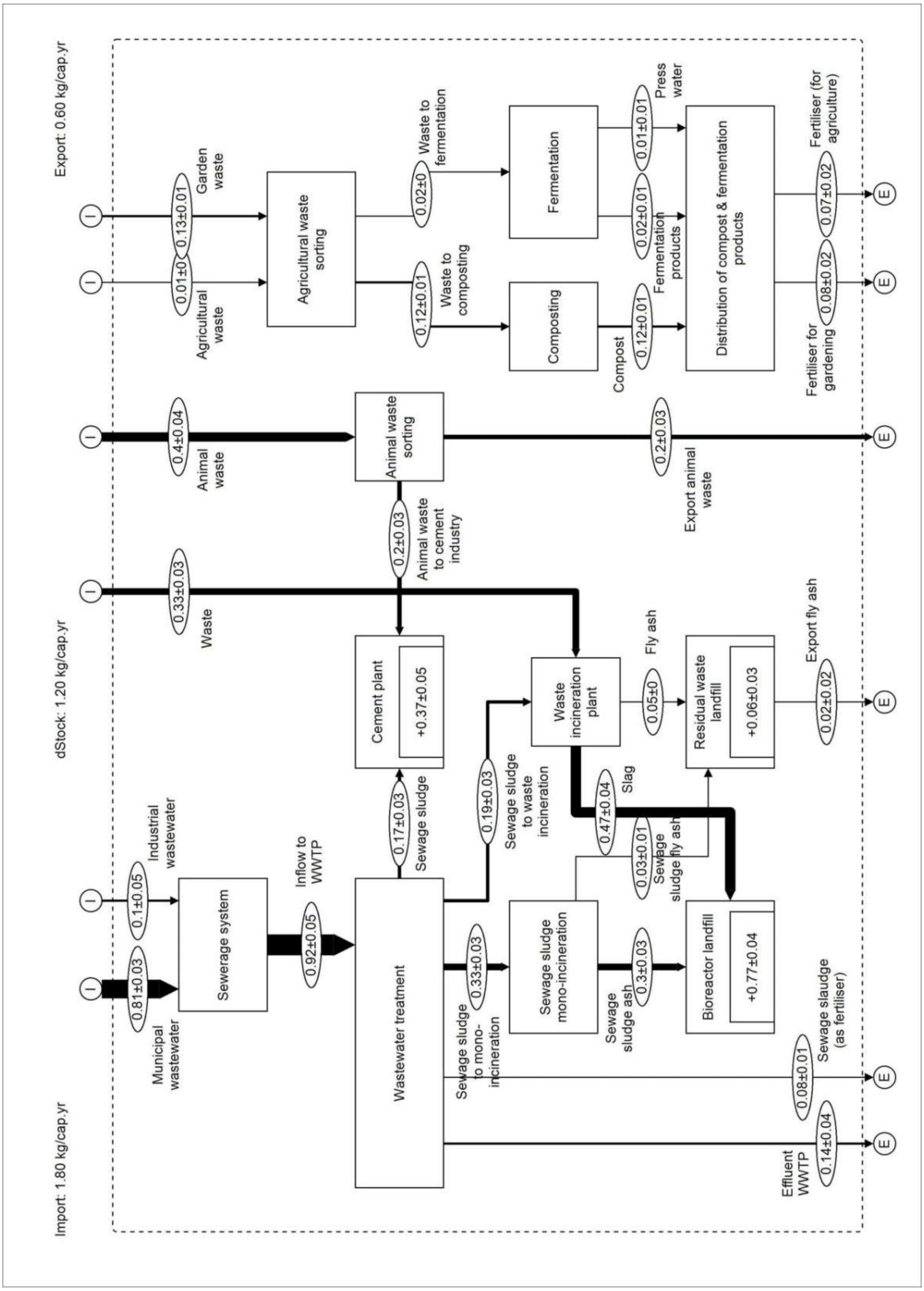


**Figure 3.17:** P balance in Switzerland, Waste management process (modified after Binder et al. 2009)

### 3.6.3 Phosphorus Recovery

**Potential Phosphorus Recovery**

Table 3.6 lists the current and potential P recycling rates in Switzerland. The MFA by Binder et al. (2009) does not distinguish between municipal and industrial sewage sludge. Therefore, no recycling rates related to municipal and industrial sewage sludge can be determined separately. Further, in the MFA by Binder et al. (2009) the agricultural activities are split into two processes: *Animal husbandry* and *Crop farming*. In order to have comparable values for the recycling rates in relation to total P input into agriculture the processes *Animal husbandry* and *Crop farming* will be seen as one. According to the Swiss P balance 0.08 kg/cap.yr of phosphorus out of 0.77 kg/cap.yr (cf. figure 3.17) of total phosphorus in sewage sludge are recycled and applied in agriculture (crop farming) resulting in a current total P recycling rate of 10.4%.

Around 0.78 kg/cap.yr of phosphorus are being applied in agriculture through mineral fertilisers. The total P input into agriculture amounts to 1.71 kg/cap.yr.

The ratio between the amount of recycled phosphorus from sewage sludge to the amount of phosphorus introduced into agriculture through mineral fertilisers equals 10.3%. If all of the phosphorus in sewage sludge were recycled entirely the ratio between recycled phosphorus to phosphorus in mineral fertiliser would rise to 98.7%. Taking into account the total P input into agriculture, fully recovered phosphorus from sewage sludge could supply 45% of total P demand in agriculture (crop farming). If all of the phosphorus in sewage sludge were recycled and applied in agriculture it could cover 88.5% of P demand in agriculture in form of mineral fertilisers.

**Table 3.6:** P recycling rates from sewage sludge in Switzerland

| P recovery from sewage sludge | |
|---|---|
| **P in sewage sludge** | |
| municipal sewage sludge | N/A |
| industrial sewage sludge | N/A |
| total sewage sludge | 0.77 kg/cap.yr |
| **P recycled from sewage sludge** | |
| municipal sewage sludge | N/A |
| industrial sewage sludge | N/A |
| total sewage sludge | 0.08 kg/cap.yr |
| **P input into agriculture** | |
| through (mineral) fertilisers | 0.78 kg/cap.yr |
| total P input | 1.71 kg/cap.yr |
| **Current P recycling rate from sewage sludge** | |
| municipal WWTP | N/A |
| industrial WWTP | N/A |
| total | 10.4% |
| **Current P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 10.3% |
| in relation to total P input | 4.7% |
| **Potential P recycling rate in agriculture** | |
| in relation to total (mineral) fertiliser input | 98.7% |
| in relation to total P input | 45.0% |
| **Potential P substitution** | |
| of (mineral) fertiliser | 88.5% |

### 3.6.4 Strategies

#### Swiss Policy

As already mentioned in chapter 3.6.1 Switzerland has already taken legal measures on P recovery from sewage sludge. The *Ordinance on the Avoidance and the Disposal of Waste* demands phosphor to be recovered from sewage sludge by 2026 (Art. 15 Sec. 1 and Art. 51). However, it does not say how much shall be recovered (Federal Assembly of the Swiss Confederation 2015).

The *Waters Protection Ordinance* rules that the cantons have to conclude a sewage sludge disposal plan which shall be updated at regular intervals (Art. 18 Sec. 1) (Federal Assembly of the Swiss Confederation 1991b). Thus the disposal of sewage sludge is managed at cantonal level. In this thesis the current strategies of Switzerland concerning P recovery from sewage sludge are shown using the examples of sewage sludge disposal plans from the cantons of Zurich and St. Gallen.

#### Canton of Zurich

The cantonal government of Zurich has instructed in 2007 to develop a long-term, ecologically and economically oriented disposal concept for sewage sludge due to expected bottlenecks in capacities of sewage sludge disposal from 2015 onwards. The concept shall not only secure future disposal of sewage sludge but it shall also include strategies of phosphorus recovery in the future. Thus, the concept aims at promoting sustainable use of resources and moving towards a circular economy (Kanton Zürich, n.d.).

Within the framework of the sewage sludge disposal plan of Zurich, it was decided that all the sewage sludge produced in the wastewater treatment plants in the canton of Zurich shall be dewatered on-site and subsequently collected at a central sewage sludge utilisation plant where the dewatered sewage sludge is being incinerated. The sewage sludge ashes are deposited and it is foreseen as soon as a P recovery plant is available in Switzerland to recover phosphorus from the sewage sludge ashes (Kanton Zürich, n.d.).

#### Canton of St. Gallen

The last sewage sludge disposal plan for the canton of St. Gallen was issued in 2012 before the new *Ordinance on the Avoidance and the Disposal of Waste* came into force in 2015. Hence, the disposal plan from St. Gallen does not feature any specific P recovery strategies which shall comply with the prescription to recover phosphorus from sewage sludge laid down in Art. 51 of the ordinance. However, in 2012 the regulation on mandatory P recovery has been already foreshadowed. In the light of this upcoming regulation the sewage sludge disposal plan from 2012 states that the canton of St.Gallen already has sufficient treatment options and capacities for the sewage sludge produced in the canton and that they are sufficient to meet the planned requirements for P recovery. Thus, the disposal plan does not suggest any supplementary measures or strategies for P recovery (Kanton St. Gallen Baudepartement 2013). An updated sewage sludge disposal plan for the canton of St. Gallen has not been issued yet.

The sewage sludge disposal plans from the cantons of Zurich and St. Gallen show that the priority and development concerning P recovery strategies differ on the cantonal level in Switzerland.

As in 2017 Switzerland had no P recovery facilities (Kabbe 2017).

# 4 Comparison

## 4.1 Potentials

In the previous chapters the P balances from Austria, Germany, the Netherlands, Sweden, Switzerland and the EU15 were analysed. The main focus was the examination of phosphorus loads in sewage sludge streams, current and potential P recycling rates and P input into agriculture. At this point, the different results from each country and the EU15 will be compared.

Table 4.1 lists the results on P loads and P recycling rates from each country and the EU15 zone of the previous chapters. At first glance it can be seen that not every parameter could be determined for every country. The reason for missing results is that the national P balances differ with regard to which processes and flows they include. Thus, some MFAs contain more information than others. For instance, only the Dutch and Austrian P balances distinguish between municipal and industrial sewage sludge streams while the MFAs from the other countries combined them to one streams.

The Netherlands has with 0.89 kg/cap.yr the largest P flow through sewage sludge among the analysed countries followed by Austria (0.85 kg/cap.yr). The lowest P load through sewage sludge has Sweden with 0.53 kg/cap.yr. The average P amount in sewage sludge among the five countries is 0.74 kg/cap.yr. Concerning the amount of phosphorus being recycled from sewage sludge meaning not being incinerated and landfilled in average the members of the EU15 zone recycle 0.43 kg/cap.yr. No other of the examined countries recycles more phosphorus per capita and per year. However, all the countries analysed in this thesis except from Switzerland were members of the EU15. All of them recycle lower quantities of phosphorus. Since the EU15 balance contains averaged data form 15 countries it suggests that other countries from the EU15 zone recycle higher amounts of phosphorus so that it increases the average value above the values of the other four countries.

Concerning the P recycling rate from sewage sludge Sweden has the highest recycling rate (64.2%) followed by the EU15 zone with 49.4% and Germany with 28.4%. The Netherlands has comparably very low recycling rates of 3.4%. The low recycling rates in the case of Netherlands can be explained due to their very stringent regulations on direct application of sewage sludge in agriculture and thus very high share of sewage sludge incineration which is is being suggested by the P balance (Smit et al. 2015) and by the data on sewage sludge disposal by Eurostat (cf. figure 3.9, Eurostat 2021c). Switzerland exhibits a current recycling rate of 10.4%. This figure is based on data from 2006 based on the Swiss P balance elaborated by Binder et al. (2009). However, present data suggests that Switzerland does not apply any sewage sludge on agriculture which would mean that the present recycling rate is 0% (cf. figure 3.15, Eurostat 2021e).

The current P recycling rates into agriculture in relation to P input through mineral fertilisers range between 6 and 27%. A high value indicates that either P input into agriculture through mineral fertiliser is very low or that P recycling into agriculture is very high. Sweden has in this respect the highest value (27.2%). Sweden does not feature a particular low P input into agriculture through mineral fertilisers. However, it recycles high amounts of P through sewage sludge application in agriculture and composting.

When looking at the ratio of recycled phosphorus from sewage sludge to total P input into agriculture Sweden has again the highest value (9.3%) followed by the EU15 countries (7%). As mentioned before, due to the fact that Sweden recycles high amounts of phosphorus through agricultural application and composting it also yields the highest current recycling rates.

Table 4.1 also shows large variations among the countries with regard to the potential P recycling rate in relation to P input into agriculture through mineral fertiliser. A high value in this case means that P input into agriculture through mineral fertilisers is rather low while large amounts of P could be potentially recovered. However, even if all of the phosphorus were recovered from sewage sludge in Austria, in Germany and in Sweden, P input through mineral fertilisers would still dominate. The Netherlands and Switzerland on the other hand exhibit rather high values suggesting that recovered phosphorus could eventually substitute mineral fertilisers in agriculture.

The values in the second last row in table 4.1 indicate the ratio of total P recovered to total P input into agriculture. According to the presented results no country could cover total P demand in agriculture through recycled phosphorus from sewage sludge. Analogous to the other P recycling rates in agriculture a higher value means that either P input into agriculture is low or that there are high quantities of phosphorus that can be found in sewage sludge.

In order to know whether recycled phosphorus could eventually cover mineral fertiliser demand, the current P input into agriculture through recycled phosphorus needs to be taken into consideration in the calculation. Assuming that P demand in agriculture does not change the following values on potential substitution of mineral fertiliser listed in the bottom row in table 4.1 result. Only the Netherlands could replace P input into agriculture through mineral fertilisers by recovered phosphorus. All the other countries would still be reliant on the use of mineral P fertilisers. Nevertheless, they differ in to what extent they depend on mineral fertilisers. While Switzerland could substitute up to 88.5% of fertiliser use while Germany could only cover 26.7% of mineral fertiliser application through recovered phosphorus.

**Table 4.1:** P recycling rates, comparison

| **P recovery from sewage sludge** | | EU15 | Austria AT | Germany DE | Netherlands NL | Sweden SE | Switzerland CH | Ø |
|---|---|---|---|---|---|---|---|---|
| **P in sewage sludge** | | | | | | | | |
| municipal sewage sludge | [kg/cap.yr] | N/A | 0.80 | N/A | 0.65 | N/A | N/A | 0.73 |
| industrial sewage sludge | [kg/cap.yr] | N/A | 0.05 | N/A | 0.24 | N/A | N/A | 0.15 |
| total sewage sludge | [kg/cap.yr] | 0.87 | 0.85 | 0.67 | 0.89 | 0.53 | 0.77 | 0.74 |
| **P recycled from sewage sludge** | | | | | | | | |
| municipal sewage sludge | [kg/cap.yr] | N/A | 0.12 | N/A | 0.0 | N/A | N/A | 0.06 |
| industrial sewage sludge | [kg/cap.yr] | N/A | 0.0 | N/A | 0.03 | N/A | N/A | 0.02 |
| total sewage sludge | [kg/cap.yr] | 0.43 | 0.12 | 0.19 | 0.03 | 0.34 | 0.08 | 0.15 |
| **P input into agriculture** | | | | | | | | |
| through (mineral) fertilisers | [kg/cap.yr] | 2.70 | 1.95 | 1.80 | 0.42 | 1.25 | 0.78 | 1.24 |
| total P input | [kg/cap.yr] | 6.18 | 3.49 | 4.26 | 5.08 | 3.67 | 1.71 | 3.64 |
| **Current P recycling rate from sewage sludge** | | | | | | | | |
| municipal WWTP | [%] | N/A | 15.0 | N/A | 0.0 | N/A | N/A | 7.5 |
| industrial WWTP | [%] | N/A | 0.0 | N/A | 12.5 | N/A | N/A | 6.3 |
| total | [%] | 49.4 | 14.1 | 28.4 | 3.4 | 64.2 | 10.4 | 24.1 |
| **Current P recycling rate in agriculture** | | | | | | | | |
| in relation to total (mineral) fertiliser input | [%] | 15.9 | 6.2 | 10.6 | 7.1 | 27.2 | 10.3 | 12.3 |
| in relation to total P input | [%] | 7.0 | 3.4 | 4.5 | 0.6 | 9.3 | 4.7 | 4.5 |
| **Potential P recycling rate in agriculture** | | | | | | | | |
| in relation to total (mineral) fertiliser input | [%] | 32.2 | 43.6 | 37.2 | 211.9 | 42.4 | 98.7 | 86.8 |
| in relation to total P input | [%] | 14.1 | 24.4 | 15.7 | 17.5 | 14.4 | 45.0 | 22.4 |
| **Potential P substitution** | | | | | | | | |
| of (mineral) fertiliser | [%] | 16.3 | 37.4 | 26.7 | 204.8 | 40.0 | 88.5 | 79.0 |

In the following the main statements related to general findings of the analysis of P balances are summarised:

- The P balances from the different countries differ in the information they convey. In addition to that they were performed for different time periods. Thus, they have to be compared carefully.
- Due to incomplete data or process descriptions the MFAs are prone to uncertainties which demands to look at the P balances with caution.

Concerning the the examination and comparison of P balances and national potentials on P recovery the following conclusions can be made:

- Only Austria and the Netherlands differ between P loads in municipal and industrial sewage sludge streams.
- Austria has, compared to the other countries, high quantities of phosphorus in sewage sludge. Austria is the country which has the highest P input into agriculture through mineral fertilisers resulting in low current P recycling rates (in relation to P input through mineral fertilisers). Further, Austria does not exhibit notably high potential P recycling rates or potential P substitution through recovered phosphorus.
- Germany has a relative high P input into agriculture through mineral fertilisers compared to the other countries. The amounts of phosphorus being transported by sewage sludge are average. Therefore, Germany exhibits rather low potential P recycling rates in case of total P recovery from sewage sludge. Further, Germany exhibits the lowest potential P substitution through recovered phosphorus given the fact that Germany has a high total P input into agriculture.
- The amounts of phosphorus transported by sewage sludge are above the average in the Netherlands while P input into agriculture through mineral fertilisers is beneath the average. Thus, the Netherlands exhibits high potential P recycling rates. Further, the Netherlands could substitute P input into agriculture through mineral fertilisers by recovered phosphorus (if all of the phosphorus in sewage sludge were recovered).
- Among the examined countries, Sweden produces the least phosphorus in sewage sludge per capita and year. Hence, Sweden features rather low potential P recycling rates. If all of the phosphorus in sewage sludge were recovered and applied in agriculture Sweden would still be reliant on mineral fertilisers.
- Total P input and P input through mineral fertilisers into agriculture in Switzerland are very small compared to the other countries. However, the amounts of phosphorus in sewage sludge are average. Therefore, Switzerland could potentially cover entirely P demand in agriculture through mineral fertiliser by recovered phosphorus from sewage sludge.

## 4.2 Policy and Strategies

The matrix in table 4.2 gives an overview which policy is being pursued by the different countries. There is no ban on sewage sludge application in agriculture in the European Union, Austria, the Netherlands and Sweden. Only Switzerland and Germany implicitly prohibit the spreading of sewage sludge by demanding phosphorus to be incinerated (cf. Federal Assembly of the Swiss Confederation 2015) or recovered (cf. BMU 2017a, BMU 2017b). In the case of Austria even though there is no prohibition of using sewage sludge in agriculture on the national level the Austrian Länder may rule against such activities on a regional level (Tyrolean Regional Government 2000, Vienna State Parliament 2000). The Netherlands do not prohibit sewage sludge spreading either but they set certain conditions for the use of sewage sludge in agriculture (Rijksoverheid 2021). However, data on sewage sludge disposal in the Netherlands (cf. figure 3.9) suggest that the regulations are so stringent that sewage sludge is actually not being applied in agriculture.

Switzerland and Germany are the only of the examined countries that have regulations concerning the recovery of phosphorus from sewage sludge. Switzerland rules that from 2026 on phosphorus shall be recovered however it does not give any indications how much or up to which percentage phosphorus shall be recovered (Federal Assembly of the Swiss Confederation 2015). German legislation does set requirements when phosphorus has to be recovered. However, those requirements are related to actual P concentrations in sewage sludge and to the size of the WWTPs but they do not set a specific target on which percentage shall be recovered (BMU 2017a, BMU 2017b).

All the countries acknowledge the importance of phosphorus as scarce resource and essential nutrient so that various strategies and commitment plans where issued. Austria, like all the other countries, aims at moving towards a circular economy and thus pursues the implementation of P recovery technology in WWTPs. It sets the target of recovering between 65 and 85% of the phosphorus in sewage sludge by 2030 (BMNT 2017, 260). Germany and the Netherlands pursue similar approaches. However, they do not determine how much phosphorus they intend to recover in future. Nevertheless they are the only countries that have already implemented P recovery in some WWTPs (Kabbe 2017). In Sweden the Environmental Protection Agency suggested in 2013 to recycle at least 40% of the phosphorus from waste (including sewage sludge) (Naturvårdsverket 2013). The final report of an governmental inquiry on sustainable sewage sludge management in Sweden proposes to recover 60% of phosphorus in the following 12 to 15 years from 2020 on (Naturvårdsverket 2013). However, no information could be found whether phosphorus is being already recovered in a large-scale in Sweden. Data from 2017 however suggest that Sweden does not have P recovery installations (Kabbe 2017). In Switzerland the pursuits for P management take place on a cantonal level. The canton of Zurich has already developed a strategy of incinerating all the sewage sludge produced in the canton of Zurich in a central incineration plan and store the ashes in deposits until there is a P recovery plant for sewage sludge ashes in Switzerland (Kanton Zürich, n.d.). Compared to Zurich the canton of St. Gallen for example has not elaborated yet a comparable strategy on P management (Kanton St. Gallen Baudepartement 2013). The European Union also recognises the importance of phosphorus in EU industry and thus has put phosphate rock on its list of critical raw materials (European Commission 2020b). However, no regulation has been put forth yet on the EU level to recover phosphorus from sewage sludge.

The Netherlands and Germany seem to be the most advanced countries concerning P recovery since they are the only countries examined in this thesis that have installed P recovery plants as in 2017 (Kabbe 2017). In both countries the incineration of sewage sludge is by far the dominant form of sewage sludge disposal and the application of sewage sludge on agricultural land is either (implicitly) forbidden or not practised. Hence, they may have a particular eager interest or strong incentive to recycle phosphorus and somehow reintroduce it into the economy. Further, in those countries there are endeavours to bring together stakeholders involved or related to P management and thus networks have been created so that those stakeholders may interact with each other and jointly work on solutions (Deutsche Phosphor-Plattform, n.d. Nutrient Platform, n.d.(a)).

**Table 4.2:** Policy on P recovery, comparison

| **Policy** | EU | AT | DE | NL | SE | CH |
|---|---|---|---|---|---|---|
| Prohibition on sewage sludge application in agriculture | no | no[a] | yes [b] | no | no | yes[c] |
| Law on P recovery | no | no | yes | no | no | yes |
| Definition of targets | – | – | no | – | – | no |
| Governmental commitments | yes | yes | yes | yes | yes | yes |
| Definition of targets | no | yes | no | no | yes | no |

[a] The prohibition of sewage sludge application on agricultural is not regulated on the national level but on the level of the *Länder*.
[b] German legislation demands sewage sludge to be recovered thus implying that sewage sludge shall not be applied in agriculture.
[c] Swiss legislation demands sewage sludge to be incinerated thus implying that sewage sludge shall not be applied in agriculture.

## 4.3 Limitations

The calculated recycling rates for each country only represent theoretical values explaining to which extent recycled phosphorus from sewage sludge could substitute mineral fertilisers. However, actual P recovery rates from sewage sludge depend on the P recovery technology applied and the incentives to actually recover phosphorus which are being influenced by costs and environmental impacts caused by P recovery processing.

### 4.3.1 Technical Feasibility

As already mentioned in chapter 1.2 there exists a wide range of technological approaches of recovering phosphorus from raw or digested sewage sludge or from sewage sludge ashes. They differ in their complexity and their performance with regard to their efficiency in recovering phosphorus.

P recovery technologies for raw or digested sewage sludge are mainly implemented directly at the wastewater treatment plants whereas installations for sewage sludge incineration and subsequent P recovery from the ashes can be centralised and supplied by several WWTPs (Egle et al. 2015). This fact suggests that the question which P recovery shall be implemented depends among many other reasons from the size, location and distribution of the wastewater treatment plants. One may suppose that small WWTPs at remote places may be, if at all, not suitable for the implementation of a P recovery facility whereas large WWTPs in areas of high population density may be suitable for the implementation of P recovery technologies. The canton of Zurich for instance pursues the method of collecting sewage sludge from the WWTPs in its canton centralised at one place, incinerate it, store it and in future recover the phosphorus from the ashes (Kanton Zürich, n.d.). It would need to be examined whether the approach from the canton of Zurich is applicable to other regions in other countries. However, Montag et al. (2015) suggest that there is no ideal P recovery method and thus they propose in the UBA report that regulations should not commit to a particular P recovery technology. This might be one of the reasons why phosphorus is not being recovered yet on a large scale in any of these countries.

### 4.3.2 Monetary Costs and Environmental Impacts

Another aspect besides technical feasibility involves the additional costs and possible negative environmental impacts (that can be expressed in monetary terms) caused by the implementation of P recovery technologies. There are several reports approaching the assessment of costs incurred by the implementation of P recovery technologies and comparing them with the costs of mining and processing phosphate rock (Montag et al. 2015, Nättorp and Remmen 2015, Roskosch and Heidecke 2018, Kraus et al. 2019).

## 5 Conclusion and Outlook

Phosphorus is an essential nutrient for life. Its main application is in agriculture which allows to have higher yields and to feed growing populations. However, phosphorus is considered a scarce and naturally non-renewable resource.

Austria, Germany, the Netherlands, Sweden and Switzerland acknowledge the importance of phosphorus and recognise the significance of managing phosphorus on a sustainable way. When looking at the P balances of each of these countries a similar pattern in P management can be discerned. Besides from food and feed imports, every country is more or less reliant on P imports in the form of mineral fertilisers which are being applied in agriculture. The P containing products from agriculture are being subsequently consumed and eventually end up in waste streams such as sewage sludge. Currently only a small proportion of phosphorus is being recycled from waste while the bulk of the phosphorus found in waste is being lost either to landfills or to the hydrosphere. Although the five examined countries currently manage phosphorus at a similar way there are slight differences that can be discerned.

Some countries recycle phosphorus by applying sewage sludge in agriculture while others do not. The reason why some countries do not spread sewage sludge on arable land is because either they have very stringent regulations which render this form of P recycling nearly impossible (e.g. the Netherlands) or they even implicitly prohibit sewage sludge reuse in agriculture (e.g. Switzerland). However, in all of the examined countries there is an awareness of the possible negative side-effects of using sewage sludge in agriculture. Even in the countries where spreading of sewage sludge is being practised there are endeavours of refraining from such practices and find other forms of P recycling.

Further, when looking at how much phosphorus could be theoretically recycled and substitute phosphorus from mineral fertilisers some differences between the five countries can be noticed. While the study of the P balance in the Netherlands suggests that recycled phosphorus from sewage sludge could entirely substitute P demand in agriculture through mineral fertilisers, the P balances in Austria, Germany, Sweden and Switzerland suggest that these countries would continue to rely on P imports in form of mineral fertilisers. However, the question of the degree to which mineral fertilisers can be dispensed not only depends on whether phosphorus is being recycled (or recovered) from sewage sludge but on how phosphorus is being managed in all the sectors.

All of the five countries endeavour to move towards sustainable P management including the recovery of phosphorus from sewage sludge. However, they differ in their states of development and their approaches towards this goal. Germany and Switzerland have already made it legally binding to recover phosphorus from sewage sludge and they have already either implemented or are planning P recovery facilities. Although Dutch law does not demand to recover phosphorus from sewage sludge in the Netherlands there are already some P recovery plants. However, phosphorus is not being recovered in a large scale yet. What these three countries have in common is that they do not apply sewage sludge in agriculture which might particularly incentivise them to implement P recovery technologies. However, neither the Swiss nor the German regulations on P recovery lay down how much phosphorus has to be recovered. Sweden and Austria do not have laws on P recovery but in these countries there exist governmental and political commitments towards P recovery and they have even laid down targets on how much phosphorus they intend to recover in future.

Progresses in the implementation of P recovery technologies do not only depend on political will. Even though the calculations in this thesis suggest that if all of the phosphorus were recovered from sewage sludge in order to substitute phosphorus demand through mineral fertilisers there are still some limitations to be expected. Those limitations may be that there is no technology on the market that can fully recover phosphorus from sewage sludge and that P recovery incurs high costs. Further, there is the question if P recovery can be reasonably implemented everywhere or if there are any limitations concerning the size and the location of wastewater treatment plants or the properties of certain sewage sludges.

Nevertheless, current endeavours look very promising of attaining the goal of a sustainable P management.

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## List of Tables

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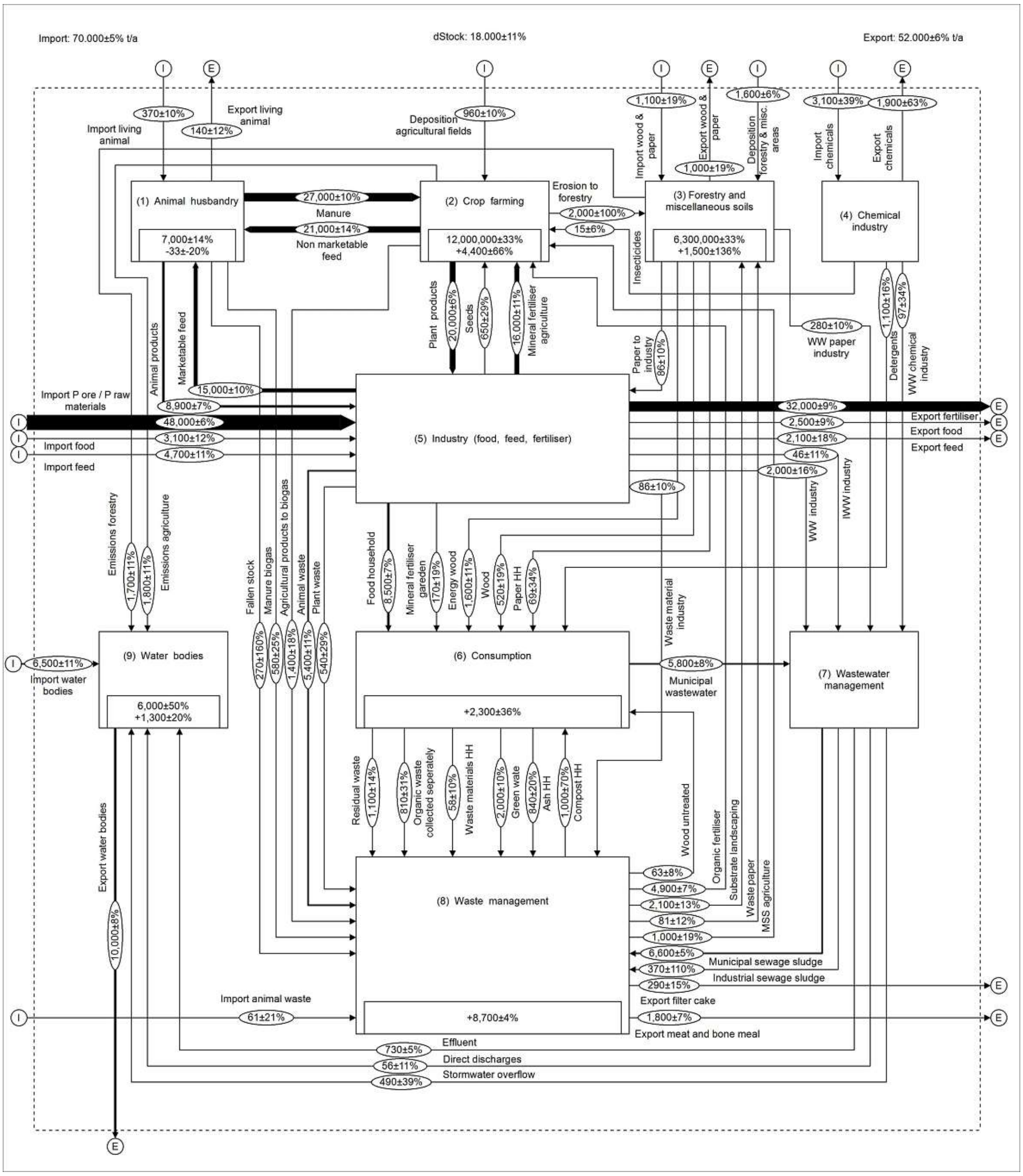
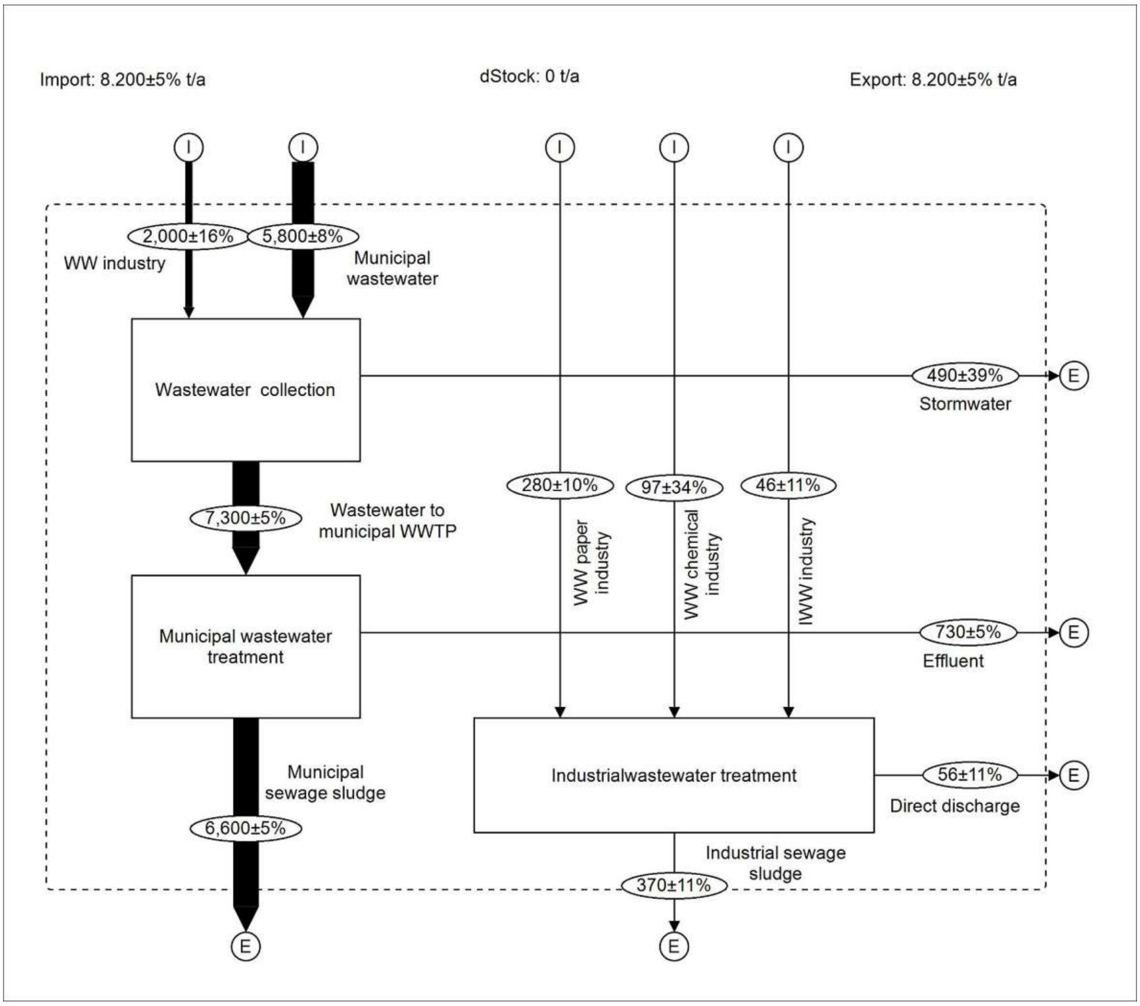
# Annex

## Annex I

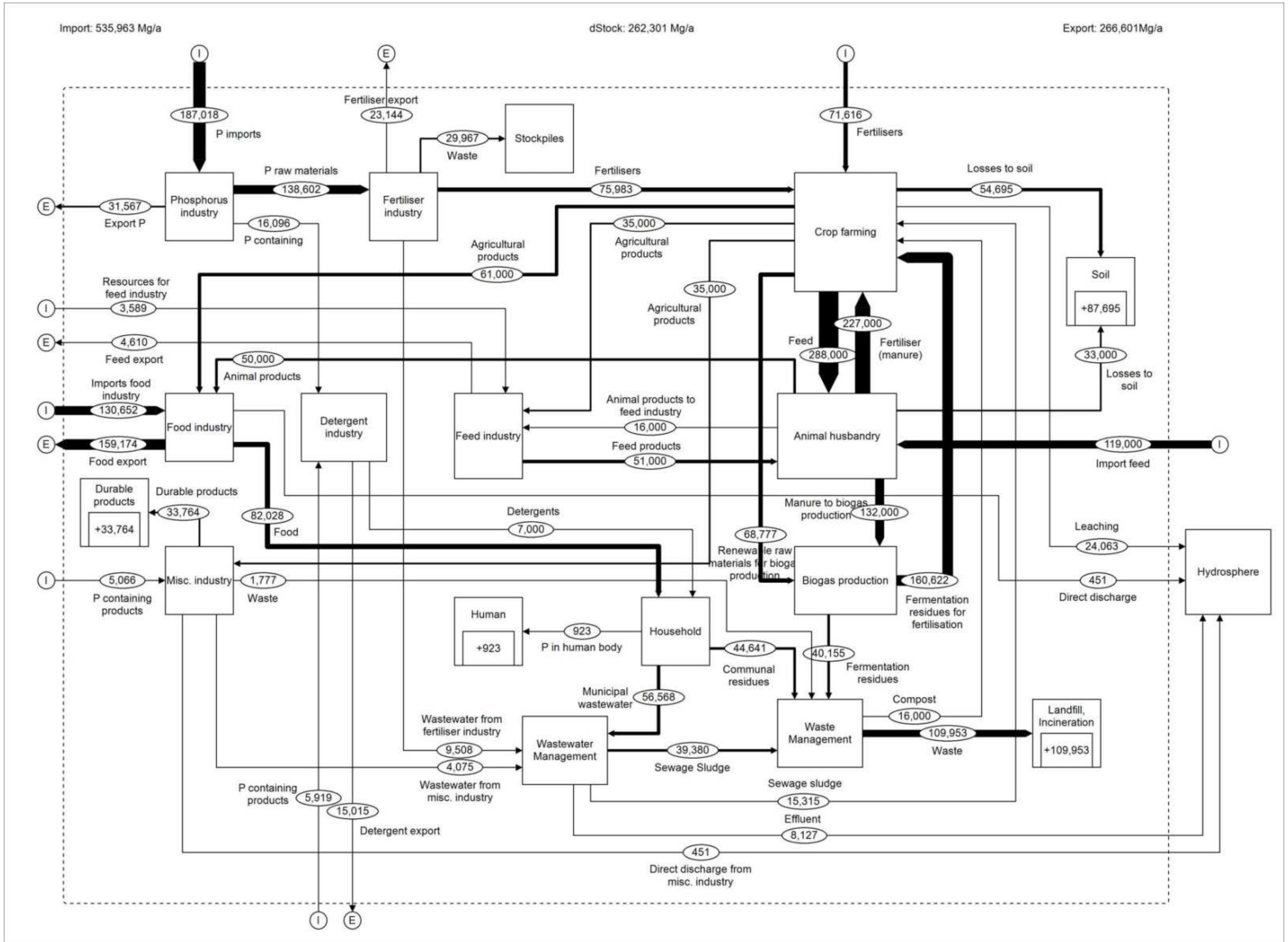
The following pages show the Austrian P balance and its wastewater management subsystem with the original stock and flow values (i.e. not related size of the Austrian population) and uncertainties by Egle et al. (2014).

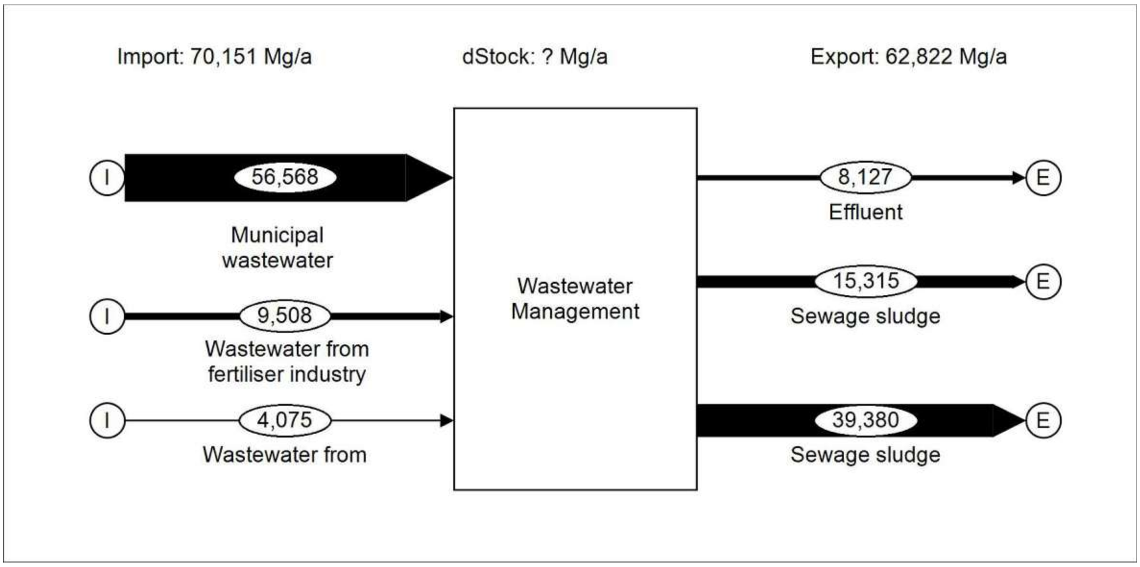

Import: 70.000±5% t/a
dStock: 18.000±11%
Export: 52.000±6% t/a
(1) Animal husbandry
7,000±14%
-33±-20%
(2) Crop farming
12,000,000±33%
+4,400±66%
(3) Forestry and miscellaneous soils
6,300,000±33%
+1,500±136%
(4) Chemical industry
(5) Industry (food, feed, fertiliser)
(6) Consumption
+2,300±36%
(7) Wastewater management
(8) Waste management
+8,700±4%
(9) Water bodies
6,000±50%
+1,300±20%
Import living animal
370±10%
Export living animal
140±12%
Deposition agricultural fields
960±10%
Import wood & paper
1,100±19%
Export wood & paper
1,000±19%
Deposition forestry & misc areas
1,600±6%
Import chemicals
3,100±39%
Export chemicals
1,900±63%
27,000±10%
Manure
21,000±14%
Non marketable feed
Erosion to forestry
2,000±100%
15±6%
Insecticides
Plant products
20,000±6%
Seeds
650±29%
16,000±11%
Mineral fertiliser agriculture
Animal products
Marketable feed
15,000±10%
8,900±7%
Import P ore / P raw materials
48,000±6%
Import food
3,100±12%
Import feed
4,700±11%
Paper to industry
86±10%
280±10%
WW paper industry
Detergents
1,100±16%
WW chemical industry
97±34%
32,000±9%
Export fertiliser
2,500±9%
Export food
2,100±18%
Export feed
46±11%
2,000±16%
86±10%
WW industry
IWW industry
Emissions forestry
1,700±11%
1,800±11%
Emissions agriculture
Fallen stock
270±160%
Manure biogas
580±25%
Agricultural products to biogas
1,400±18%
Animal waste
5,400±11%
Plant waste
540±29%
Food household
8,500±7%
Mineral fertiliser gareden
170±19%
Energy wood
1,600±11%
Wood
520±19%
Paper HH
69±34%
Waste material industry
Import water bodies
6,500±11%
5,800±8%
Municipal wastewater
Residual waste
1,100±14%
810±31%
Organic waste collected seperately
58±10%
Waste materials HH
2,000±10%
Green wate
840±20%
Ash HH
1,000±70%
Compost HH
Wood untreated
Organic fertiliser
Substrate landscaping
Waste paper
MSS agriculture
63±8%
4,900±7%
2,100±13%
81±12%
1,000±19%
6,600±5%
Municipal sewage sludge
370±110%
Industrial sewage sludge
290±15%
Export filter cake
Import animal waste
61±21%
1,800±7%
Export meat and bone meal
Export water bodies
10,000±8%
730±5%
Effluent
56±11%
Direct discharges
490±39%
Stormwater overflow


Import: 8.200±5% t/a
dStock: 0 t/a
Export: 8.200±5% t/a
I
2,000±16%
WW industry
5,800±8%
Municipal wastewater
Wastewater collection
490±39%
Stormwater
E
7,300±5%
Wastewater to municipal WWTP
280±10%
97±34%
46±11%
WW paper industry
WW chemical industry
IWW industry
Municipal wastewater treatment
730±5%
Effluent
Industrialwastewater treatment
56±11%
Direct discharge
Municipal sewage sludge
6,600±5%
Industrial sewage sludge
370±11%

**Annex II**

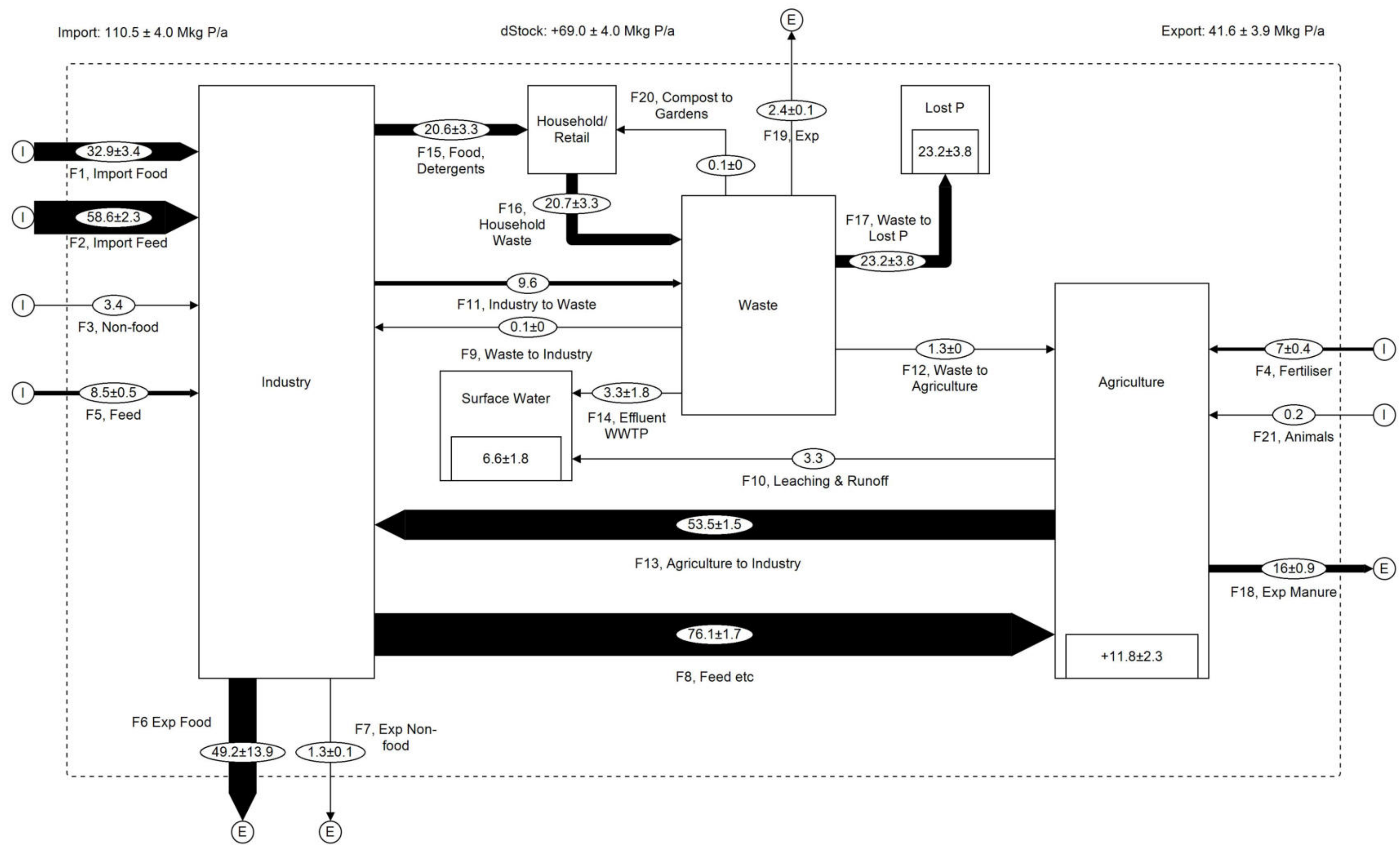
The following pages show the German P balance and its wastewater management subsystem with the original stock and flow values (i.e. not related size of the German population) and uncertainties by Gethke-Albinus (2012).

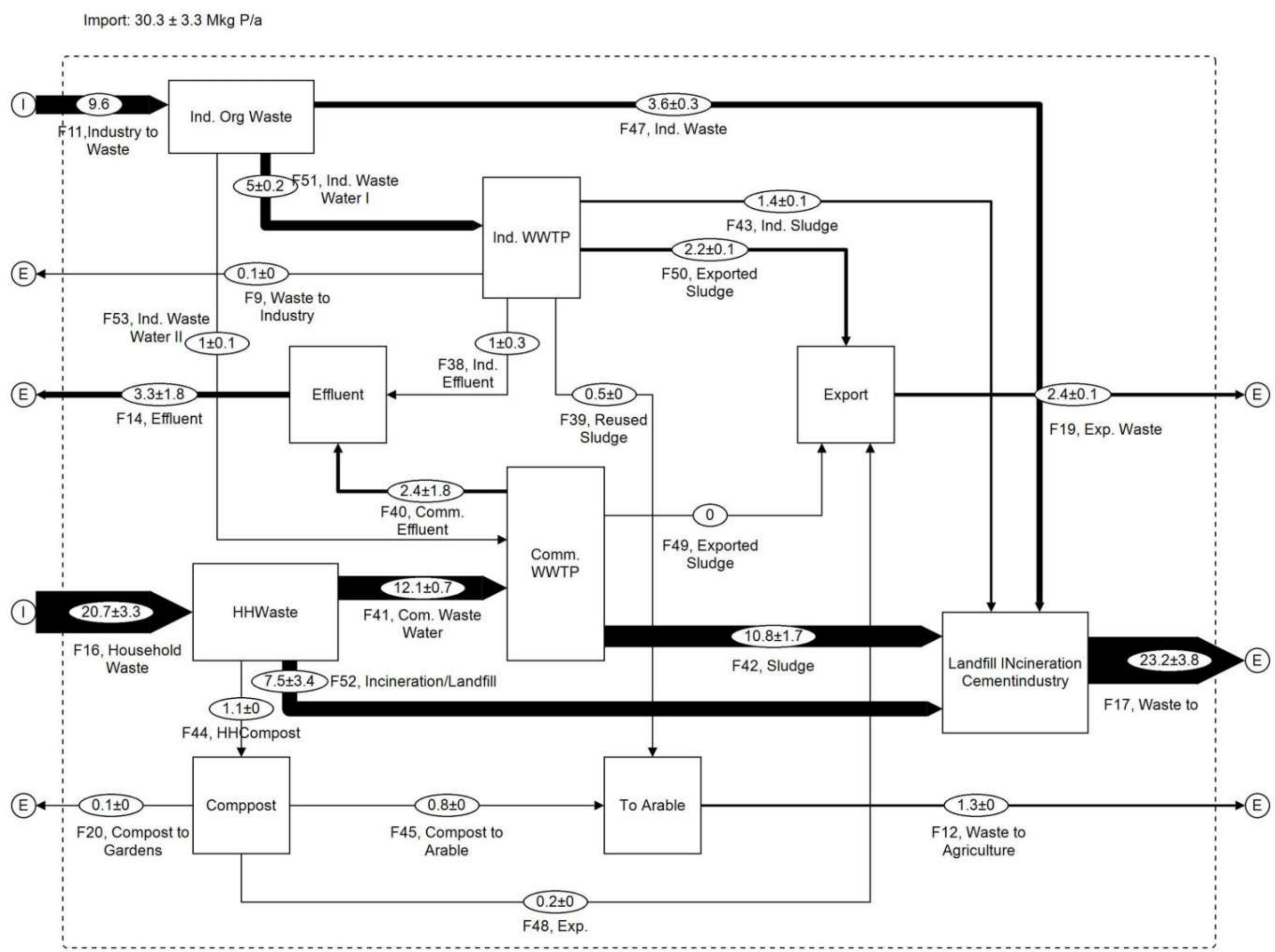

Import: 535,963 Mg/a
dStock: 262,301 Mg/a
Export: 266,601Mg/a
187,018
P imports
Phosphorus industry
31,567
Export P
P raw materials
138,602
16,096
P containing
Fertiliser export
23,144
Fertiliser industry
29,967
Waste
Stockpiles
Fertilisers
75,983
71,616
Fertilisers
Crop farming
Losses to soil
54,695
Soil
+87,695
33,000
Losses to soil
Agricultural products
61,000
35,000
Agricultural products
35,000
Agricultural products
Resources for feed industry
3,589
4,610
Feed export
50,000
Animal products
Imports food industry
130,652
Food industry
159,174
Food export
Detergent industry
Feed industry
Animal products to feed industry
16,000
Feed products
51,000
Feed
288,000
227,000
Fertiliser (manure)
Animal husbandry
119,000
Import feed
Durable products
+33,764
Durable products
33,764
82,028
Food
Detergents
7,000
Manure to biogas production
132,000
68,777
Renewable raw materials for biogas production
Leaching
24,063
Hydrosphere
5,066
P containing products
Misc. industry
1,777
Waste
Biogas production
160,622
Fermentation residues for fertilisation
451
Direct discharge
Human
+923
923
P in human body
Household
44,641
Communal residues
40,155
Fermentation residues
Municipal wastewater
56,568
Compost
16,000
Landfill, Incineration
+109,953
Wastewater from fertiliser industry
9,508
Wastewater Management
39,380
Sewage Sludge
Waste Management
109,953
Waste
4,075
Wastewater from misc. industry
P containing products
5,919
15,015
Detergent export
Sewage sludge
15,315
Effluent
8,127
451
Direct discharge from misc. industry


Import: 70,151 Mg/a
dStock: ? Mg/a
Export: 62,822 Mg/a
56,568
Municipal wastewater
9,508
Wastewater from fertiliser industry
4,075
Wastewater from
Wastewater Management
8,127
Effluent
15,315
Sewage sludge
39,380
Sewage sludge

## Annex III

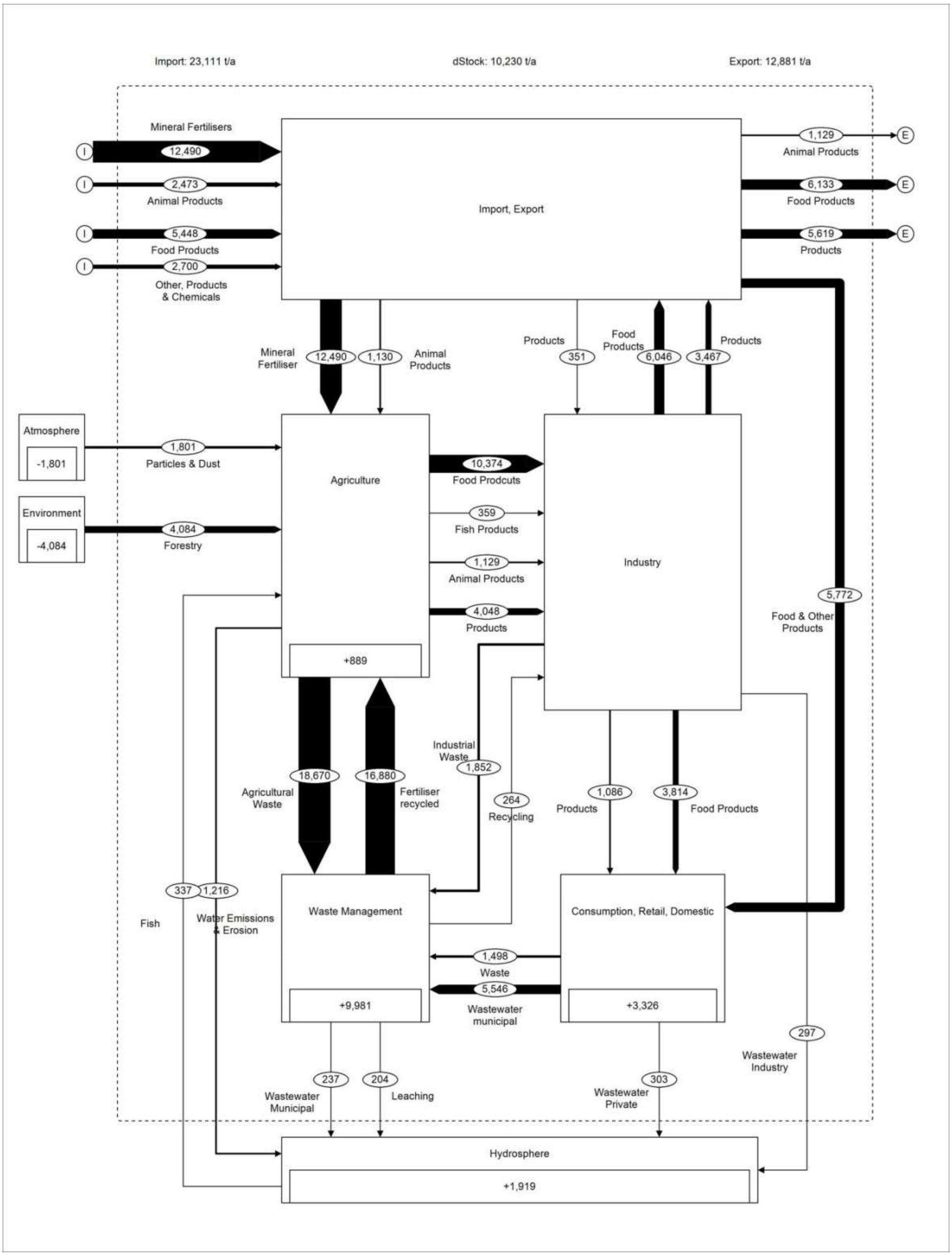
The following pages show the Dutch P balance and its waste management sub-system with the original stock and flow values (i.e. not related size of the Dutch population) and uncertainties by Smit et al. (2015).

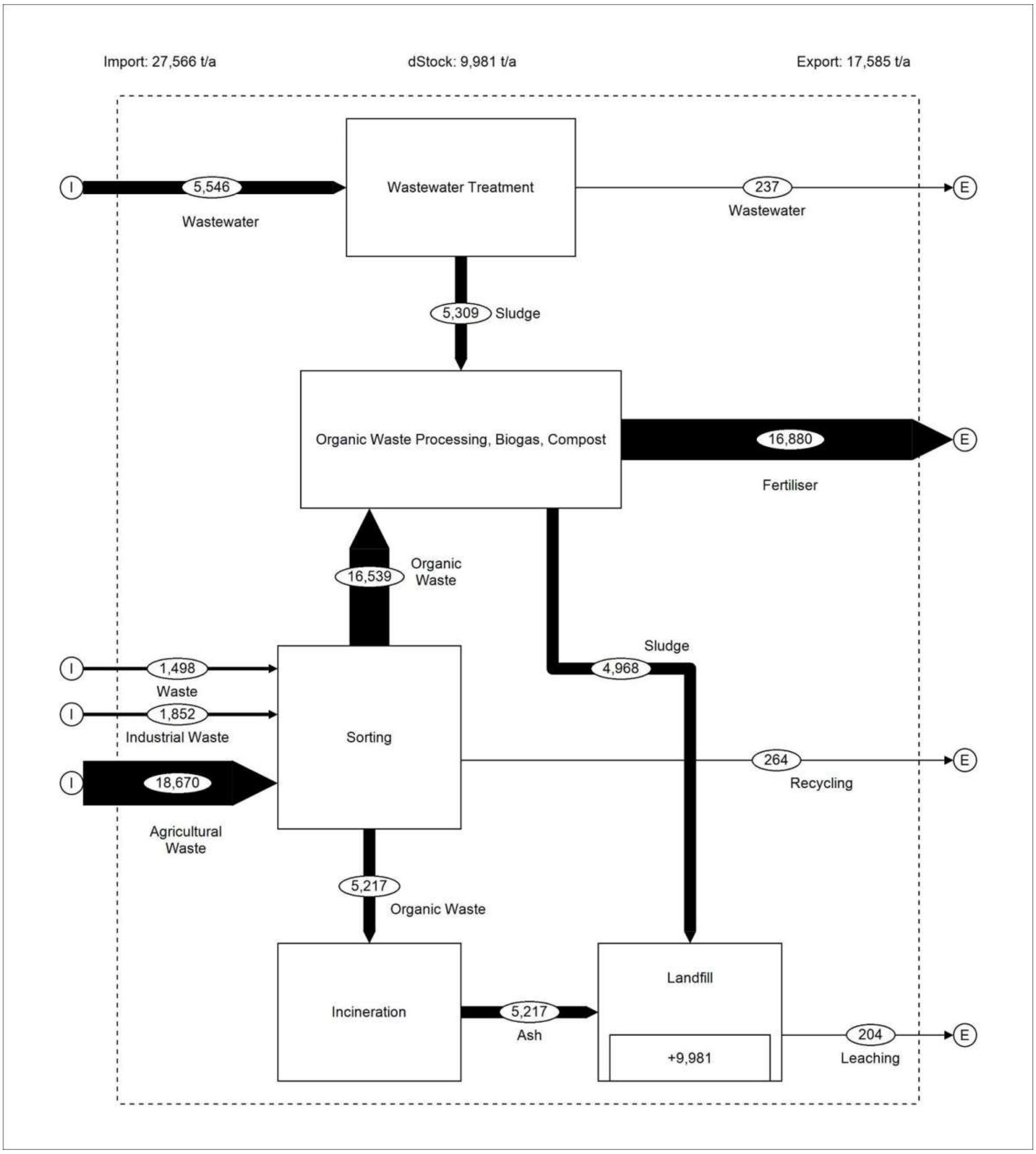

Import: 110.5 ± 4.0 Mkg P/a
dStock: +69.0 ± 4.0 Mkg P/a
Export: 41.6 ± 3.9 Mkg P/a
32.9±3.4
F1, Import Food
58.6±2.3
F2, Import Feed
3.4
F3, Non-food
8.5±0.5
F5, Feed
Industry
20.6±3.3
F15, Food, Detergents
Household/ Retail
F20, Compost to Gardens
0.1±0
2.4±0.1
F19, Exp
Lost P
23.2±3.8
F16, Household Waste
20.7±3.3
F17, Waste to Lost P
23.2±3.8
9.6
F11, Industry to Waste
0.1±0
F9, Waste to Industry
Waste
1.3±0
F12, Waste to Agriculture
Surface Water
6.6±1.8
3.3±1.8
F14, Effluent WWTP
3.3
F10, Leaching & Runoff
Agriculture
7±0.4
F4, Fertiliser
0.2
F21, Animals
53.5±1.5
F13, Agriculture to Industry
16±0.9
F18, Exp Manure
76.1±1.7
F8, Feed etc
+11.8±2.3
F6 Exp Food
49.2±13.9
1.3±0.1
F7, Exp Non-food


Import: 30.3 ± 3.3 Mkg P/a
Ind. Org Waste
9.6
F11,Industry to Waste
3.6±0.3
F47, Ind. Waste
5±0.2
F51, Ind. Waste Water I
Ind. WWTP
1.4±0.1
F43, Ind. Sludge
2.2±0.1
F50, Exported Sludge
0.1±0
F9, Waste to Industry
F53, Ind. Waste Water II
1±0.1
1±0.3
F38, Ind. Effluent
Effluent
3.3±1.8
F14, Effluent
0.5±0
F39, Reused Sludge
Export
2.4±0.1
F19, Exp. Waste
2.4±1.8
F40, Comm. Effluent
Comm. WWTP
0
F49, Exported Sludge
HHWaste
20.7±3.3
F16, Household Waste
12.1±0.7
F41, Com. Waste Water
10.8±1.7
F42, Sludge
Landfill INcineration Cementindustry
23.2±3.8
F17, Waste to
7.5±3.4
F52, Incineration/Landfill
1.1±0
F44, HHCompost
Comppost
0.1±0
F20, Compost to Gardens
0.8±0
F45, Compost to Arable
To Arable
1.3±0
F12, Waste to Agriculture
0.2±0
F48, Exp.
I
E

## Annex IV

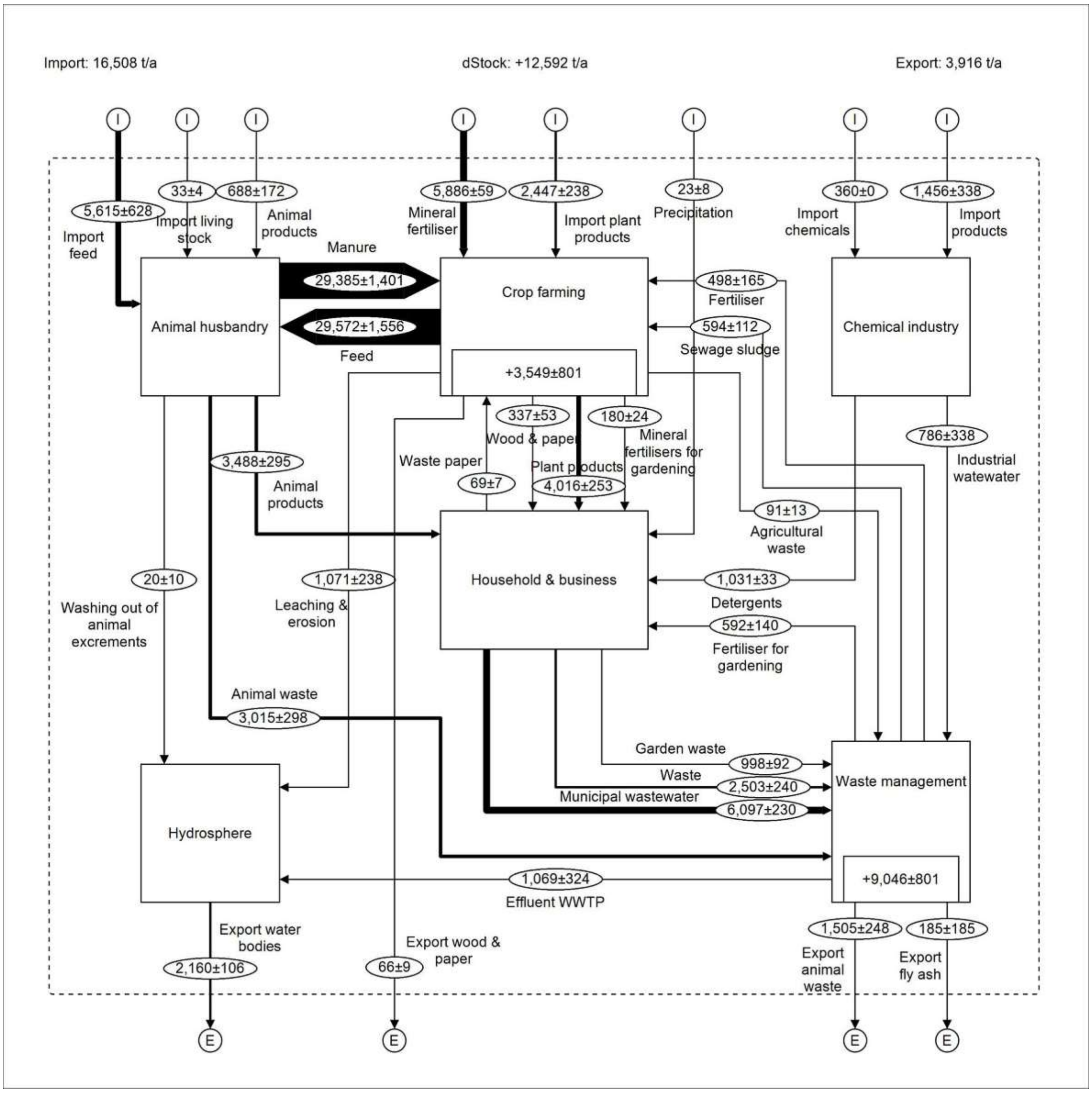
The following pages show the Swedish P balance and its waste management sub-system with the original stock and flow values (i.e. not related size of the Swedish population) and uncertainties by Wikberg (2019).

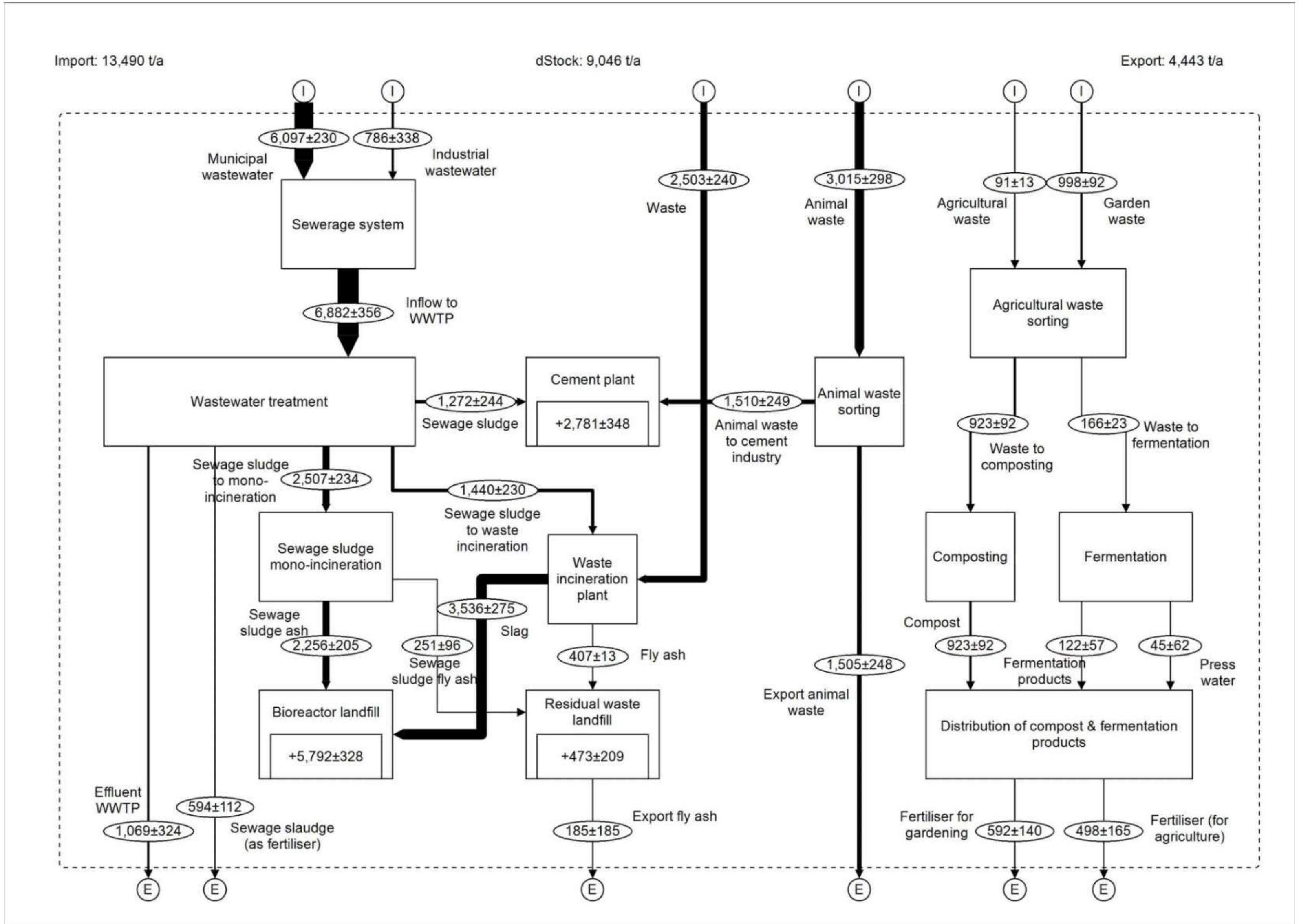

Import: 23,111 t/a
dStock: 10,230 t/a
Export: 12,881 t/a
Mineral Fertilisers
12,490
2,473
Animal Products
5,448
Food Products
2,700
Other, Products & Chemicals
Import, Export
1,129
Animal Products
6,133
Food Products
5,619
Products
Mineral Fertiliser
12,490
1,130
Animal Products
Products
351
Food Products
6,046
3,467
Products
Atmosphere
-1,801
1,801
Particles & Dust
Environment
-4,084
4,084
Forestry
Agriculture
10,374
Food Prodcuts
359
Fish Products
1,129
Animal Products
4,048
Products
+889
Industry
5,772
Food & Other Products
Industrial Waste
1,852
18,670
Agricultural Waste
16,880
Fertiliser recycled
264
Recycling
1,086
Products
3,814
Food Products
337
1,216
Fish
Water Emissions & Erosion
Waste Management
+9,981
Consumption, Retail, Domestic
+3,326
1,498
Waste
5,546
Wastewater municipal
297
Wastewater Industry
237
Wastewater Municipal
204
Leaching
303
Wastewater Private
Hydrosphere
+1,919


Import: 27,566 t/a
dStock: 9,981 t/a
Export: 17,585 t/a
Wastewater Treatment
5,546
Wastewater
237
Wastewater
5,309 Sludge
Organic Waste Processing, Biogas, Compost
16,880
Fertiliser
16,539
Organic Waste
Sludge
4,968
1,498
Waste
1,852
Industrial Waste
Sorting
264
Recycling
18,670
Agricultural Waste
5,217
Organic Waste
Incineration
5,217
Ash
Landfill
+9,981
204
Leaching
I
E

## Annex V

The following pages show the Swiss P balance and its waste management sub-system with the original stock and flow values (i.e. not related size of the Swiss population) and uncertainties by Binder et al. (2009).


Import: 16,508 t/a
dStock: +12,592 t/a
Export: 3,916 t/a
5,615±628
Import feed
33±4
Import living stock
688±172
Animal products
5,886±59
Mineral fertiliser
2,447±238
Import plant products
23±8
Precipitation
360±0
Import chemicals
1,456±338
Import products
Manure
29,385±1,401
29,572±1,556
Feed
Animal husbandry
Crop farming
+3,549±801
498±165
Fertiliser
594±112
Sewage sludge
Chemical industry
337±53
Wood & paper
180±24
Mineral fertilisers for gardening
3,488±295
Animal products
Waste paper
69±7
Plant products
4,016±253
786±338
Industrial watewater
91±13
Agricultural waste
Household & business
20±10
Washing out of animal excrements
1,071±238
Leaching & erosion
1,031±33
Detergents
592±140
Fertiliser for gardening
Animal waste
3,015±298
Garden waste
998±92
Waste
2,503±240
Municipal wastewater
6,097±230
Waste management
Hydrosphere
1,069±324
Effluent WWTP
+9,046±801
Export water bodies
2,160±106
Export wood & paper
66±9
1,505±248
Export animal waste
185±185
Export fly ash



Import: 13,490 t/a
dStock: 9,046 t/a
Export: 4,443 t/a
6,097±230
Municipal wastewater
786±338
Industrial wastewater
Sewerage system
6,882±356
Inflow to WWTP
Wastewater treatment
1,272±244
Sewage sludge
Cement plant
+2,781±348
2,503±240
Waste
3,015±298
Animal waste
Animal waste sorting
1,510±249
Animal waste to cement industry
91±13
Agricultural waste
998±92
Garden waste
Agricultural waste sorting
923±92
Waste to composting
166±23
Waste to fermentation
Composting
Fermentation
Sewage sludge to mono-incineration
2,507±234
1,440±230
Sewage sludge to waste incineration
Sewage sludge mono-incineration
Waste incineration plant
3,536±275
Slag
Sewage sludge ash
2,256±205
251±96
Sewage sludge fly ash
407±13
Fly ash
Bioreactor landfill
+5,792±328
Residual waste landfill
+473±209
Compost
923±92
122±57
Fermentation products
45±62
Press water
1,505±248
Export animal waste
Distribution of compost & fermentation products
Effluent WWTP
1,069±324
594±112
Sewage slaudge (as fertiliser)
185±185
Export fly ash
Fertiliser for gardening
592±140
498±165
Fertiliser (for agriculture)