Review

The aim of this study is to evaluate the current situation of phosphorus, an element classified and considered as critical element by the European Union, at global, European and Spanish level. Its importance, although used in many industrial application it is associated to its ole as a nutrient in fertilizers production and use. It is estimated that the phosphate resources, in the form of phosphatic rock, are limited so it is considered a non-renewable source of phosphorus and its reserves are concentrated in a few deposits in a few number of countries. This has caused the entry of phosphorus into the designated critical elements in the EU and the necessity to apply the circular economy model for its use. In this way it is intended to close the cycle of phosphorus from secondary sources. The analysis carried out of the P cycles worldwide allow to conclude that recovery of phosphorus from a) the urban water cycle, specially from the sludge generated in the waste water treatment plants (WWTP), b) compost produced from the faeces (swine solids) from animal farms or, c) ashes originated from sludge incineration are the main secondary resources to be considered nowadays. However, it has been identified the need to promote tertiary sources by improving the efficiency of phosphorus processing and use in all sectors (mining and beneficiation, agriculture), also including restricting laws limiting the use of phosphorus for essential needs and changes feeding systems.

In this project, a balance flow of phosphorus in Spain using the Substance Flow Analysis (SFA) methodology, allowed to the identification of the available secondary sources and compare with other ready-made for EU27 and reference countries as Japan. Additionally to the SFA for Spain a proposal to promote and improve phosphorus cycling was centred in the Barcelona Metropolitan Area (BMA). WWTP from the BMA were as main secondary resource to promote the recovery of phosphorus from the WWTPs streams. This assessment required a detailed study of the Phosphorous balance in the BMA by using raw data provided by the WWTP management system of the BMA during the years 2011-2015. From the different streams evaluated sludge streams were considered key actors and specially the management routes and fates of sludge in these years. In 2011 most of the sludge was destined to cement industry, in a material co-substitution of coque, a fact that was declining until 2015 which were sent directly to composting plants due to the crisis in the construction sector with the reduction of cement production. This suggests the use of the sludge for the cement industry again, but the truth is that the objectives of EU on the circular

economy approach for critical elements will cause that sewage sludge would not be use by the cement industry and then different sewage sludge options promoting the recovery of phosphorus will be needed.

From these premises, four scenarios, postulating P-cycling options in the BMA by proposing the integration of different sludge management processes (anaerobic digestion, mono-incineration, composting and recovery technology phosphorous, called Ecophos) were raised and evaluated in this project. Combining each other, a detailed analysis for energy balances, mass balances, phosphorus recovery, environmental and economic impact has been performed.

Summary

Summary figures

Summary tables

1. Glossary

ACSHs – Amorphous Calcium Silicate Hydrates
AD – Anaerobic Digestion
Al – Aluminium
$AlPO_4$ – Aluminium Phosphate
AM – Arbuscular Mycorrhizal
AP – Animal Production
AS – Ammonium ulphate
As – Arsenic
ATP – Adenosine triphosphate
BAT – Best Available Tecnologies
BG – Biogas Production
BMA – Barcelona Metropolitan Area
Ca – Calcium
$Ca(H_2PO_4)_2 \cdot H_2O$ – Monocalcium Phosphate
$Ca(OH)_2$ – Calcium hydroxide
$Ca_3(PO_4)_2$ – Tri-calcium phosphates
$CaCl_2$ – Calcium Chloride
$CaCO_3$ – Calcium carbonate
$CaHPO_4 \cdot 2H_2O$ – Dicalcium Phosphate
CaP – Calcium Phosphate
$CaSO_4 \cdot 2H_2O$ – Calcium Sulfate Dihydrate
Cd – Cadmium
C_E – Fuel Consumption Empty
C_{FL} – Fuel Consumption Full Load
CH_4 – Methane
ChemP – Chemical Phosphorus removal
CHP – Combined Heat and Power
C_i – Mass of the Flow i
CO_2 – Carbon Dioxide
CO_2-eq – Carbon Dioxide equivalent
CP – Crop Production
Cr – Chromium
C_T – Total Fuel Consumption
Cu – Copper
DM – Dry Matter
DNA – Deoxyribonucleic acid
E – Energy Consumption
EBPR – Enhanced Biological Phosphorus Removal

EC – Energy Content of CH_4 Produced
EP_C – Centrifugation Electric Power Consumption
EPP – Electric Power Production
ES – Energy Content of Sludge
EU – European Union
FAO – Food and Agriculture Organization of the UN
Fe – Iron
$FeCl_3$ – Ferric Chloride
F_i – Quantity of P in the Flow i
FORM – Fracción Organica y Restos de Materia
FP – Food processing
F_{total} – Total P in the Flow
GDP – Gross Domestic Product
GHG – GreenHouse Gas
GWP – Global Warming Potential
H_2SO_4 – Sulfuric Acid
H_3PO_4 – Phosphoric Acid
HAP – Hydroxyapatite
HC – Consumption
HCl – Hydrochloric Acid
Hg – Mercure
HS – Hedbrant and Sörme Model
IC – Investment Cost
IEX – Ion Exchange
K – Potassium
KCl – Potassium Chloride
km_T – Total Distance
LCA – Life Cycle Assessment
LHV – Lower Heating Value
LPA – Lower content of Phytic Acid
m_{ASH} – Ash Mass
m_{DM} – Dry Matter Mass
MFA – Material Flow Analysis
Mg – Magnesium
$MgCl_2$ – Magnesium Chloride
m_S – Mass of Sludge to digest
MSWI – Municipal Solid Waste Incineration
MTH – CH_4 Production
N – Nitrogen
N_2O – Nitrous Oxide
Na_2S – Sodium Sulphide
$Na_5P_3O_{10}$ – Sodium Triphosphate

NaOH – Sodium Hydroxide
NF – Non-Food Production
NH_3 – Ammonia
NH_4NO_3 – Ammonium Nitrate
NPK – Nitrogen Phosphorus Potassium
N_T – Number of Transport
OM – Organic Matter
OMC – Operation and Maintenance Cost
P – Phosphorus
P.E. – Population Equivalent
P_2 – Diphosporus
P_2O_5 – Phosphorus pentoxide
P_4 – Elemental Phosphorus
P_4O_{10} – Phosphorus Pentoxide
P_4S_{10} – Phosphorus Pentasulfide
PAdeCS – Phosphorus Adsorbent derived from Concrete Sludge
Pb – Plumb
P_C – Compost Production
PCl_3 – Phosphorus Trichloride
Pi – Inorganic Phosphorus
P_i – Percentage of P in the Flow
PL – Polymer Consumption
PO_4^{-3} – Phosphate ion
$POCl_3$ – Phosphoryl Chloride
P_R – Phosphorus Recovered
P_{RL} – Phophorus in Return Liquor
RD – “Real Decreto”
RL – Return Liquor
RNA – Ribonucleic acid
SD – Digested Sludge
SD_{DM} – Digested Sludge in Dry Matter
SFA – Substance Flpw Analysis
SO_2 – Sulfur dioxide
SS – Sewage Sludge
SSA – Sewage Sludge Ash
SV_D – Solid Volatile Degraded to biogas
TP – Thermal Power Consumption
TPP – Thermal Power Production
TP_{RL} – Total P in Return Liquor
TP_{SD} – Total P in Digested Sludge
TRV – “Triturado de Restos Vegetales”
U_i – Uncertainty of the i value

UN	– United Nations
UPC	– “Universitat Politècnica de Catalunya”
USA	– United States of America
USGS	– United States Geological Service
U_T	– Total Uncertainty
VS	– Volatile Solids
V_S	– Volume of Sludge to digest
VS_{in}	– Volatile Solids entrance
WGI	– World Governate Indicator
WWTP	– WasteWater Treatment Plant
Zn	– Zinc

2. Introduction

The key for the stability in short and long term of the food chain established at present is to close the cycles of the resources necessaries to support it, between these resources are nutrients as phosphorus (P) and nitrogen (N). This leads to the concept of circular economy (Ellen Macarthur Foundation, 2015), according to which it is attempting to recover and reuse resources before they become waste and to become an economic and environmental problem rather than the solution to sustainability.

According to the forecast of the UN world population will increase from 7.3 billion today to 9.7 billion in 2050 (United Nations, 2015). This represents an increase of 33% over the next 35 years. This growth leads to increased demand for fertilizers needed to grow crops that increasing population will demand. The fertilizer consumption forecasts made by FAO and provides for an annual increase of 1.8% over the next years until 2050. (Food and Agriculture Organization of the United nations (FAO), 2015).

This increase in demand for fertilizers, the low diversity of the deposits of phosphate rock (see Figure 2), ore from which P is removed, and the fact that the phosphate rock is considered a nonrenewable resource, makes P a resource critical for any nation that perform agricultural activity. The different predictions about the deadline for the depletion of deposits of fosofric rock are summarized in Table 3.

This situation would unleash an increase in crop prices and consequently the food, which can create geopolitical tensions which make it difficult to obtain primary sources of P to dependents countries of this resource. Only USA, China, Russia and Morocco can supply itself (Reijnders, 2014), so other nations, including those belonging to the EU, must initiate a change in the cycle of this critical resource to reduce their dependence on primary sources. In 2014 EU included the P on the critical materials list (European Commission, 2014) due to the facts and projections referred to above.

As has been seen so far, P management will be critical to ensure greater independence from primary sources. This management will be done at all scales, from international to territorial levels (Biswas Chowdhury, Moore, Weatherley, & Arora, 2014).

The biggest problem that occurs in large urban areas with high population density is that they can not absorb all P coming from its secondary sources so they have to send it to other areas, mainly rural, where the P can reuse in sustituación of mineral fertilizers from primary sources.

On the other hand, due to future legislative changes arising from the EU (European

Commission, 2015), you can not allocate secondary sources of P to sectors other than agriculture. That is, the use of secondary sources of P for purposes not close the cycle P raised according to the circular economy will be prohibited. In the particular case of the Barcelona Metropolitan Area (BMA), this is the end use of sludge from sewage treatment plants as fuel for the cement industry, as happened in the period 2011-2013 (see Figure 32). It has been identify while most of G8 contries are developing studies on P mass flow at different both regional and national levels, such type of studies are lacking in neither Catalunya nor Spain.

2.1. Objectives of the project

The objectives of this project are centered in two main objectives:

a) To develop a mass flow analysis of the P cycle in Spain, to identify what are the main needs of primary resources of P and what could be the amin secondry resources avaliables

b) To study the potencial contribution of secondary P resources associated to urban waste waters, one of the target contribution actors identified by the EU to fight agains P scarcity. As model system the management of sewage sludge from sewage plants of Metropolitan Area of Barcelona (BMA) as a secondary source of P has been selected.

2.2. Scope of the project

The project will combine data on P cycles, industrial and agricultural uses to develop the mass flow analysis using data bases available for public consultation. When data are not available data from published country or region mass flow analysis have used. From this information a Flow Mass Analysis at national level has been developed

Similarly, as local case study for determining the P secondary resources from the urban waste water cycle, the Barcelona Metropolitan Area has been selected. Information of the P loading rates of the different streams (raw, treated and solid wastes generated) from waste water treatment plants have been provided by the BMA. Then a metropolitan scale analysis has been performed.

3. Phosphorus

3.1. Overall situation of phosphorus

Phosphorus is a chemical element with symbol **P** and atomic number 15. As an element, phosphorus exists in two major forms—white phosphorus and red phosphorus—but due to its high reactivity, phosphorus is never found as a free element on Earth. Phosphorus is essential for life. Phosphates (compounds containing the phosphate ion, PO_4^{-3}) are a component of DNA, RNA, ATP, and also the phospholipids, which form all cell membranes.

Phosphorus is not found free in nature, but it is widely distributed in many minerals, mainly phosphates. Inorganic phosphate rock, which is partially made of apatite, (an impure tri-calcium phosphate mineral) is today the chief commercial source of this element.

In a commercial sense, the vast majority of phosphorus compounds are consumed as fertilisers. Phosphate is needed to replace the phosphorus that plants remove from the soil, and its annual demand is rising nearly twice as fast as the growth of the human population. Other applications include the role of organophosphorus compounds in detergents, pesticides, and nerve agents. Sodium tripolyphosphate made from phosphoric acid is used in laundry detergents in some countries, but banned for this use in others. It is useful for softening water to enhance the performance of the detergents and to prevent pipe/boiler tube corrosion.

Table 1 Main P compounds used for industrial applications (Greenwood & Earnshaw, 1997)

Widely used compounds	Use
$Ca(H_2PO_4)_2 \cdot H_2O$	Baking powder and fertilizers
$CaHPO_4 \cdot 2H_2O$	Animal food additive, toothpowder
H_3PO_4	Manufacture of phosphate fertilizers
PCl_3	Manufacture of $POCl_3$ and pesticides
$POCl_3$	Manufacture of plasticizer
P_4S_{10}	Manufacturing of additives and pesticides
$Na_5P_3O_{10}$	Detergents

The majority of phosphorus-containing compounds are produced for use as fertilisers. For this purpose, phosphate-containing minerals are converted to phosphoric acid. Two distinct routes are employed, the main one being treatment of phosphate minerals with sulfuric acid. The other process utilises white phosphorus, which may be produced by reaction and distillation from very low grade phosphate sources. The white phosphorus is then oxidised to phosphoric acid and subsequently neutralised with base to give phosphate salts. Phosphoric acid obtained via white phosphorus is relatively pure and is the main source of phosphates used in detergents and other non-fertiliser applications.

Fertilisers provide phosphate as required for all life and is often a limiting nutrient for crops. Phosphorus, being an essential plant nutrient, finds its major use as a constituent of fertilisers for agriculture and farm production in the form of concentrated phosphoric acids, which can consist of 70% to 75% P_2O_5. Global demand for fertilisers led to large increase in phosphate (PO_4^{3-}) production in the second half of the 20th century (Figure 1). Due to the essential nature of phosphorus to living organisms, the low solubility of natural phosphorus-containing compounds, and the slow natural cycle of phosphorus, the agricultural industry relies on fertilisers that contain phosphate. A major form of these fertilisers is superphosphate of lime, a mixture of two salts, calcium dihydrogen phosphate $Ca(H_2PO_4)_2$ and calcium sulfate dihydrate $CaSO_4{\cdot}2H_2O$, produced by the reaction of sulfuric acid and water with calcium phosphate.

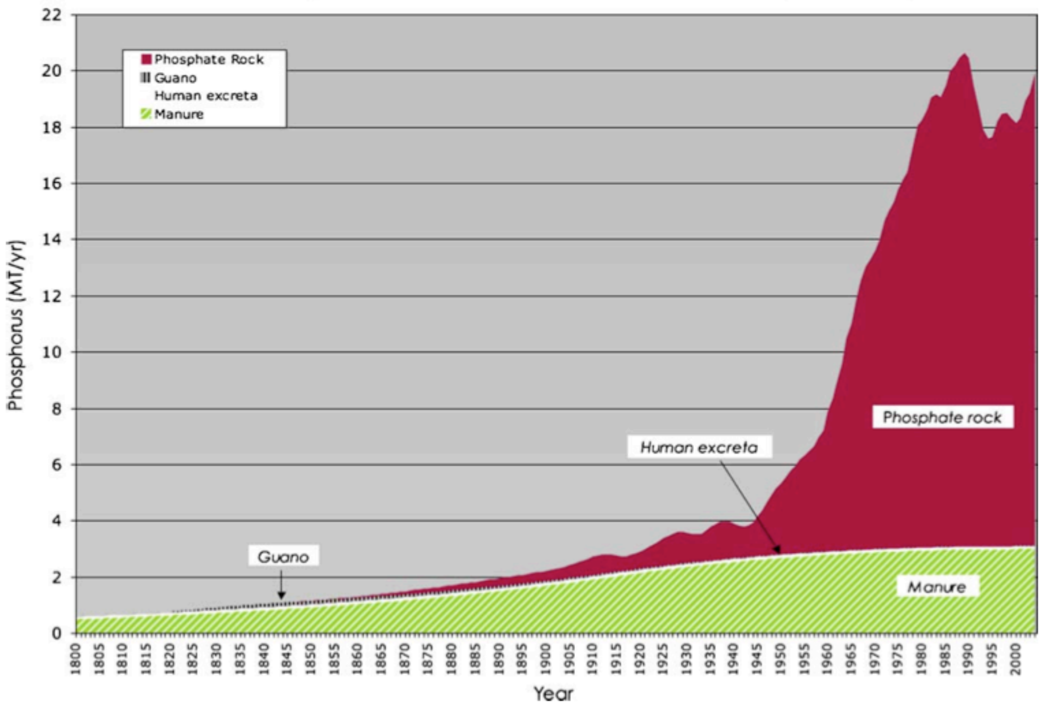


Figure 1 Historical sources of phosphorus for use as fertilizers, including manure, human excreta, guano and phosphate rock (1800-2000)(Cordell, Drangert, & White, 2009).

The US Geological Service (USGS) estimated that the world consumption of phosphorus pentoxide will increase from 41,9 million tonnes in 2012 to 45,3 million tonnes in 2016. The last estimation is that world consumption of P_2O_5 contained in fertilizers and industrial uses were projected to increase gradually from 43.7 million tons in 2015 to 48.2 million tons in 2019 (U.S. Geological Survey, 2016).

It postulates that the world resources of phosphate are 300 billion tons; world reserves are shown in Table 2 and Figure 2. The biggest deposits are located in northern Africa, China, the Middle East, and the USA. Large deposits of phosphates are also located on the continental shelf and on seamounts in the Atlantic and Pacific Oceans, but exploiting these deep-sea sources is still too costly. Besides the sedimentary phosphate deposits, some igneous rocks are rich in phosphate minerals (apatite), generally without significant contents of uranium. However, sedimentary deposits are more abundant and usually higher in grade; 80% of the global production of phosphate rock is exploited from sedimentary phosphate deposits.

Table 2 World phosphate rock reserves (kt). Source: (U.S. Geological Survey, 2016)

Country/Region	**Reserves**
Morocco	50000000
China	3700000
Algeria	2200000
Syria	1800000
Jordan	1300000
South Africa	1500000
USA	1100000
Russia	1300000
Peru	820000
Saudi Arabia	960000
Australia	1000000
Iraq	430000
Other countries	2615000
World total (rounded)	69000000

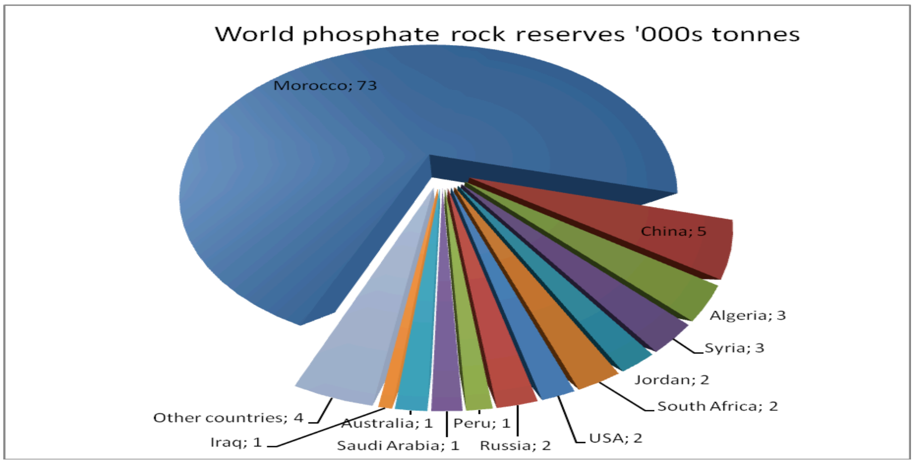


Figure 2 World phosphate rock reserves (kt). Source: (U.S. Geological Survey, 2016)

There are diferents hypotesys about depletion of reserves of P, most of them predics that reserves will be depleted before the end of the century and therefore production will become increasingly concentrated to just few countries, predominantly Morocco (Cooper & Carliell-Marquet, 2013). Table 3, summarizes the estimates provided for different authors for remaining fossil P resources and estimated remaining fossil resources in years of estimated current fossil P maining.

Table 3 Estimates of remaining fossil phosphorus resources in 10^{15} gP and years of estimated current fossil P mining

Reference	**Estimated remaining fossil P resources in 10^{15} gP**	**Estimated remaining fossil P resources in years of estimated current fossil P minig ($3x10^{13}$ gP/yr)**
Steen (1998)	16.4 - 26.6	$5.5x10^2 – 8.9x10^2$
Smil (2000)	22.7	$7.6x10^2$
Cordell et al. (2009)	2.4	$8x10^1$
Van Vuuren et al. (2010)	7.1 – 38.8	$2.4x10^2 – 1.3x10^3$
Cordell et al. (2011)	7.3	$2.4x10^2$
Sverdrup and Ragnarsdottir (2011)	5.2 – 6.1	$1.7x10^2 – 2.0x10^2$
Scholz and Wellmer (2013)	24	$8x10^2$

From a critical evaluation of data as reported on table 3, different scenarios and predictions have been published in the last decade, and as one example the Peak phosphorous curve provided on Figure 3 has been reported by Jasinski et al (Jasinski, 2006). The indicative peak phosphorus curve, is illustrating that, in a similar way to oil, global phosphorus reserves are also likely to peak after which production will be significantly reduced, 2040 according to the data.

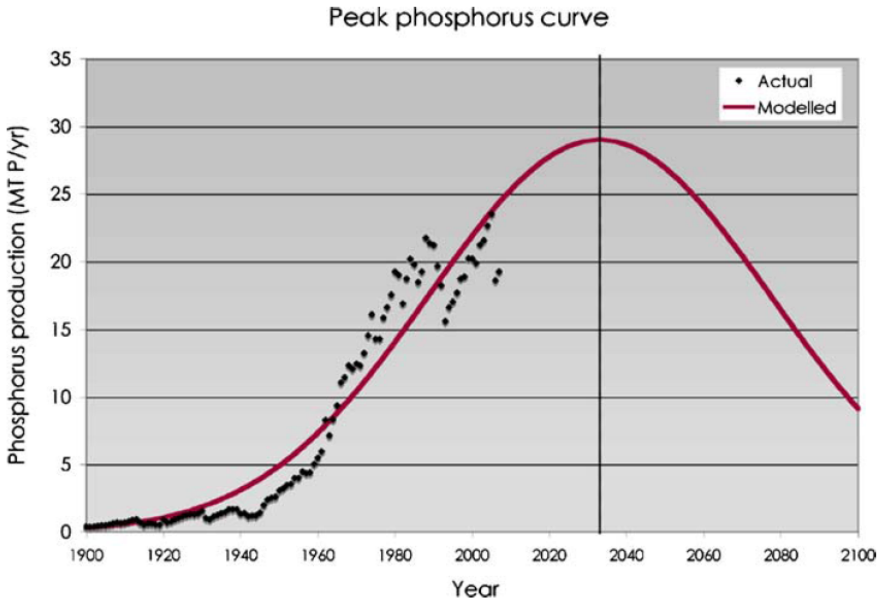


Figure 3 Indicative peak phosphorus curve, illustrating that, in a similar way to oil, global phosphorus reserves are also likely to peak after which production will be significantly reduced (Jasinski, 2006; European Fertlizer Manufacturers Association, 2000).Source: (Cordell, Drangert, & White, 2009)

Phosphorus is a non-substitutable raw material whose availability has been identified as a globally relevant bottleneck for fertiliser and food supply.Europe has an import dependency above 90% with regards to mineral phosphorus as it is whon in Figure 4. As a consequence, phosphate rock was declared a critical raw material by the European commission in 2014 (Figure 5).

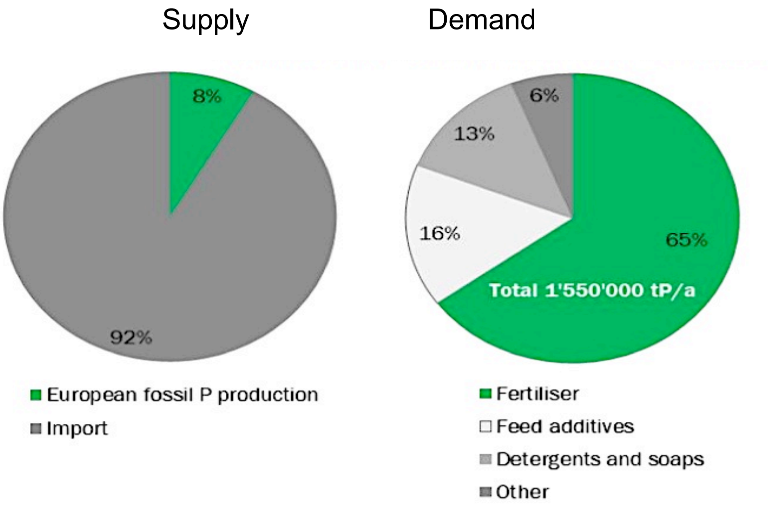


Figure 4 Supply and demand in relation to the total phosphorus demand 1.550.000 tP/yr. Data sources: Jasinski, B.S.M. in 2011 Minerals Yearbook (U.S. Geological survey, 2013).Source: (P-Rex, 2014)

The European Commission carried out a criticality assessment at EU level on a wide range of raw materials (in 2010, 41 raw materials were assessed, in 2013, 54 raw materials were assessed). The indicators were:

- *Economic importance* **-** the proportion of each material associated with industrial megasectors such as construction, combined with its gross value added to EU GDP. This total is scaled according to total EU GDP to define the overall economic importance of a material.

- *Supply risk* **-** the World Governance Indicator (WGI) is used to measure the supply risks of raw materials. This indicator takes into account accountability, political stability and absence of violence, government effectiveness, regulatory quality, and rule of law.

Then, if both indicators are quantified a supply risk versus economic importance plot could be constructed as it is shown in Figure 5. Then, and according to the thresholds selected a number of elements, group pf elements or even minerals (e.g. phosphate rock) have been selected to be defined or classified as critical elements.

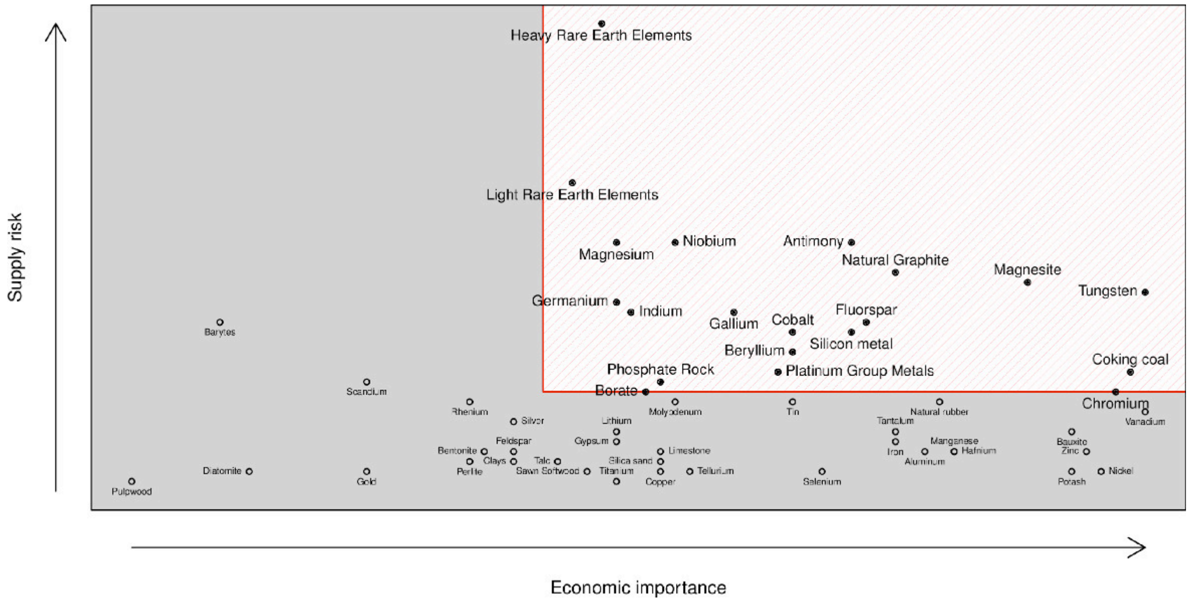


Figure 5 Critical raw material identified by the EU (European Commission)

In Europe, phosphorus is being treated in an unsustainable way. Through fertilizers, sewage and animal manure, large amounts of phosphorus and other nutrients end up in ground water and water bodies.

This is a direct threat for our aquatic ecosystems due to the process of eutrophication: increased levels of nutrients resulting in oxygen depletion. The impact on biodiversity is critical, since certain fish and other aquatic animal populations do not survive or invasive new species are introduced.

While phosphorus is a limited fossil element, its extensive recovery from “secondary deposits” is of paramount importance and follows the principles of the European Roadmap for Resource Efficiency (http://www.p-rex.eu). In this context EU funded the Sustainable sewage sludge management fostering phosphorus recovery and energy efficiency P-REX Project in 2012. The P-REX project (http://www.p-rex.eu) it builds on the outputs of previous European research projects and will perform the first holistic full-scale evaluation of technical phosphorus recovery techniques using municipal sludge or ashes in comparison with phosphorus recycling by land application of sewage sludge. The technical, operational and economic data as well as comprehensive ecotoxicological and plant-availability assessments will provide the basis of comprehensive life cycle and life cost assessments of phosphorus recovery processes.

For the implementation to market, new technologies need to be proven capable and feasible. Within P-REX, novel and available technical solutions for phosphorus recovery and recycling will be demonstrated in full-scale. Their performance and feasibility will be systematically assessed and validated, as well as the quality of obtained recycling products. Together with the analysis of the market barriers and the market potential for novel recycling technologies and their products, strategies and recommendations will be developed for efficient and wide-spread phosphorus recovery and market penetration with regards to specific regional conditions, aiming to increase the European phosphorus recycling rate from municipal wastewater up to 80%.

3.2. Circular Economy

As Ellen Macarthur Foundation describes, circular economy is an economy that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. It is conceived as a continuous positive development cycle that preserves and enhances natural capital, optimises resource yields, and minimices system risks by managing finite stocks and renewable flows. It works effectively at every scale. The circular economy rests on three principles, as shown in Figure 6.

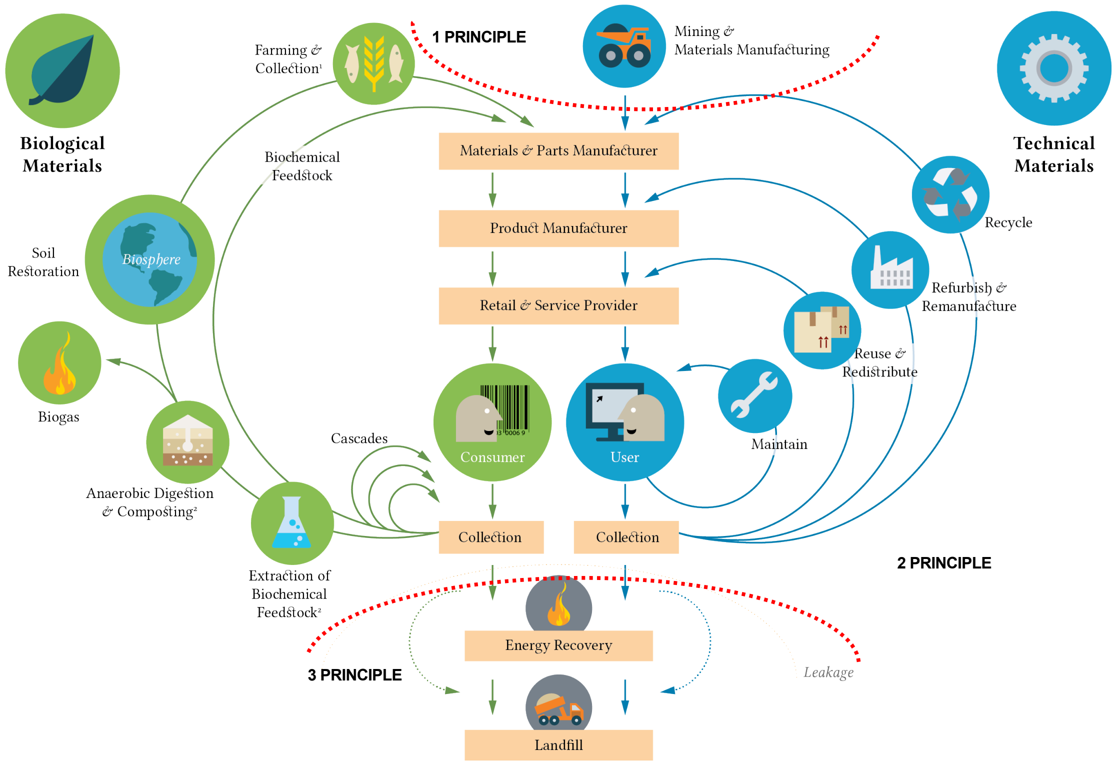


Figure 6 Outline of Circular economy (Ellen Macarthur Foundation, 2015)

Principle 1: *Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows.* When resources are needed, the circular system selects them wisely and chooses technologies and processes that use renewable or better-performing resources, where possible. A circular economy also enhances natural capital by encouraging flows of nutrients within the system and creating the conditions for the regeneration of soil, for example.

Principle 2: *Optimise resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles.* This means designing for remanufacturing, refurbishing, and recycling to keep technical components and materials circulating in and contributing to the economy. Circular systems maximise the number of consecutive cycles and/or the time spent in each cycle, by extending product life and optimising reuse. Circular systems also encourage biological nutrients to re-enter the biosphere safely for decomposition to become valuable feedstock for a new cycle. In the biological cycle, products are designed by intention to be consumed or metabolised by the economy and regenerate new resource value.

Principle 3: *Foster system effectiveness by revealing and designing out negative externalities.* This includes reducing damage to systems and areas such as food, mobility, shelter, education, health, and entertainment, and managing externalities, such as land use, air, water and noise pollution, and the release of toxic substances.

While the principles outlined above act as principles for action, the following fundamental characteristics describe a circular economy:

Waste is “designed out”. In a circular economy, waste does not exist, and is designed out by intention. Biological materials are non-toxic and can easily be returned to the soil by composting or anaerobic digestion. Technical materials – polymers, alloys, and other man-made materials – are designed to be recovered, refreshed and upgraded, minimising the energy input required and maximising the retention of value (in terms of both economics and resources).

Diversity builds strength. A circular economy values diversity as a means of building strength. Across many types of systems, diversity is a key driver of versatility and resilience. In living systems, for example, biodiversity is essential to surviving environmental changes. Similarly, economies need a balance of various scales of businesses to thrive in the long term. The larger enterprises bring volumen and efficiency, while the smaller ones offer alternative models when crisis occur.

Renewable energy sources power the economy. The energy required to fuel the circular economy should be renewable by nature, in order to decrease resource dependence and increase systems resilience (to oil shocks, for example). This will be further enabled by the reduced threshold energy levels required in a circular economy.

Think in systems. In a circular economy, systems-thinking is applied broadly. Many real-world elements, such as businesses, people or plants, are part of complex systems where different parts are strongly linked to each other, leading to some surprising consequences. In order to effectively transition to a circular economy, these links and consequences are taken into consideration at all times.

Prices or other feedback mechanisms should reflect real costs. In a circular economy, prices act as messages, and therefore need to reflect full costs in order to be effective. The full costs of negative externalities are revealed and taken into account, and perverse subsidies are removed. A lack of transparency on externalities acts as a barrier to the transition to a circular economy.

3.3. Secondary resources of P

As part of the circular economy, secondary sources of phosphorus take great importance. The secondary source is basically recycling of P due to human and animal activity. This recycling can be distinguished as the public or private sector. Different innovative on P recovery are being developed in the last years been the ost activies countries Japan and the middle and northen countries of European Union (e.g. Germany, Sweden, The Netherlands, Switzeland). As an example, it should be mentioned thay only recently Switzeland is the frist country where P recovery from wastewater is obligatory (Suitainable P platform, Scope Newsletter Nr 108)

3.3.1. P Recycling in Public Sector

Municipal wastewater is one of the major secondary resources of P. Phosphorus is removed from municipal wastewater in a wastewater treatment plant (WWTP), aiming to control eutrophication in natural bodies of water. Obviously, the direct application of sewage sludge to agricultural land is the simplest option to recycle P from municipal wastewater.

Sewage sludge contains a variety of organic contaminants, heavy metals, and pathogens, which may place human health at risk. Long-distance transportation of sewage sludge from urban areas to arable land where it may be applied is another problem. P needs to be recovered from sewage sludge and used for the manufacture of fertilizers that are safer to store, handle and apply. However, not all the P removal technologies can be applied to P recovery for recycling, because the quality of the recovered product is critical to P recycling (Ohtake & Okano, 2015).

3.3.1.1. P recovery from incinerated sludge ash

Inorganic phosphorous (Pi) is thermally stable and does not volatilize during sludge incineration at 800-900°C. Pi can be concentrated in the incinerated sludge ash as whitlockite-type, tri-calcium phosphates ($Ca_3(PO_4)_2$). However, the direct application of incinerated sludge ash to farmland as Pi fertilizer is not possible because it contains toxic heavy metals (e.g. Cd, Pb and Hg). In addition, the P accumulated in incinerated sludge ash exhibits low bioavailability when applied as Pi fertilizer. The P in incinerated sludge ash needs to be transformed to a more biologically available form for recycling. Chemical Pi leaching is a technology option for recycling P in incinerated sludge ash.

Examples of this kind of recovery are processes Ecophos and LeachPhos, developed by Ecophos S.A. and BSH Umweltservice GmbH respectively. The Leachphos process can recover 70% of P from the ashes, but uses considerable amounts of chemicals for leaching and pH control. Phosphorus (P) is extracted from sewage sludge ash (SSA) by addition of diluted sulfuric acid. 80-95 % of P is transferred into the leachate (Figure 7).

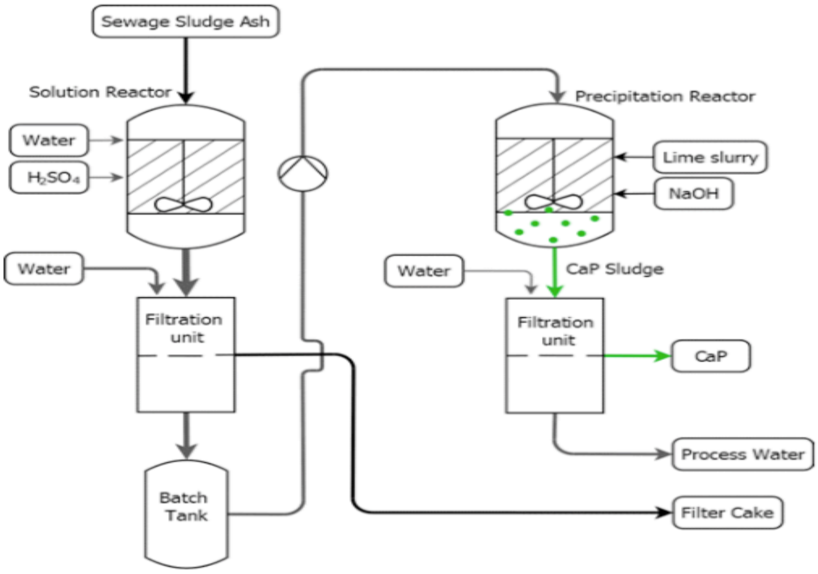


Figure 7 LeachPhos Scheme Process (P-REX) (Remy & Jossa, 2015)

The Ecophos process yields a very pure product (H_3PO_4) with low toxicity potencials via digestion of ashes in diluited H_3PO_4 and subsequent multistage purification of the leachate in ion exchangers (Figure 8). This process can recover up to 97% of P load in ashes and generate other valuable by-products ($FeCl_3$, $CaCl_2$) of the purification process.

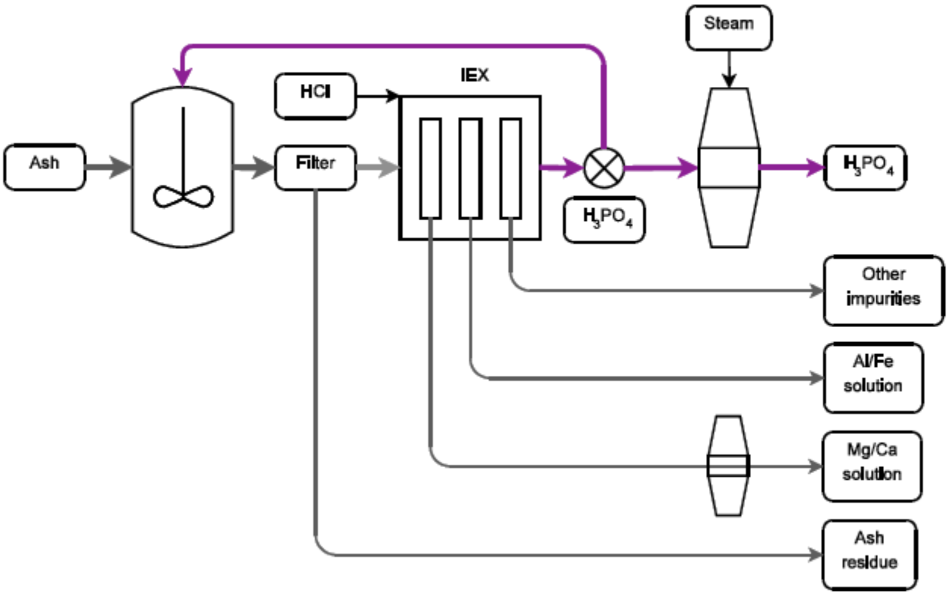


Figure 8 Ecophos Scheme Process (P-REX) (Remy & Jossa, 2015)

Solid residues after P extraction and proper removal of most toxic metals (e.g. Cd, Hg, Pb, Zn and Cu) can be accepted by a cement company, because of their low P content. However, the expanded use of this technology requires the reduction of operating cost, which is strongly dependent on the amount of chemicals for Pi extraction and precipitation as well as for the appropriate removal of the highly toxic metaltic impurities.

3.3.1.2. Struvite recovery from sludge digestion liquor

Anaerobic sludge digestion is a well-established process for stabilizing sewage sludge and reducing its volume by biogás production. If an anaerobic sludge digestion process is available, P can be released from P-rich sludge biomass into the liquid phase of the digester. The blockage of pipes by struvite precipitates causes significant operational problems, leading to an increase in the maintenance cost of WWTPs. Conversely, if struvite precipitation is minimized in the digester, struvite can be recovered from the Pi-rich stream in the downstream process of the digester

A couple of examples about this process are the PEARL process (OSTARA Nutrient recovery technologies Inc.) (www.ostara.com) and STRUVIA process (Veolia Water) (www.veolia.com), and are designed to prevent unwanted struvite incrustation after sludge dewatering in Enhanced Biological Phosphorus Removal (EBPR) WWTPs (Figure 9).

Struvite particles are formed in a fluidized-bed tower reactor. They are circulated in the tower reactor by air bubbles until being withdrawn from the corn-shaped bottom part of the reactor. The recovered struvite is possible sold to fertilizer companies as a chemical fertilizer.

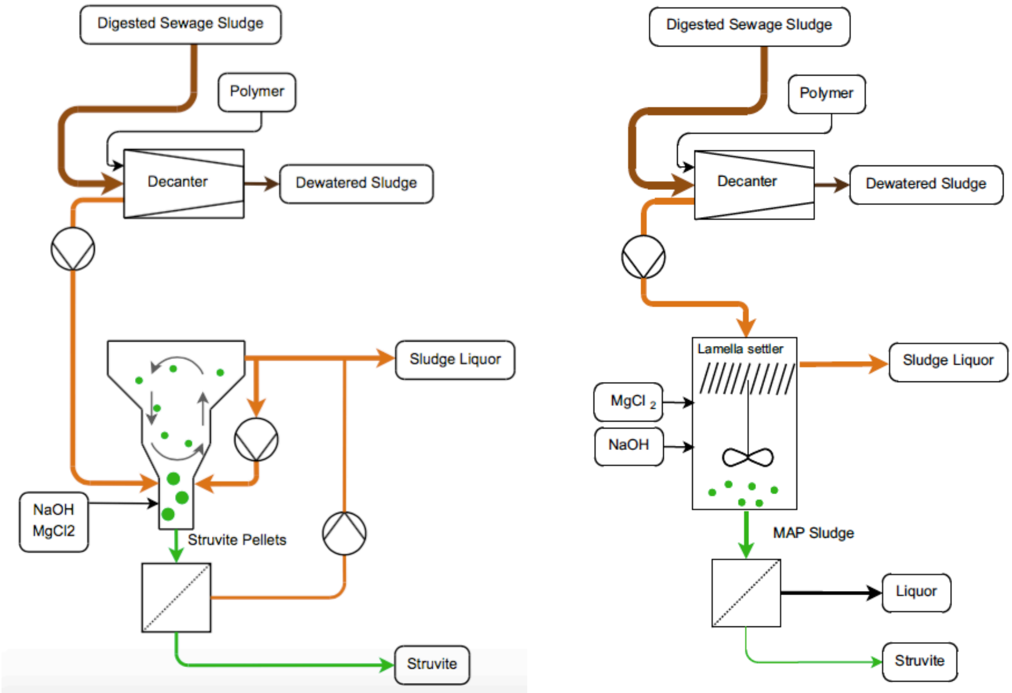


Figure 9 a) PEARL Process (www.ostara.com) b) STRUVIA Process (wwww.veolia.com) (Remy & Jossa, 2015)

3.3.1.3. P recovery from blackwater

Blackwater is a type of wastewater containing human feces and urine. In local areas without a sewage treatment facility, human feces and urine are separately collected and transported by truck to a blackwater treatment plant.

Pi is precipitated with $CaCl_2$ from the liquid rejected by a membrane-type solid-liquid separator after N removal. On average, the liquid contains approximately 45 mgP/L. The reactor for Pi precipitation is a continuously stirred tank, to which a $CaCl_2$ solution is fed in continuous mode. HAP crystals are allowed to grow to an average diameter of 370 mm in the reactor during the retention time of 2 h. HAP particles are withdrawn from the reactor and transferred into a flexible container bag that can serve as a separation filter. Approximately 20% P is recovered as HAP, whereas the remaining 80% P ends up in dewatered sludge, which is incinerated and landfilled. The HAP obtained is possible sold to a fertilizer company, which manufactures a more versatile fertilizer using HAP as a raw material (Ohtake & Okano, 2015).

3.3.2. P Recycling in Private Sector

3.3.2.1. Phosphoric acid production using incinerated sludge ash

Also phosphoric acid producers have identified incenerated sludge ash as raw matrials. In 2009, Nippon Phosphoric Acid Co. (NPA) began a feasibility study of the use of incinerated sludge ash for the manufacture of phosphoric acid. This was triggered by the increase in the Pi rock price surge in 2008[ref?]. Incinerated sludge ash samples, whose P_2O_5 levels were in the range of 24-35 wt%, were collected from different WWTPs and examined for their suitability in the wet process. The collected ash samples contained less As, Cd, and Hg than those of Pi rock. However, their Pb and Zn levels were significantly higher than Pi rock. Accordingly, needed to blend incinerated sludge ash with imported Pi rock to guarantee the quality of phosphoric acid as well as the by-product gypsum.

Incinerated sludge ash is blended with roller-milled Pi rock and fed to a non compartmentalized reactor. The mixture is then dissolved in concentrated sulphuric acid to generate phosphor-gypsum slurry. The phospho-gypsum slurry is continuously filtered to separate phosphoric acid from gypsum. Gypsum is used as a raw material for the manufacture of building boards and cement. The blend ratio of incinerated sludge ash with roller-milled Pi rock is currently less tan 2.5% (<97.5% Pi rock). This is needed to guarantee the quality of both phosphoric acid and gypsum. Increasing the blend ratio changes the structural change of gypsum from the rhombic form to the needle-type form (Ohtake & Okano, 2015).

3.3.2.2. P recovery from industrial wastewater

Approximately 15% of the global P demand is consumed in the manufacturing industry. For example, high-grade phosphoric acid is used as an iron-coating material in the automotive industry, etching agents for liquid crystal glass substrates, and feedstock for food additives, chemical catalysts, and flame retardants. P is also one of the crucial raw materials for the manufacture of rechargeable batteries.

Recently, the manufacturing industry has begun to consider P recycling as an economically beneficial option in waste management. This is because P recycling can potentially reduce waste disposal costs by turning P-rich waste into a resource purposes. Some companies that synthesize alcohol can potentially produce ethanol (95 v/v%) by a direct ethylene hydration process, in which high-grade Pi is used as a chemical catalyst.

Those companies used a P recovery process for wastewater. The process uses a commonly used technology, involving Pi precipitation with $Ca(OH)_2$ at a high pH. To avoid unwanted $CaCO_3$ formation, decarbonation is carried out by lowering the pH with H_2SO_4 before the addition of $Ca(OH)_2$. The formed HAP is partially recycled to increase the pellet size before dewatering and drying. Approximately 75% P is recovered as HAP from the wastewater. The HAP pellets, which contain 30 wt% P_2O_5 and 10 % as water, are sold to a fertilizer company at a low price. Because the wastewater is basically a Pi solution, the recovered product is very suitable for the manufacture of fertilizer (Ohtake & Okano, 2015).

In the industries of fermentation, the fermentation process using Pi as an essential raw material, thereby generating Pi-rich wastewater. P is removed from the wastewater by precipitation with $Ca(OH)_2$ (P removal > 90%). The recovered product is HAP (typically 29 wt% P_2O_5 and 59 wt% CaO).

Another way to P recovery is from wastewater from the production of edible oil. Edible oil is purified from crude oil, which is extracted from grains and fruits including soybeans, grapes, peanuts, and walnuts. Crude vegetable oil contains various phosphatides such as phosphatidyl choline, phosphatidyl inositol, phosphatidyl ethanolamine, and phosphatidic acid. They need to be removed in the early refining stage, because they are responsible for refining losses due to emulsion formation. The elimination of phosphatides from crude vegetable oil (called degumming) is the key step in vegetable oil refining. High-grade Pi is used to remove nonhydratable phosphatides by the liberation of phosphatides from Ca and Mg salts. Recovery of Pi from the wastewater by chemical precipitation with $Ca(OH)_2$ is also applied. Since the wastewater contains essentially no harmful substances, the quality of the recovered product (HAP) is suitable for the manufacture of fertilizer.

In the manufacture of liquid crystal glass substrates, Pi is commonly used as an aluminum-etching agent. Wastewater from an aluminum chemical etching process contains Pi as high as 5,000 mg/L. Although the Pi-rich wastewater can be chemically treated with $FeCl_3$ or $Ca(OH)_2$, this generates large amounts of precipitates, which must be disposed of as industrial wastes. The wastewater contains Pi, acetic acid, nitric acid, and aluminum (pH 2.0). Then, Pi is separated from acetic and nitric acids using a two-step reverse osmosis membrane system at 0.7-2 and 4 MPa, respectively. Since Pi is not transported through the reverse osmosis membrane, it can be concentrated to 4-7%, which is 40-60 times higher than that of the spent etching solution. This technology uses essentially no chemicals to recover Pi from a spent etching solution. Pi can be further condensed to 50% or higher by reduced-pressure distillation. The resulting Pi solution contains no impurities such as heavy metals. The recovered P can be used as a raw material for the manufacture of P-containing chemicals (Ohtake & Okano, 2015).

3.3.2.3. P recycling from other secondary resources

Animal manure has often been considered as a waste product and disposed of by application to land within a limited region of where it is produced. However, animal manure should be one of the major secondary P resources that have a potential to reduce reliance on mineral Pi fertilizer. P is added to the diet of pigs and poultry to prevent health problems, weak bones, and impaired fertility. Since much of the P ingested by animals is excreted in the feces, animal manure is a valuable source of plant nutrients and organic matter if it is adequately managed and applied.

Use of animal manure is currently hindered by its bulky nature, the risk of transmitting pathogens, the contamination of heavy metals, its undesirable odor, and the geographical separation of livestock farming from crop production. Many farms do not have enough land on which they can use the manure as organic fertilizer. Since the concentration of P in animal manure is not high, transporting them, especially over long distances, costs more than the P is worth. Additionally, if animal manure is applied as organic fertilizer over a long period, Pi over accumulation in soil can lead to the transfer of Pi to surrounding water bodies, leading to eutrophication.

More and more regions in and outside the EU are confronted with manure surpluses, due to the increase and the enlargement of non-land based livestock breeding. In the scope of the European Nitrates Directive, various member states have drawn up action plans to cope with these nutrient surpluses (Press Release - ManuREsource, 2015). The treatment of manure is one of the possible actions to reduce and manage the surpluses, and at the same time it is a way to recover the valuable nutrients.

The development of new techniques for manure treatment leads to new end products, which often can’t be defined as animal manure anymore. During anaerobic digestion, waste streams and agricultural residues are also used as input material. With the latest treatment techniques manure is refined into N-, K- and P-concentrates of which the composition tends to be a mineral instead of an organic fertilizer. This evolution brings a lot of work on European, national and regional policy level, in order to give an appropriate statute to these end products. Although the incineration of animal manure has been proposed to solve a manure disposal problem, it still remained economically infeasible owing the high cost of ash disposal.

P recovery from incinerated chicken manure ash has also been investigated using the acid leaching-alkali precipitation method on a pilot scale. Approximately 92% P could be recovered, demonstrating the potential of incinerated chicken manure ash as a secondary P resource.

3.3.3. Technologies and material at the development stage

3.3.3.1. Solid adsorbents for P recovery

Although Pi can be recovered from wastewater by chemical precipitation, the recovered product unavoidably contains a considerable amount of organic and inorganic impurities. In addition, after chemical precipitation, it is difficult to remove a low concentration of Pi remaining in the secondary treatment effluent of a WWTP. Asahi Kasei Chemicals Corporation (AKC) has developed a high-speed P adsorbent made of ion-exchangeable ceramic beads. The ceramics beads, which have an average diameter of 0.55 mm and 85% porosity, exhibit a high specificity for Pi (Fig. 10). The high porosity allows fast Pi diffusion and smooth Pi adsorption on the ceramic beads. In addition, the ceramics are very stable in a wide pH range from 2 to 14. Their Pi adsorption capacity is maintained even after being used more than 100 times.

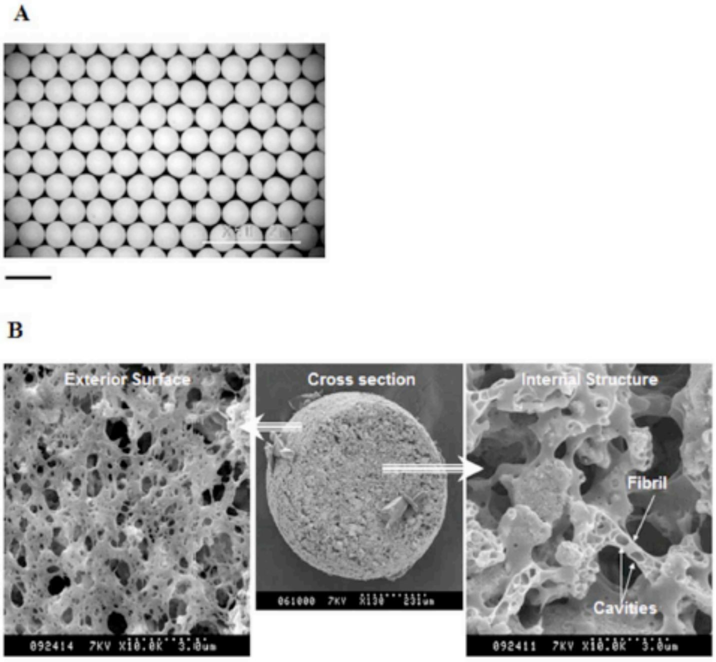


Figure 10 High-speed P adsorbent made of ion exchangeable ceramic beads. (A) ceramic beads packed in a column (bar, 0.5 mm); (B) scanning electron microscopy image of the ceramic beads (bar, 2 mm). Photograph courtesy of I. Midorikawa (Asahi Kasei Chemicals Corp. (Ohtake & Okano, 2015)

Another solid adsorbent for P recovery is prepared from concrete sludge, which is an alkaline industrial byproduct consisting of hydrated cement aggregates and water. It has developed an inexpensive solid adsorbent, named PAdeCS (Phosphorus Adsorbent derived from Concrete Sludge), for recovering Pi from wastewater. To produce PAdeCS, concrete sludge is mixed with water at room temperature and atmospheric pressure. After solid-liquid separation, solids are dewatered, dried, and pulverized. Since the liquid phase is strongly alkaline and rich in calcium, it can be used as an aqueous solution for CO_2 absorption. The resulting precipitates can be recovered as a marketable $CaCO_3$ with a purity of more than 95 wt%. Various sizes of PAdeCS particles can be prepared, depending on their application. PAdeCS can rapidly remove Pi from aqueous solutions, simultaneously acting as the calcium source, alkali substance, and seed material. Pi is removed in the form of low-crystallinity HAP on PAdeCS particles (Ohtake & Okano, 2015).

3.3.3.2. Direct struvite recovery from digested sludge

Direct removal of struvite from digested sludge is effective not only for preventing scaling problems but also for improving sludge dewaterability. The improvement of sludge dewaterability leads to a significant reduction in sludge disposal costs, since it reduces the volume of sludge that needs to be transported and incinerated. More struvite can be recovered directly from digested sludge than from liquor rejected by a solid/liquid separator.

AirPrex process is an example for a direct P recovery from digested sludge. In this process pH increase is achieved by CO_2 stripping with intensive aeration. Additional Mg(II) is added as $MgCl_2$ solution. Sedimented struvite crystals are harvested at the bottom of the reactor (Figure 11).

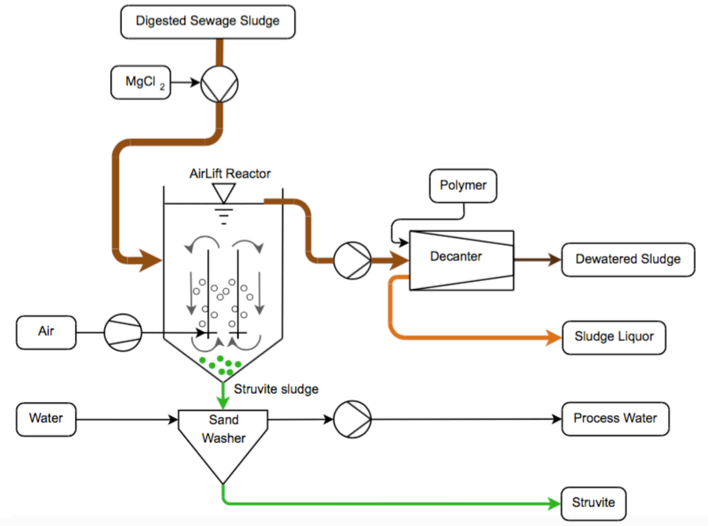


Figure 11 Airprex Process Scheme (Remy & Jossa, 2015)

3.3.3.3. P recovery by amorphous calcium silicate hydrates

Amorphous calcium silicate hydrates (ACSHs) are a new cost-effective adsorbent for recovering Pi from aqueous solution. ACSHs, which have a Ca/Si molar ratio of 1.0 or greater, could be synthesized using unlimitedly available, inexpensive materials such as siliceous shale and calcium hydroxide. Since the reaction of Pi with ACSHs occurs at pHs 7.0-9.0, it is not necessary to adjust the solution to alkaline pH. The high settleability, filterability, and dewaterability of recovered P are the advantages of ACSHs over conventional $CaCl_2$ and $Ca(OH)_2$. Because of the high settleability, no chemical coagulant is required for Pi recovery by ACSHs. Moreover, unlike Ca(OH)2, no significant carbonate inhibition occurs in Pi recovery using ACSHs.

ACSHs consist of inorganic silicate residues having an average chain length of 3.5 in the form of liquid slurry. The short-length silicate polymers are linked to each other through ion bindings with Ca^{2+}. ACSHs release short-length silicate polymers when they are dispersed in aqueous solution. This allows the divalent hydrogen phosphate anion (HPO_4^{2-}) to form ion bindings with Ca^{2+} in place of the silicate polymers. Conventional P recovery from wastewater is a multiple-step reaction process that requires costly automatic process control. In this respect, ACSHs have a potential to simplify P recovery processes. ACSHs can be added to a Pi-rich aqueous solution in slurry form. After 10-20 min of mixing, P adsorbed by ACSHs is recovered by settling without using any chemical coagulant. Importantly, the recovered P can be directly used as a byproduct Pi fertilizer.

3.3.3.4. P recovery from swine solids and wastewater

Carbonization is highlighted as one of the important technological options to recover P from swine manure. Carbonization can promote the conversion of animal manure into charcoal, thereby reducing the solid volume. It is used as a pretreatment of raw biomass which is not suitable for direct combustion because of the low energy density and high moisture content. Since carbonization requires relatively low technical resources, it is suitable for small-scale swine farms.

Nearly all of the P present in pig manure can be accumulated on the surface of the hydrothermally prepared bio-char. This was possible when pig manure was heated indirectly and evenly at a constant temperature of 400°C. P can be recovered in condensed form (20 wt% P_2O_5) by mechanically collecting the P-rich surface fraction of the bio-char (P-rich bio-char). The remaining fraction of bio-char contains less P (typically 12 wt% P_2O_5). Approximately 120 kg of P-rich bio-char is produced from 1,000 kg of pig manure compost. These P-rich materials are effectively used as P fertilizer (Ohtake & Okano, 2015).

BioEcoSIM developed and demonstrated a resource and energy efficient pilot plant for the continuous conversion of wasted livestock manure into stable materials that can be easily handled, transported, and applied: pathogen and antibiotic free, phosphorous rich organic soil amendment (biochar), mineral fertilisers: ammonium sulphate (AS), calcium phosphate (CP) and struvite, reclaimed water and syngas.

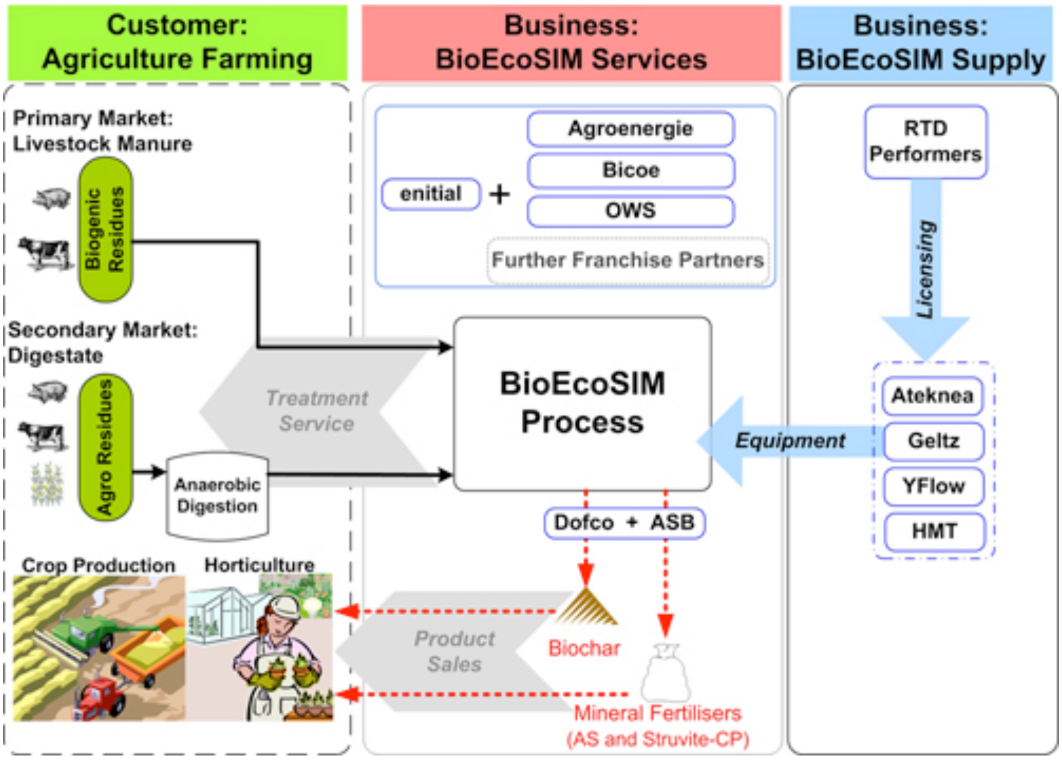


Figure 12 Business model of BioEcoSIM for the valorization of swine solids and waswater (BieEcoSim, 2012)

The Figure 12 summarises the principle of the BioEcoSIM business model and shows the primary exploitation routes anticipated by each individual project partner. A business model was developed to enable impact within the medium term

3.3.3.5. Thermochemical conversion of incinerated sludge ash to fertilizer

P leaching from incinerated sludge requires large amounts of chemicals, thereby making it difficult to lower the cost than the economic value of the recovered product. If heavy metals need to be removed, additional cost is required to obtain safe recovered products. An alternative for chemical Pi leaching from sludge incineration ash is via thermochemical methods. Problematic heavy metals can be removed from sludge incineration ash by heating at 900-1000°C in the presence of KCl or $MgCl_2$. P loss during the thermo-chemical treatment can be minimized by granulating sludge ash into pellets. Thermochemically treated sludge ash can be used as NPK fertilizer after being supplemented with NH_4NO_3. Since fertilizer is a relatively inexpensive commodity, the potential of the thermochemical method as a P recycling option depends on how to reduce the fuel cost for calcination (Ohtake & Okano, 2015).

The ASHDEC process thermochemically treats sewage sludge ash (SSA) in a rotatory kiln and has been jointly developed by Outotec and BAM Federal Institute for Materials Research and Testing (Figure 13).

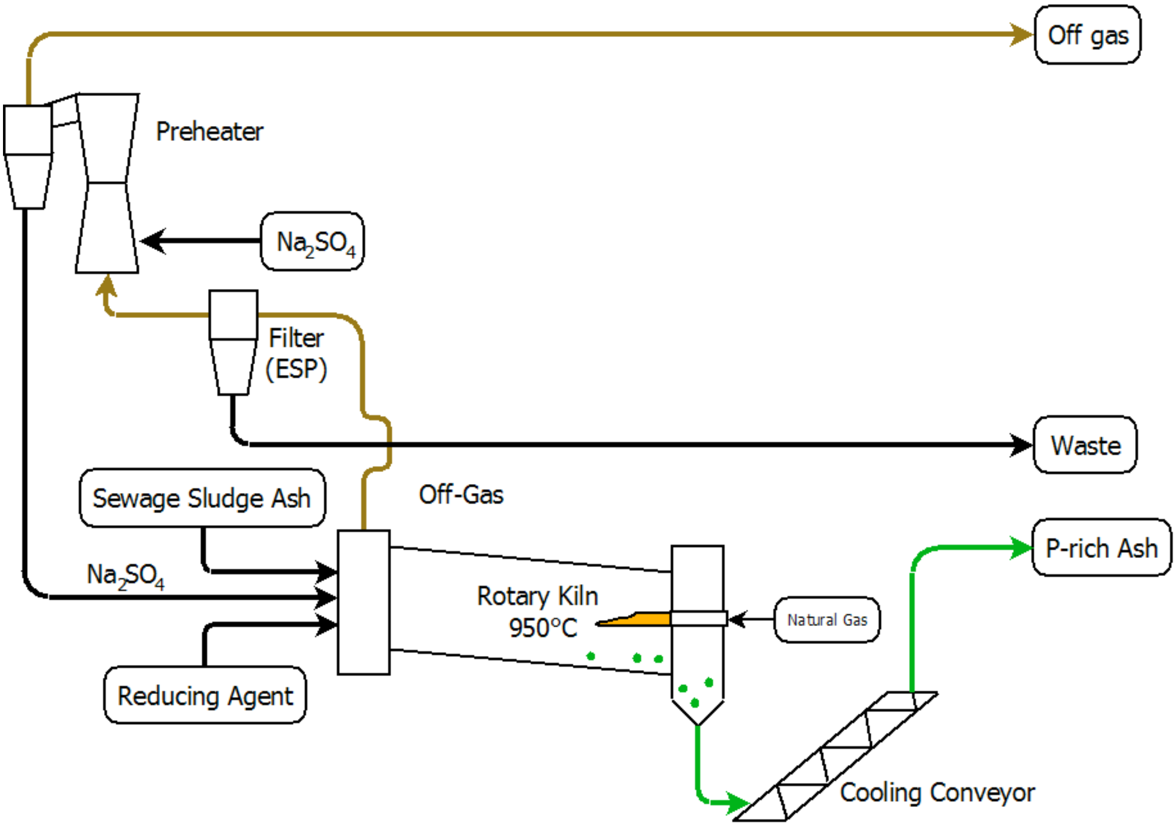


Figure 13 Ashdec Process Scheme (Remy & Jossa, 2015)

3.3.3.6. P recovery from steel-making slag

In the steel-making process, P is present in raw materials such as iron ore, coal, and limestone at concentrations as low as 0.03 wt% P_2O_5. Since P has detrimental effects on the mechanical properties of steel, it needs to be removed into hot metal pretreatment slag (dephosphorization slag). Dephosphorization slag contains approximately 2-10 wt% P_2O_5. P emitted into dephosphorization slag is about two times more than that of sewage sludge. Hence, dephosphorization slag should be a quantitatively important secondary P resource, but it is currently landfilled or used as cement and road construction materials. Since P-rich particles exhibit antimagnetic properties, it is possible to separate P-rich particles after pulverizing dephosphorization slag using the wet magnetic separation technology. It has also been investigated to recover P from steel-making slag using microwave irradiation at a bench scale. P is carbothermically reduced into the metallic phase and then extracted from the metal by carbonate flux treatment at 1200^{o}C. As a result, P is concentrated in the fluxes at more than 9 wt%. Microwave processing is a simple and efficient way of heating steel-making slag.

Recently, the iron and steel industry has paid considerable attention to P removal from dephosphorization slag for economic and environmental reasons. The global production of iron ore is approximately 2,000 mt/y. Assuming that the P content of iron ore is 0.03 wt% on average, it can be estimated that approximately 0.6 mt/y of P ends up in dephosphorization slag. This is equivalent to one-fifth of the annual world demand of industrial P (2.8 mt/y) (Ohtake & Okano, 2015)

3.3.3.7. Elemental P regeneration from secondary resources

The wet acid process for the manufacture of phosphoric acid requires highly beneficiated Pi ores as a raw material and makes a rather impure grade of phosphoric acid. High-purity phosphoric acid, which is an essential raw material in high-tech industries, is obtained mainly by burning elemental P (P_4) to phosphorus pentoxide (P_4O_{10}). Currently, production of elemental white P is limited to China, Vietnam, USA, and Kazakhstan (Ohtake & Okano, 2015). In particular, China produces approximately 70% of the world production. Japan imports approximately 30 kt/y of white P. However, the manufacturing industry has often struggled with the soaring price of imported elemental P. Consequently, the manufacturing sector has paid considerable attention to the sustainable supply of industrial-grade P, particularly white P.

Pi can be reduced to elemental P using coke at a temperature of over 500ºC. Since the boiling point of elemental P is 280ºC, it is evaporated as tetrahedral P_4 gas. $AlPO_4$ and $Ca_3(PO_4)_2$ can release P_4 when they are heated anaerobically at over 1,000 and 1,050ºC, respectively. Consequently, Pi in incinerated sludge ash can be reduced to white P at over 1200^{o}C as long as the iron content is sufficiently low. Iron forms ferrophosphorus with P, thereby disrupting the formation of P_4 gas. The reductive melting of incinerated sludge ash requires the use of an electrical heating furnace with an enclosed structure. P_4 gas from the furnace can be recovered in liquid form using a cooling condenser at a temperature higher than the melting point of white P (44^{o}C). P_4 can also be oxidized to P_2O_5 and absorbed in water.

It is also possible to use a high-temperature kiln-based process to generate P_4 gas from P-rich incinerated sludge ash as a substitute for high-grade Pi rock. Interestingly, it has been observed that a detectable amount of P is removed from steel-making slag to the gas phase as diphosphorus (P_2) in a bench-scale experiment using an arc plasma furnace. This observation suggests the possibility of recovering elemental P from steel-making slag, if the arc plasma furnace is kept sealed.

3.4. Tertiary resources of P

Tertiary phosphorus resources are referred to as those that improve the efficiency of products, materials or other activities to reduce the amount of P that are used in them. P management has been an issue in handling sewage since the early 20th century, the focus appears to have been more on prevention of eutrophication by direct discharges to surface water and less on reuse of clean P. On the other hand correlations have been found between natural resource efficiency and profitability of industries and farms.

Partially such incentives might be sought in the development of new social norms (e.g.in the case of source separation of organic wastes by households), in stricter regulation of P utilization andin ecotaxation of virgin P use.

Technically speaking, there is substantial potential for changing uses of P in the economy in a way favouring P resource conservation. In improving P resource conservation, current sideeffects of P use such as ecosystem deterioration due to eutrophication and human intakes of P which are too high may be reduced, if compared with ‘business as usual’.

Changes conducive to the conservation of remaining P resources include: restricting phosphorus use to essential uses; improving the efficiency of P use; food system change; and increasing P recycling in the economy

3.4.1. Restricting phosphorus use to essential uses

To conserve phosphate resources, there is a case for restrictingfossil P use to essential uses. Essential uses are definedhere as uses of P in the economy for which no substitute exists or uses of P for which substitutes exist but are more of an environ-mental burden.

The applications of P compounds in the economy currently leading to substantial losses of P from the economy are in part substitutable. The applications in baking powder, producing potatochips, in detergents, as water binder in meat and fish products, in tap water to lower Pb levels, as pH regulator in drinks, as metal coating and as fire-retardant in electronics and polymers are examples thereof.

Substituting P compounds may have substantial impacts on P losses from the economy. Substituting phosphates in detergents may reduce P losses from the world economy by about 0.9–1.1 × 10^{12} g yr^{-1} at no net costs and ending the use of P as food additive may reduce worldwide P losses from the economy by about $0.2.10^{12}$ g yr^{-1}. (Reijnders, 2014)

However there are also applications of phosphorus without substitutes. Quantitatively very important (> 80% of fossil P) among the inputs of phosphate in the economy is the application of phosphateas nutrient in agriculture. High agricultural yields are critically dependent on inputs of functional P. In view ofthe current and expected near future demand for food, this application of P should be considered essential.

3.4.2. Improving the efficiency of P use

P losses from the economy in phosphorites mining and beneficiation and in agriculture are relatively large. Improving the P efficiency in mining and beneficiation corresponds here with improving the overall recovery of P from phosphorites. Efficiency in agriculture is defined here in terms of yield (kg dry weight) per g P added (Reijnders, 2014). Losses of P from the economy associated with postharvest food losses are also relatively important.

3.4.2.1. Improving P efficiency in mining and beneficiation

Losses of P originating in mining of phosphate rock and the beneficiation of mined phosphate rock might, ceteris paribus, well increase when the trend that mining generates on average phosphate rock with lower P content continues. There is, however, substantial scope for producing phosphate from current tailings (production residues) at mines and increasing P efficiency of beneficiation. Particle size control in grinding operations may be conducive to improved P recovery from mined phosphate rock. Flotation is an important process in many mining and beneficiation operations and improvements therein may be conducive to the better P recoveries from mined phosphorites. Such improvements regard process additives, the application of dissolved air flotation, cyclonic flotation and anionic-cationic reverse flotation. The application of online analytic technology and, where applicable, the application of calcination and magnetic and electrostatic separation technologies may also contribute to the improvement of P recoveries. Selective P leachingby organic acids might be considered to increase the P efficiency of beneficiating calcareous phosphate ores.

3.4.2.2. Improvements in agricultural practices

Agriculture alone results in the depletion of approximately 19 Mt/y of P from phosphate rock for fertilizer production (Schroder, Smit, Cordell, & Rosemartin, 2011). However, due to inefficiencies in the food production and consumption chain, only one-fifth of this P reaches the food eaten by the global population. The depletion rate of reserves for P fertilizer production (and the associated emissions of P due to the use of fertilizers, manures and human waste), are expected to increase as the world population will grow by another 3 billion people over the next 40 years (Schroder, Smit, Cordell, & Rosemartin, 2011). Moreover, increased per capita use of fertilizer P is imminent due to a gradual change towards diets richer in meat and dairy products for which more feed crops must be produced. Further, an additional need for fertilizer P may be triggered by the decision to grow bio-energy crops, in particular if these crops are to be grown on ‘marginal’ land, poor in nutrients, to avoid competition with food and feed production and if nutrients in the associated ashes or cakes are not recycled (Schroder, Smit, Cordell, & Rosemartin, 2011)

Efficiency alone, however, is not sufficient to manage a finite resource as long as the loss rate is orders of magnitude greater than the geological regeneration of new reserves. High grade phosphate rock reserves are likely to be depleted within 50–150 years. Further, the critical point in time when production peaks ('peak phosphorus') is predicted to occur by 2035, after which demand will outstrip supply. It is widely accepted that phosphate rock reserves are decreasing in grade (% P_20_5) and accessibility, and increasing in contamination levels, requiring additional energy inputs and costs.

Such measures can essentially buy the time to develop and implement a truly sustainable solution that involves complete recycling of P from industries and urban areas back to agriculture. A full and safe recycling of that P requires re-integration of our food production, processing and consumption system.

This section reviews a range of potential measures to improve P use efficiency. The analysis starts with agricultural land use as such and the losses to which tilled soils in particular are exposed. Subsequently, we take a closer look at the P flows crossing the boundaries of an individual field. Finally, we expand this system with a livestock component and the attending measures needed for a better P use efficiency in farms that involve both crops and animals.

i. Optimising land use

Agriculture is mainly an outdoor activity and growing conditions are thus not always fully under control. Consequently, some losses of P are probably inevitable even if soils, crops and fertilizers are managed according to the best available techniques. On a global scale these inevitable losses from fields will be more extensive. It is therefore imperative to find the optimal balance between a sufficiently high productivity per hectare, limiting land demand but requiring a sufficient P content, and keeping P contents in soils low as to minimize losses per hectare. Whatever the position on this balance, the composition of the human diet is also a determinant of land use and attending P losses, since more land is generally needed to produce meat and dairy products than vegetal-based products. The same holds for additional land claims to produce bio-energy crops.

ii. Preventing erosion

Erosion encompasses water erosion, wind erosion, tillage erosion and the erosion resulting from soil particles adhering to lifted crops such as sugar beets. Louwagie et al. (2009) reported that of the total European land area 12% suffers from water erosion and 4% from wind erosion (Louwagie, Hubertus Gay , & Burrell, 2009).

Quantifying the P loss associated with erosion is fraught with difficulty. Firstly, eroded material is not really lost as long as it is deposited and subsequently accounted for as an input in the receiving agricultural area. Secondly, quantification is also troublesome because data sets tend to be derived from experiments in regions where erosion is an issue. Up-scaling these data to a larger area including the more flat regions in particular those with a permanent cover in the form of grassland, is an inaccurate process. Estimates of the amounts of soil lost via erosion range from 5 to 40 Mg/ha^{-1}a^{-1} for an average European arable soil to 10 Mg/ha^{-1}y^{-1} at most for the major part of Europe. Thirdly, it is even more complicated to translate these losses of soil into P losses as that requires knowledge of the P-concentration in the eroded material. Data provided in Schroder et al. (2011) suggest that P-concentrations in an average European soil range between 0.05% and 0.10%. This implies that erosion of 10 Mg of soil ha^{-1} a^{-1} represents an annual loss of 5–10 kg P ha^{-1}. This is a considerable amount but less than the numbers given Schroder et al. (2011) who found that at a global scale 20–30 Mt a^{-1} of P is lost via erosion. This would be equivalent to an annual loss of 15–20 kg P ha^{-1}, Assuming that erosion from land other than arable land is negligible. Schroder et al. (2011) found data suggesting that approximately 13,8 and 3 kg P ha^{-1} is annually lost from arable soils, overgrazed pastures and ordinary pastures, respectively. Many of the erosion abatement measures are hence directed at improving the infiltration capacity of soils, such as: minimum tillage without removal of crops residues, ridge tillage, sub-soiling, terracing, contour ploughing, buffer stripping, cover crop establishment, conversion of arable land into grassland, agro-forestry, or complete reforestation. Schroder et al. (2011) found that this type of measures were able to reduce erosion loss in the United States by 42% between 1982 and 1997. Schroder et al. (2011) also found that recently evaluated mitigation options for P loss from winter cereals in the United Kingdom. They concluded that disturbing the soil in fixed wheel tracks (‘tramlines’) with a tine, in particular, reduces erosion-related P loss by up to 99%. Common European bans on the spreading of fertilizers and manures on frozen or snow-covered land, combined or not with a mandatory incorporation, also reduce the risk of erosion and P loss.

iii. Maintaining soil quality

The presence of P in a soil is not a guarantee for its productiveness. Soils must fulfil many other characteristics to assure that this P is available to crops and that it can be efficiently utilized, once taken up. This complex set of characteristics is called soil quality. However too much focus can harm rather than improve the use efficiency of resources. The concept of soil quality is therefore still a subject of fierce debates. Regardless of this ongoing debate, it is absolutely safe to say that more P will be needed to attain a certain yield if the pH of a soil is suboptimal, if soils contain too little or too much water, or if soil compaction hampers root growth. Optimising the structural soil quality can thus increase the accessibility of P reserves in deeper soil layers, reduce the need for fertilizer P supplements, and improve the use efficiency of P. Schroder et al. (2011) found that it is indeed the organic matter mediated soil structure rather than the organic matter itself that improves the availability of phosphorus. A 60% increase of the organic matter content (i.e. from 1.5% to 2.4%) reduced the Olsen P value required for near maximum yields in their Rothamsted trials from, on average, 46 to 17 mg kg^{-1} under field conditions, whereas this apparent effect of organic matter did not occur in a pot experiment once these soils were sieved and lost their structure.

iv. Improving fertilizer recommendations

From 70–80% of the soils in Europe show an average or high level P-status. At such type of conditions it would be possible to maintain yields for several years even without P-fertilisation. It is recommended range of soil fertility of approximately 500 kg $P.ha^{-1}$ would be needed to bring the soil from the lowest to the highest recommended fertility level. This amount is equivalent with the P taken off by crops in around 20 years and it was suggested a critical revision of the recommendation systems to ensure a more efficient use of P fertilizer (Schroder, Smit, Cordell, & Rosemartin, 2011).

In more general terms P utilization can be improved if uniform blanket dressings would be replaced by differentiated applications, tuned to specific needs of individual crops and fields, of patches within fields, of particular positions within the bulk soil, and of periods within seasons. Farming practices characterized by fixed ‘insurance’ shots of P, should hence be replaced by more reasoned ‘precision farming’ applications of P. There is an obvious need for a correct assessment of the true P requirement of soils and a better knowledge of the P-supplying ability of the various types of inputs. As for the true P requirement of soils, P should not be applied on a routine basis but instead be determined by the amounts of plant-available P. These amounts depend on earlier inputs and exports in crop produce and on the tendency of some soils, for example those rich in iron or aluminium, to fix P. The truly ‘inevitable’ P loss is therefore relatively low, unless soils are rich in iron and aluminium. ‘Inevitable’ P losses can also be high if growers want to maintain the P concentration in the bulk soil at an unnecessarily high level, like keeping a colander filled up with water up to its brim.

v. Fertilizer placement methods

As indicated earlier, P should preferably be applied in the most intensely rooted parts of a soil. According to fertilizer recommendations in The Netherlands, twice as much P is needed for a similar yield response if the fertilizer is broadcast instead of sub-surface positioned close to seed row (Schroder, Smit, Cordell, & Rosemartin, 2011). It is the combination of the application method of P containing inputs and the subsequent tillage that determines whether supply and demand spatially match. This has implications for the optimal positioning of inputs in both the vertical and horizontal plane. As far as the vertical aspect is concerned, the positioning of manure may be too deep for a good utilization of P in an attempt to reduce the volatilization losses of ammonia-N from manure. As for the horizontal aspect of placement, proper attention must be given to spreading techniques. Irregular, patchy spreading patterns increase the heterogeneity of the soil fertility. Consequently, some parts of the field may become over-fertilised, whereas other parts may become deficient. The previous warning for a too patchy distribution of manure must not be seen as a general argument for a uniform distribution. In crops with a wide row distance, for instance, yields and P utilization may benefit from techniques that apply manure close to the anticipated position of rows.

vi. Improving crop genotypes and promoting mycorrhizas

At a young stage root length can be the limiting factor for the acquisition of soil P. Genotypic differences in terms of the way a plant allocates its assimilates to either aboveground parts or roots, and differences in specific root length, branching or in the distribution of a given length of roots through the soil profile, may hence affect the ability of plants to absorb P. P use efficiency of crops is, however, not just determined by the uptake efficiency but also by the utilization inside the plant once the P is taken up. There is little benefit in a better uptake efficiency if production of the economically relevant plant parts per unit P taken up is lower, as production per unit P applied would then not be improved. It is difficult to say a priori whether there is sufficient genotypic variation of both traits to justify breeding programs explicitly directed at the improvement of P use efficiency. Decisions on investments in breeding research should consider the value for money that is to be gained via alternative investments, that is on adjusted soil and crop management.

Crops can also extend their uptake capacity through a symbiosis with beneficial fungi. Associations between crops and these socalled arbuscular mycorrhizal (AM) fungi can thus improve the availability of soil P. Schroder et al. (2011) attribute this to an effectively enlarged root system rather than to an enhanced solubility of P by the fungi. Their review shows, however, that carbon costs are involved in hosting AM fungi. Crops manage to suppress AM fungi when the association does not pay off due to a high P soil status. Even when the soil P status is low, the composition of the crop rotation and tillage practices do not always support a sufficient presence of AM fungi. This may require adoption of minimum tillage techniques, seed inoculation or adjustments of the crop rotation.

The use of LPA mutants (cereals with a lower content of phytic acid) for food and animal feed, may be another promising avenue. Schroder et al. (2011) found that a widespread use of these mutants could lead to considerable reductions in global P fertilizer requirements.

vii. Adjusting inputs to outputs

In the preceding sections the focus was on P inputs and their availability to crops. Obviously, P surplus and use efficiency are also determined by the P output. The amount of P that eventually leaves the farm via the gate may be easily overestimated.

Circumstantial evidence for a structural overestimation of the amounts of P exported in produce and an underestimation of the amounts of P available from the various types of inputs is reflected by the ongoing increase of the P status of many soils in Western Europe. This suggests that P inputs can be reduced and much better balanced with outputs.

viii. Exporting manure

Any P export justifies P inputs. P can leave the farm in the form of crops, milk, eggs, meat and wool, but also in the form of manure. From a purely theoretical P use efficiency point of view, it does not matter whether livestock are fed home-produced feeds or imported feeds as long as the P that is not retained in marketable products, that is the P in manure, returns to the land where the feed originates from. The positive relationship between regional livestock densities and P soil surpluses shows, however that in reality such a perfect recycling is complicated by economic and energetic considerations. Consequently, soils generally accumulate P in regions with a high livestock density, whereas soils may become P depleted in regions where the feed originates from, unless the latter are supplemented with mineral fertilizer P. A more even distribution of livestock over the area where the feed is produced could thus contribute to a more efficient use of P.

In regions with manure surpluses there may be incentives to over-apply manure-P even on stockless farms. Horticultural farms, for instance, are inclined to cover their need for organic matter (OM) and N with ‘free’ excess manure from neighbouring livestock farms. Farms in need of N rather than P could still use manures without the risk of P accumulation, if they were only to use the ‘liquid’ fraction resulting from manure slurry separation. The associated ‘solid’ fraction, rich in P, is less bulky and can thus be more easily exported to remote farms in need of P.

ix. Adjusting livestock diets

The ability of mammals, non-ruminants in particular, to absorb P from feed is limited. To avoid production losses due to temporary P deficiencies, livestock farmers in industrialized countries therefore select feed stocks with naturally high P concentrations or even add P salts to feed stuffs. Globally, 5% of P demand is for feed additives, that is approximately 1 Mt a^{-1} of P. In the EU27, however, a much larger share is used in feed. The EU27 imports 0.3 Mt a^{-1} of P as feed additive, next to 1.6 Mt a^{-1} of P imported as raw material for fertilizer production or as commercial fertilizer. This increased P input via feed additives reduces the relative utilization of P within the animal and results in more manure P being produced. This can lead to an undesired local P soil surplus. The production of manure P can not only be reduced by reducing livestock numbers but, what may be economically more attractive, also by reducing the amounts of manure-P excreted per unit milk or meat produced. P excretion can, for instance, be reduced by supplying less feed-P the older the animal gets , by tuning the daily ration of individual animals to their actual production level, and by the use of artificial enzymes . Such enzymes can improve the availability of feed-P . Dietary adjustments such as these can reduce the throughput of P in farms and can, hence, increase the utilization of P (Schroder, Smit, Cordell, & Rosemartin, 2011).

3.4.2.3. Food system change

Substitution of meat protein by plant protein might on average improve P use efficiencyof food protein currently supplied by meat by about a factor 7-13. Reducing post-harvest food losses is another way to improve the efficiency of P use, partly, by system changes. Such post-harvest food losses have been estimated at about 19% of harvested produce for China. In the United States a progressive increase in food waste over the 1974-2003 period has been noted and a recent study suggests that in the USA about 27% of harvested food is been lost. Lower percentages of harvested food lost (<10%) have e.g. been suggested for sub-Saharan Africa estimate the yearly amount of P associated with worldwide post-harvest food wastes at about $2.3.10^{12}$g P. (Reijnders, 2014)

It has noted that losses of perishable foods are relatively high, as are losses at immediate post-harvest stages in developing countries. Improvement of collaboration by those involved in the food supply chain tends to be viewed as important in reducing post-harvest food waste. Other options suggested for reducing food losses include: improvements in storage along the food supply chain; better transport containers; cost-saving waste minimization in the food industry and food services; improved automatic forecasting of demand by retailers, Improved food labelling; donations to charitable organizations and; campaigns to change awareness of environmental impacts and behaviour of consumers and food services.

4. Phosphorus flow analysis

4.1. Substance flow analysis (SFA): a tool for managing phosphorus

Since the early 1990s, Substance Flow Analysis (SFA), also referred to as Material Flow Analysis (MFA), has been used to examine resources such as water and energy, metals and toxic substances at a wide range of geographical scales (from global to local) (Cordell, Schmid, & Prior, The phosphorus mass balance: identifying 'hotspots' in the food system as a roadmap to phosphorus security, 2012). The method was established in the field of Industrial Ecology to aid environmental management by assessing the 'metabolism' of human or technical systems, often referred to as the technosphere or anthroposphere. The method is based on the principle of mass balance, which enables a systematic assessment and tracking of the flow of goods, materials or substances between various processes in the relevant sectors, as well as imports to and exports from the system that are typically measured in units of mass per year. A conceptual substance flow analysis diagram showing the interactions between the 'anthroposphere' (human activity system) and the natural environment is shown in Figure 14.

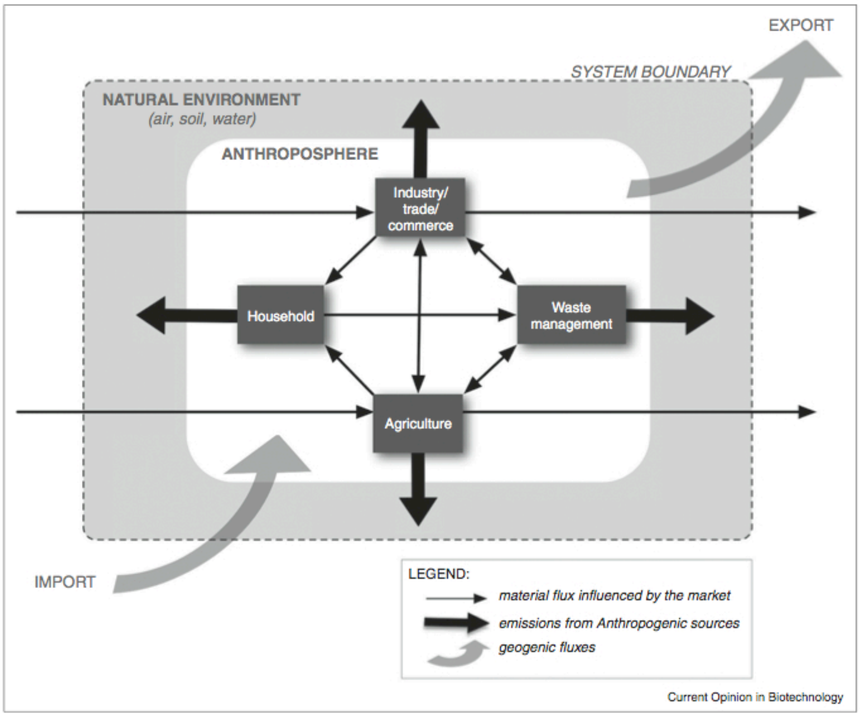


Figure 14 Conceptual substance flow analysis diagram showing the interactions between the 'anthroposphere' (human activity system) and the natural environment. Redrawn from Baccini and

Brunner (Cordell, Schmid, & Prior, The phosphorus mass balance: identifying 'hotspots' in the food system as a roadmap to phosphorus security, 2012)

SFAs can aid the identification of key flows or 'hotspots' of the substance under investigation, thereby facilitating more effective and prioritized management of the substance within that system. However, SFAs only provide a quantitative (rather than qualitative) picture, and data availability and reliability are often poor.

Nutrients, and in particular phosphorus, have been the subject of many substance flow studies. The early focus of this work was primarily pollution and leakage, but has more recently shifted to assessments of scarcity and food security, as the latter issues have received increased attention. A recent workshop focused on national-level phosphorus SFA studies stressed that both pollution and scarcity aspects are important to include. The workshop demonstrated the need for an integrated assessment of phosphorus flows between sectors (such as fertilizer, food and sanitation sectors) at the national/regional scale in order to decrease losses and increase efficiency, recovery and reuse of phosphorus within the food system.

The selection of the proper geographical scale is important to ensure the inclusion or exclusion of any vital sector because the outcome of the P flow analysis often depends on this. It is therefore apparent that P flow analysis without informed choice of geographical scale will often exclude certain sectors, and may not provide the comprehensive information required to make policy decisions, which ultimately indicates the necessity of cross-scale or multi-scale analysis (Biswas Chowdhury, Moore, Weatherley, & Arora, 2014). Analysis of P flow utilizing the linkages between different geographical scales could generate new knowledge required to achieve better P management. For instance, if P recovered from a waste stream at the city scale is utilized in the agricultural production sector at the regional scale, it will eventually reduce the P inflow as imported fertilizer at the country scale.

At the city scale, human consumption and waste management are the two key sectors of P flow. Through trade and commerce sector is quite important in terms of P flow at the city scale. Agricultural production is the main sector at the regional scale, and the key difference between the city and regional scale lies in the presence of this sector. However, the small-scale agricultural sector is sometimes found in some cities, and occasionally considered in the city scale analysis. The phosphorus fertilizer production sector is not usually found at the regional scale, and in some cases, at the country scale too, except for those in countries having high reserves of phosphate rock and/or P fertilizer production such as China and the US. The country scale is spatially far bigger than the city and regional scales, and usually includes the P mining and/or fertilizer production sectors, and a coastal water sector along with other key sectors that are contained in the city and regional scales (Figure 15). The global and multiple country scales consider the sectors available at the country scale along with the sectors that extend beyond the country scale such as river systems, coastal waters and the ocean.

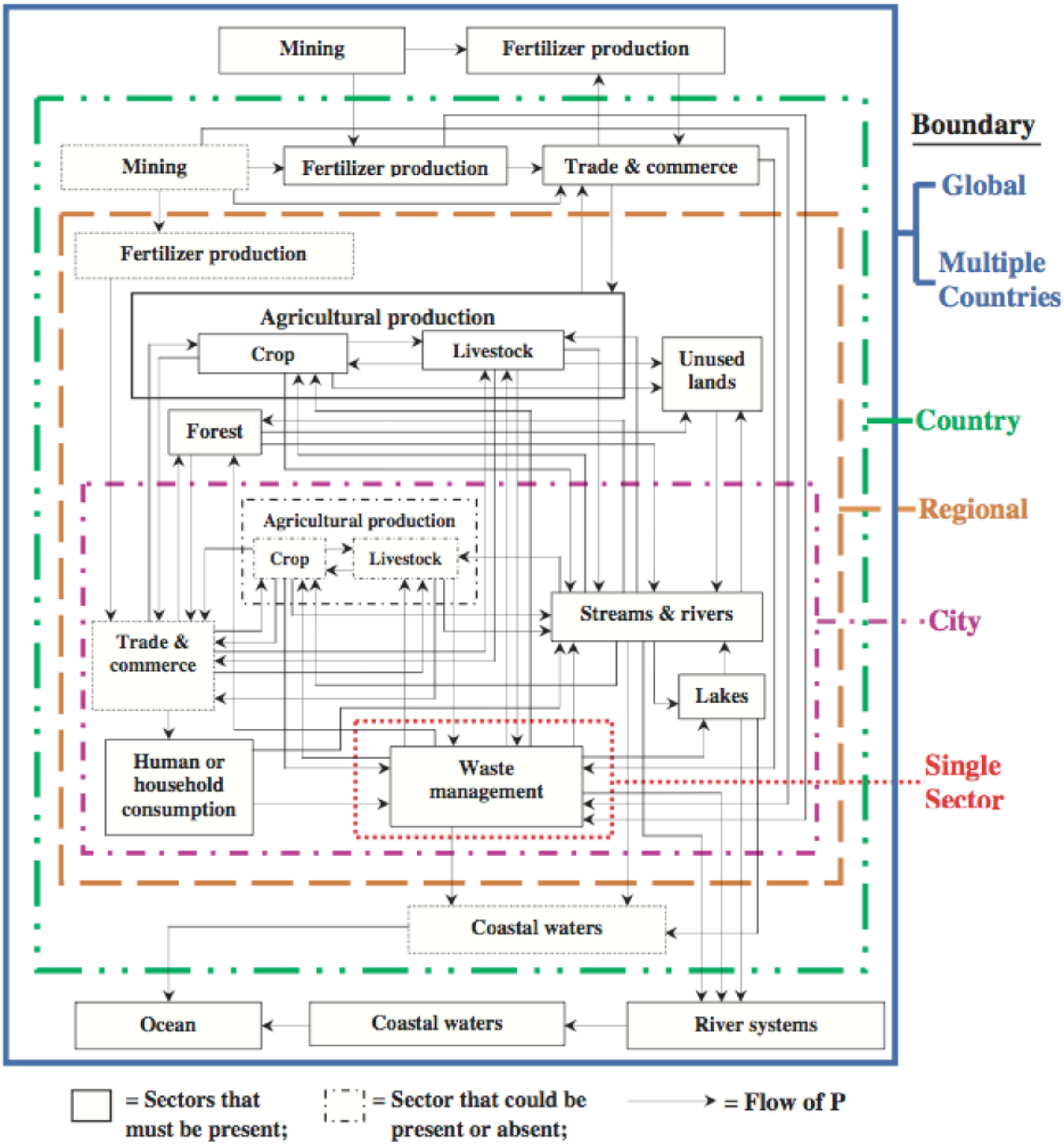


Figure 15 Key sectors of P flow across different geographical scales and the intersectoral interactions in terms of P flow (Biswas Chowdhury, Moore, Weatherley, & Arora, 2014)

Understanding the key P inflows and outflows related to a particular geographical scale is vital to identify the priority areas of P management for that scale.

The main P inflow at the city scale occurs through imported food to human consumption sector, food has been identified to account for nearly 100% of the total P inflow (Table 4). In some of the city scale studies, either chemical P fertilizer, animal feed, or detergent has been observed to be one of the key P inflows after food however, these flows account for less than 35% of the total inflow. At the regional scale, the major P inflow has been identified to occur either as fertilizer, mineral ore, or animal feed. In the absence of P fertilizer production industry, the major P inflow at the regional scale occurs either through the import of chemical P fertilizer or animal feed, and with its presence, the main P inflow usually occurs as mineral ore import.

In most of the country scale studies, either mineral ore or chemical P fertilizer import has been observed to be the key P inflow. Import of P as chemical fertilizer is another main inflow at the country scale particularly in the countries with low reserves of phosphate rock. P inflow in the country scale can also occur either through the import of animal feed or human food.

Table 4 Main inflow, outflow, stock and recycling flow of P at different scales according with (Biswas Chowdhury, Moore, Weatherley, & Arora, 2014)

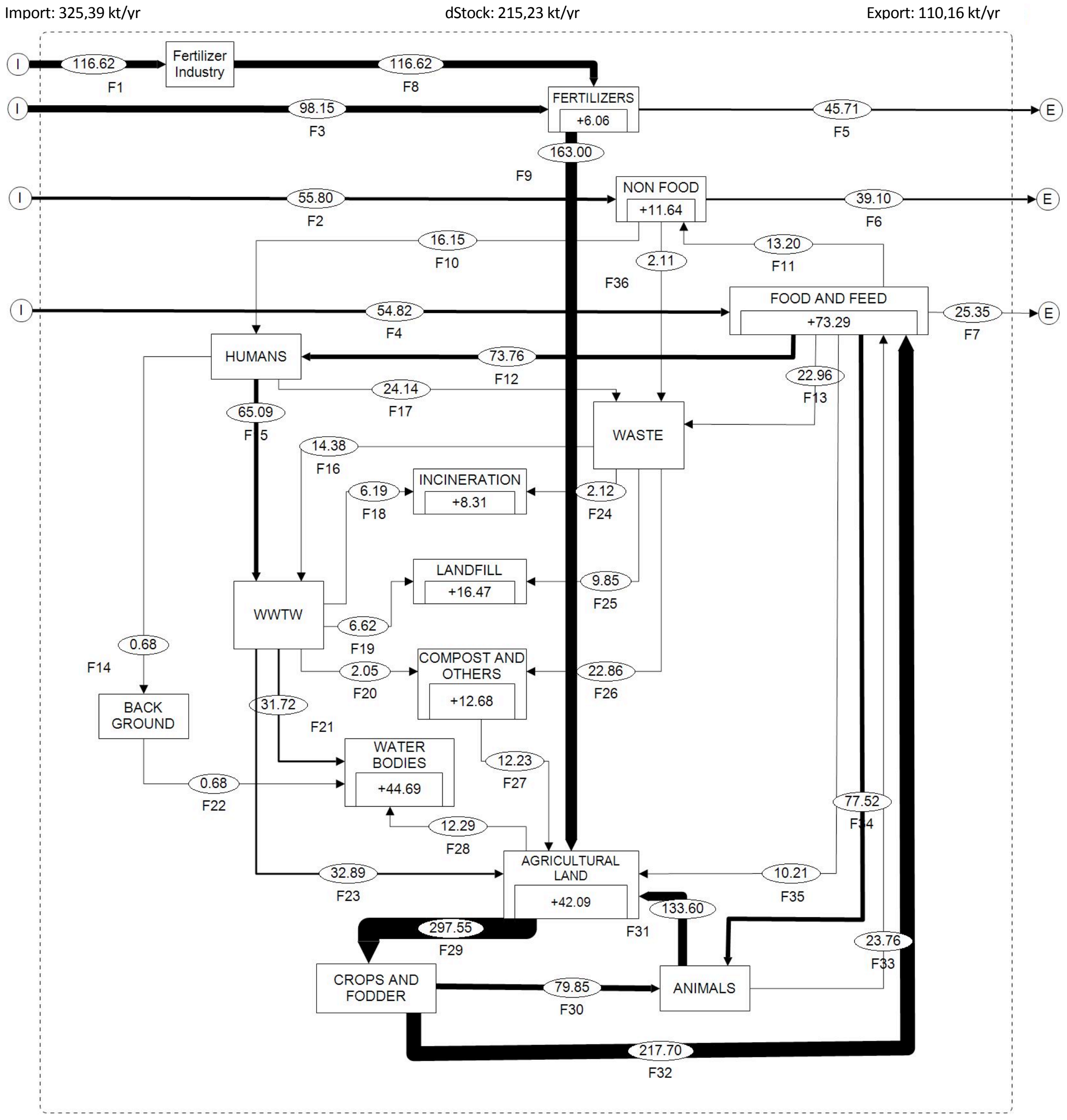
Scale	**Major Inflow**	**Stock**	**Major Outflow**	**Recycling flow**
City	Food	Landfill	Wastewater	Organic fertilizer from the waste management sector to the agricultural production sector.
Regional	Chemical P fertilizer or animal feed.	Soil of the crop production sector.	Exported food and agricultural products, waste (solid and liquid), or soil losses (erosion, runoff, and/or leaching).	Manure from the livestock production sector to the crop production sector.
Country	Mineral ore or chemical P fertilizer.	Soil of the agricultural (both crop and livestock) production sector.	Food and agricultural products or soil losses (erosion, runoff, and/or leaching) and this is particularly the case for the countries without adequate reserves of phosphate rock.	Manure from the livestock production sector to the crop production sector.

4.2. Spain SFA

The geographical system boundary for this substance flow analysis is Spain, which includes Balears and Canarian islands. Flows of P into, out of and throughout Spain will be analyzed, focusing primarily on agriculture and the food production system since agriculture accounts for more than 90% of all P applications (Cooper & Carliell-Marquet, 2013), but also including other industrial applications that interact with this system, such as P in detergents which may be removed from wastewaters and applied to agricultural land within sewage sludge. The base year of 2012 was chosen as this represented the most recent year for which an almost complete dataset could be gathered at the time of writing (2015-16). However, it should be noted that this is a static model and that annual variations can be significant.

A Substance Flow Analysis (SFA) is used when focusing on the element, in this case P, no matter what form it may appear in (Cooper & Carliell-Marquet, 2013). The amount of P in a material, such as within fertilizer, is often described as an amount of P_2O_5. In order to avoid confusion, every reference to an amount of P will have been converted beforehand and will therefore be referring specifically to quantities of the element P. The values for P flows will refer to the annual amount and will be expressed in thousand tons of P per year (kt P/yr). Existing stock are expressed in kt P. The underlying principle of a SFA is the conservation of mass, where a material can be transformed but not lost (Cooper & Carliell-Marquet, 2013). P may move within flows and between stocks, being transformed into different chemical forms or accumulating within stocks, but never being destroyed. Therefore, all flows into a system must either accumulate within that system or flow out of that system, known as being in balance.

This analysis has employed the STAN program to balance the results based on the uncertainty associated with each flow (Vienna University of Technology). Figure 16 presents the results of the SFA, using the STAN program. The boxes represent the main processes and stocks, while the connecting arrows represent the main flows. The flows are presented in the Sankey format, with the width of the arrow being proportional to the size of each flow. The quantity of each flow is included in the circle along each arrow, expressed in kt P/yr, followed by the uncertainty. Names of each flow are given in Table 5.



P flow Spain, 2012

Figure 16 Results for the SFA for Spain food production and consumption system. Diagram produced using the STAN program and presented in a style adapted from Senthilkumar et al. (2012) and James C and Chyndia C. (2013). All values are expressed in kt P/yr. Calculations, assumptions and uncertainties for each flow value are detailed in Table A.1 (Annex A).

Table 5 Definitions of P flows used for the SFA

Number	Flow Name	Description
F1	Rock import	Imported P rock
F2	Non-food import	Imported P in non-food commodities
F3	Fertilizer import	Imported P fertilizer
F4	Food and feed import	Imported P in food and feed
F5	Fertilizer export	Exported P fertilizer
F6	Non-food export	Exported P in non-food commodities
F7	Food and feed export	Exported P in food and feed
F8	Fertilizer production	Produced P in fertilizers
F9	Fertilizer application	Applied P fertilizer to agricultural land
F10	Human non-food consumption	P consumed as detergents
F11	Non-food commodities	P within food type commodities that have uses other than food, feed or seed (Biodiesel).
F12	Human food consumption	P consumed in domestic food market
F13	Food and feed processing waste	P loss during manufacturing food
F14	Other disposal for human excreta	P within human excreta which is not disposed of to sewers
F15	Human excreta to WwTW	Human P waste to treatment facilities
F16	Waste to sewers	P within human waste to sewers
F17	Human waste	P within human waste food
F18	Sewage sludge to incineration	P within sewage sludge
F19	Sewage sludge to landfill	P within sewage sludge
F20	Sewage sludge to composting or other disposal	P within sewage sludge
F21	WwTW final effluent	P within WwTW effluent discharged to water bodies
F22	Background losses to water	P within background losses to water bodies
F23	Sewage sludge to agriculture	P within sewage sludge
F24	Waste for incineration	P within waste for incineration
F25	Waste for landfill	P within waste for landfill
F26	Waste for composting or other disposal	P within waste for composting or other disposal
F27	Non-farm manures	P within non-farm manures
F28	Agricultural losses to water	P lost to water bodies from agricultural land
F29	Crop uptake	P removed from agricultural land in crops and grasses
F30	Animal grazing	P taken up during animal grazing
F31	Animal manure	P in animal manure applied to agricultural land
F32	Crop products	P within crop products
F33	Animal products	P within animal products
F34	Animal feed	P within animal feed
F35	Seed and planting material	P within seed and planting material
F36	Non-food processing waste	P loss during manufacturing non-food

The collection of data is an important step to establish an SFA. The focus in this step is to permit traceability of the used data, to minimize resulting uncertainties, and to employ actual data as far as possible. Scientific papers, national and international statistics, statistical data from organizations like MAGRAMA, INE, ITC, ANFE, EUROSTAT, European Commission and FAO mainly provided the relevant information for this balance. If no data was available, the mass balance principle is applied and missing flows are calculated. Another point to consider is the uncertainty that comes from the variation of P concentrations in goods or variability of mass flows.

In some cases various estimates have been used for the same point, so there have been averages of these flows, which are shown in Table A.1 (Annex A). This is useful to show the dispersion of the results that have been used to obtain this average value. A statistical method of measuring the dispersion of the results is to calculate the standard deviation (s). This method was used by (Seyhan, 2009) and (Cooper & Carliell-Marquet, 2013) to produce a range, which represented the uncertainty of the results. The standard deviation has been employed within this study to provide some measure of the uncertainty of the averaged results. For a final value within the confidence limits of 95% it has been used 2 standard deviations. As the work of (Cooper & Carliell-Marquet, 2013) shows, such statistical approaches are more suited to large data sets, which are normally distributed, and therefore less suited to the small number of data points obtained in SFA studies. An alternative method of producing a confidence range for SFA studies was developed by (Hedbrant & Sörme, 2001), and is referred to as the HS model. This method involves assigning uncertainty levels to various data sources, such as official statistics or values from literature, and applying an interval to each level.

For example, level 1 data sources may have an interval of */1.1 which means the data is multiplied or divided by 1.1 to achieve a range of results. The intervals are developed through user experience and the range produced corresponds to 95% confidence limits, which is the same as that produced using two standard deviations. Studies employing the HS model, such as (Cooper & Carliell-Marquet, 2013), (Danius, 2002), Antikainen et al. (2005) and Asmala and Saikku (2010), often adapt the number of levels and the factors applied at each level (Cooper & Carliell-Marquet, 2013). The intervals used within this study and some examples are specified within Table 6.

Using the HS model, a range of calculations are used to produce estimates for the same data points. To beaten this, a confidence interval was developed for each separate calculation using the methodology and equations outlined in Antikainen et al. (2005), and then an average confidence interval was taken for the overall data point. These average interval values are presented in Table 6.

Table 6 Uncertainty intervals used on the SFA

Level	Interval	Source of information	Example
1	*/1,05	Official statistics at Spain scale.	Spain population estimate
2	*/1,1	Official Statistics at Spain scale. Value from literature.	Area of land, crop yields, animal numbers from MAGRAMA or INE. P contents from literature
3	*/1,2	Official statistics scaled up to Spain scale. Values from literature.	Detergent consumption scaled up to Spain scale. Specific values from other studies in literature.
4	*/1,33	Values from literature without reference or methodology. Significantly scaled results or other assumptions.	Quoted values or own assumptions of P content. Assumptions about waste disposal or use of animal wastes

To compare intervals produced by the two methods, it was necessary to convert the range * / in a range of ±. This was done by converting an interval of * / 1.1 into ± 10%, as performed Cooper et al. (2013), which gives an equivalent upper limit but extends the lower limit. The limits produced from this method are presented in Table A1 (Annex A).

The largest of these two uncertainty limits for each data point was then entered into the STAN program and used within the balancing application to validate the model and produce the final results. The final results are presented in Figure 15 and Table A.1 (Annex A), along with the 95% confidence limits, which is the largest range produced by the two uncertainty methods.

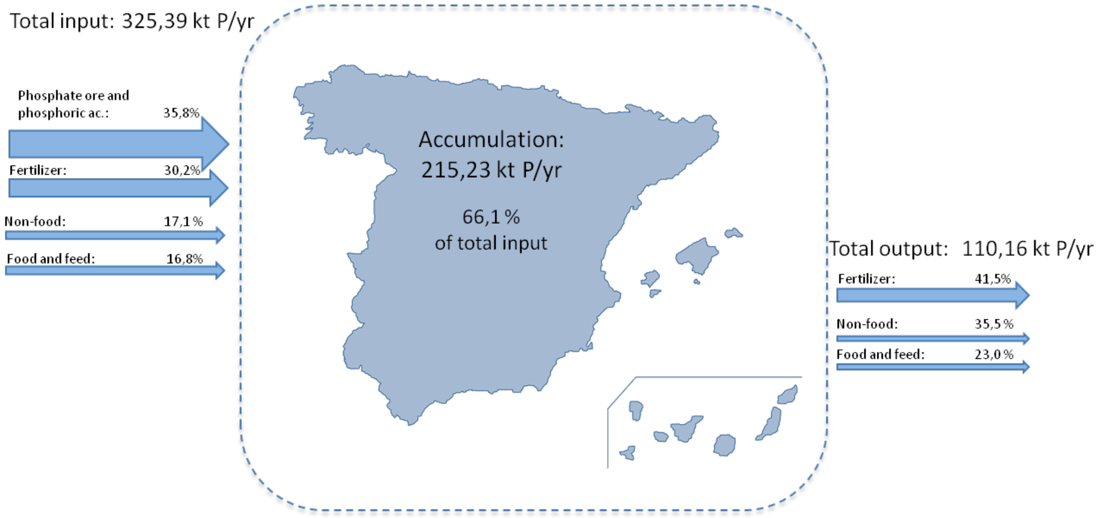


Figure 17 Spain imports, exports and accumulationof P in 2012 according to SFA

As shown in Figure 17, Spain imports at total of 325,39 kt P/yr, mostly within phosphate ore, phosphoric acid and fertilizers but also as food, animal feed and non-food commodities such as detergents. Total exports amount to 110,16 kt P/yr resulting in a net import of around 215,23 kt P/yr. The net import represents an annual accumulation of P within Spain.

The total phosphorus input to agricultural land is estimated at around 341,70 kt P/yr, which includes mineral fertilizer (48%), manure (39%), sewage sludge (10%) and compost and others (3%) as it is shown in Figure 18.

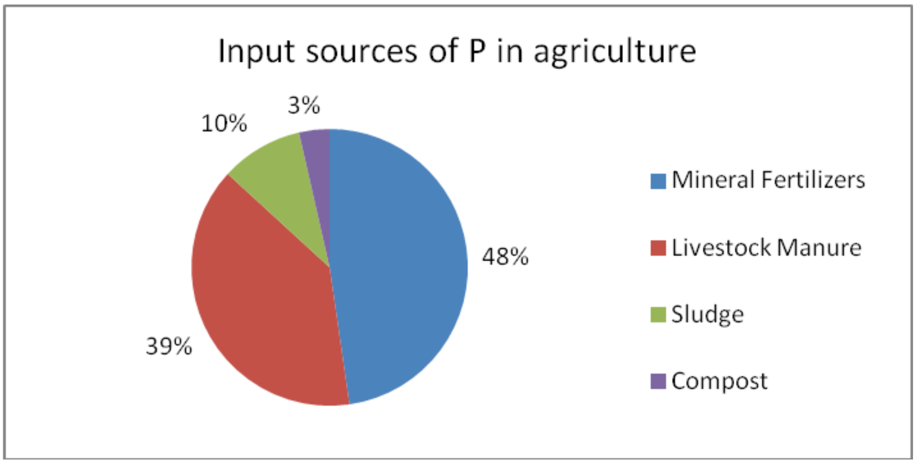


Figure 18 Different input sources of P and its proportion in agriculture according to SFA

The outputs of crops and grasses are 217,70 and 79,85 kt P/yr respectively, given a total output of 297,55 kt P/yr at an average of 21,65 kg P/ha. The efficiency of the agricultural system in converting P inputs within fertilizers and manures (341,70 kt P/yr) into outputs as crops and grass (297,55 kt P/yr) is around 85%. The difference between total inputs and outputs suggests an annual surplus of 54,38 kg P/yr. Agricultural losses to water are estimated at 12,29 kt P/yr, giving an annual accumulation of 42,09 kt P/yr in agricultural land.

If the stock of agricultural animal remain constant, the P input to animals consisted of P within grasses during animal grazing and P within animal feed, estimated to contain 79,85 and 77,52 kt P/yr respectively, giving a total input of 157,37 kt P/yr. The main outputs from animals are manure and animal products, which are estimated to contain 133,60 and 23,76 kt P/yr respectively. The efficiency of the animals system converting P inputs into animal products is only around 15,10%, so 84,90% of the inputs become manure.

The food and feed system receives inputs from agriculture as crops and animal products, as well as imported food and feed materials. The total inputs to the system are 296,28 kt P/yr and the output are 223,00 kt P/yr. The difference between inputs and outputs suggests an annual stock of 73,28 kt P/yr as is assumed that there is accumulation within this system. This accumulation may be due to lack of information that justify the exit of P towards other processes being a not real accumulation, at least not in this quantity, also it is possible to give because of a royal accumulation due to the generation of food stock as cereals, due to needs or interests of market.

Animal feed estimated at 77,52 kt P/yr is the largest output followed by Human food consumption with 73,76 kt P/yr. Its estimated that this system produces around 22,96 kt P/yr as waste, giving an efficiency of 92 %.

Spanish water industry receives P within wastewaters at WWTP, estimated to around 79,47 kt P/yr, which is either discharged to water bodies or removed within sewage sludge. As shown in Figure 19, it is estimated that around 31,72 kt P/yr is discharged in the final effluent, suggesting a P removal efficiency of around 61 %. Approximately 69 % of the 47,75kt P/yr removed within sewage sludge is recycled to agriculture, 27 % is sent directly to landfill, which include the ashes from incineration and 4 % is sent to composting or other uses. The amount of P recycled to agriculture within sewage sludge represents around 10 % of the total P input to agricultural land.

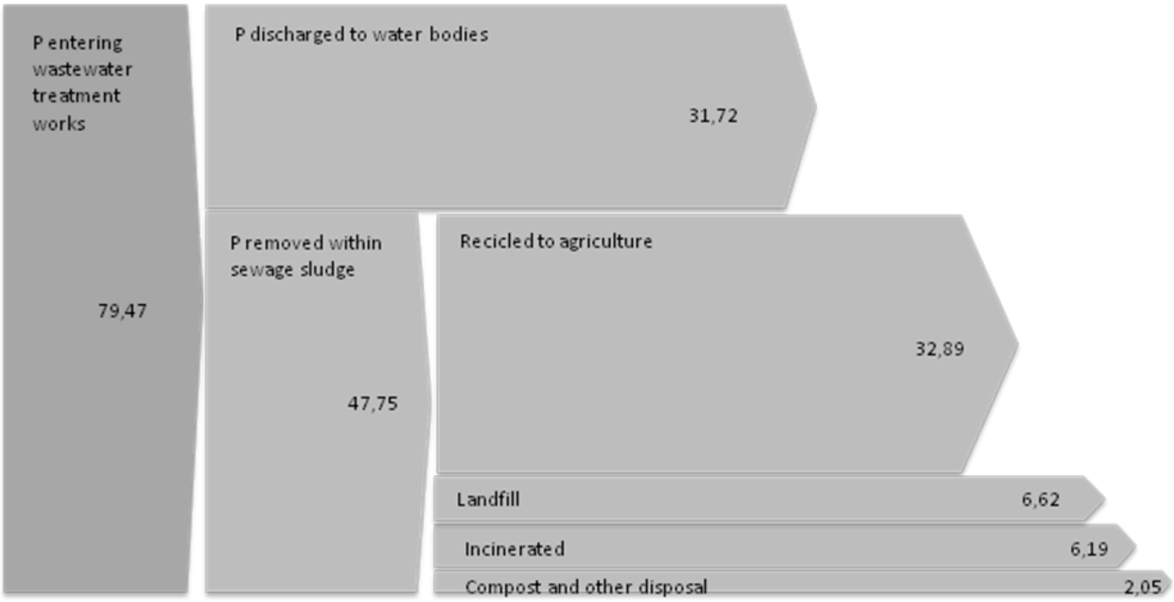


Figure 19 Phosphorous flows through Spanish WWTP according to SFA

P accumulated in Spain is retained in two different ways; either accumulates in markets stocks of food and feed, fertilizers and non-food, with a total of 90,99 kt P/yr, either lost to the environment through incineration, landfill, losses to water bodies and land accumulation, which means a total of 111,56 kt P/yr. The largest proportion of losses to environment is due to losses to water bodies, with around 44,69 kt P/yr, followed by agricultural land accumulation with 42,09 kt P/yr accumulating in Spanish land as shown in Figure 20. The biggest contributor of P losses to water bodies is from WwTW final effluent, estimated in

31,72 kt P/yr, which represent around 71 % of total losses to water bodies.

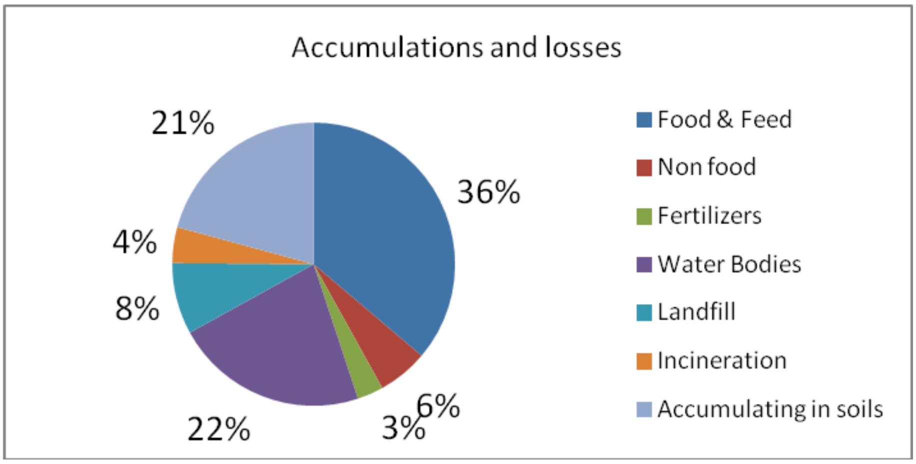


Figure 20 Spain accumulation and losse of P according to SFA

The P accumulation in the soils is estimated at around 42,09 kt P/yr, which is equivalent to 12 % of the total input to agricultural land, or equivalent to 26% the amount of P within mineral fertilizer applications. Another loss within Spain is the loss of P to landfill, estimated to contain around 24,78 kt P/yr. The largest proportion of this is within urban organic waste land filled, which is estimated to contain around 16,47 kt P/yr. Sewage sludge and waste incineration ash is assumed to be disposed of to landfill within 6,19 and 2,12 kt P/yr respectively.

4.3. EU27 SFA

In the first study for the whole of the EU-15 (Ott & Rechberger, 2012), analyzed data corresponding to different years between 2002 and 2008, so it is not possible close the P cycle for a particular year, which It brings considerable uncertainty. On the other hand, the last study for the EU27 (Van Dijk, Lesschen, & Oenema, 2016) data relate entirely to 2005, and it should close the cycle this year, in order to identify and quantify differents P flows.

In a recent study, Van Dijk, Lesschen, and Oenema, 2016 it was shown the use, reuse and P losses from different EU countries, taking into account the entire society. This includes the food industry (food chain: production-consumption-disposal), non-food industry as pet food, detergents and forestry. Overall the sectors analyzed are crop production, animal production, food processing, non-food production and consumption.

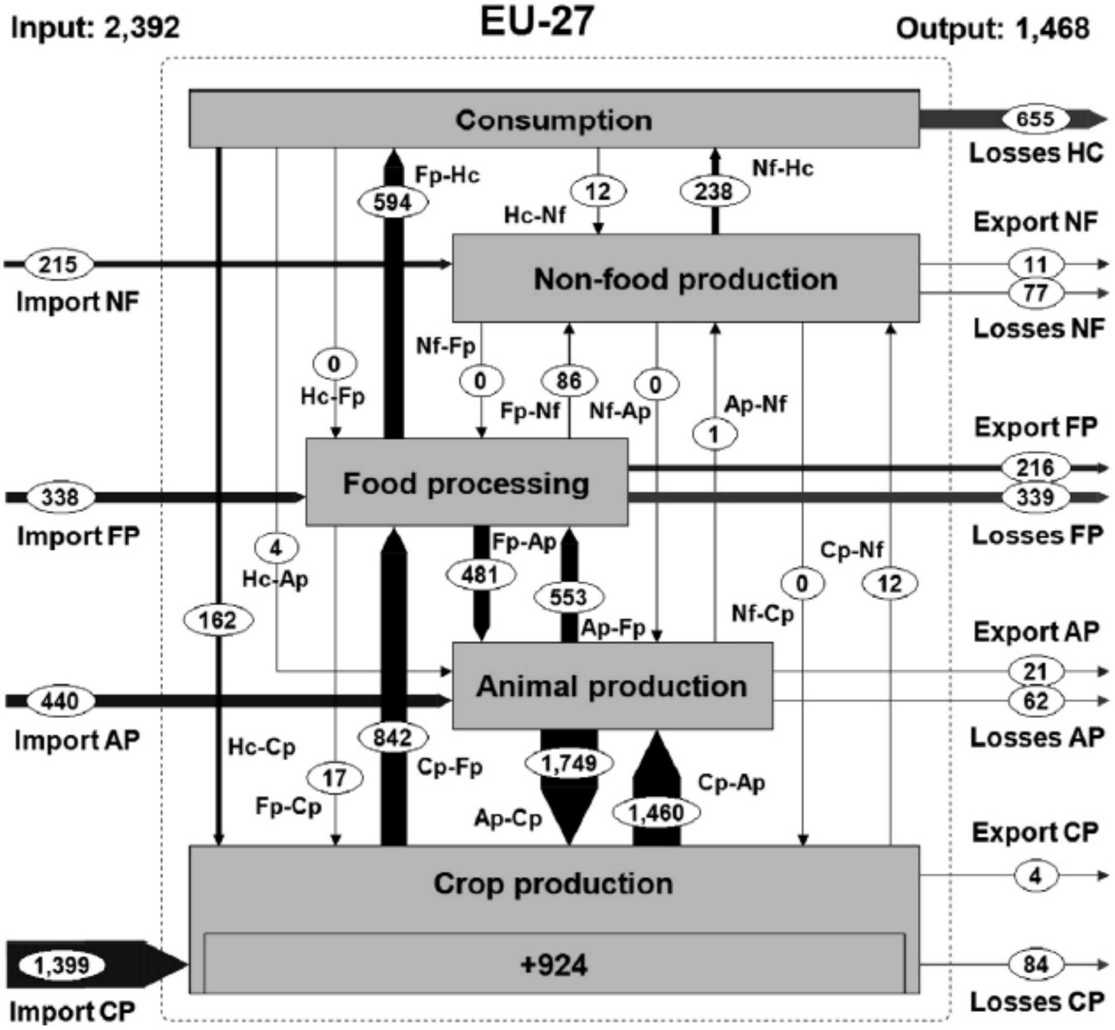


Figure 21 Phosphorus (P) use for the EU-27 in 2005 [kt P/yr]; aggregated at the food and non-food production–consumption–waste chain based on 96 sub-flows; showing the imports (blue), exports (purple), losses (red) and internal upward/downward flows (black) for crop production (CP), animal production (AP), food processing (FP), non-food production (NF) and consumption (HC) sectors (indicated with square blocks); the arrow thickness shows the relative flow sizes; the positive balance of+924 in CP represents annual net accumulation of P in agricultural soils in 2005;Source: (Van Dijk, Lesschen, & Oenema, 2016)

According to Van Dijk, P total import in 2005 amounted to 2.392 kt P/yr and total export was 251 kt P/yr, which indicates a net import of EU 2.141 kt P/yr. Approximately half of this annual surplus accumulates in agricultural soils due to the fertilization performed during the production of crops (924 kt P) and the other half is lost from the system (1.217 kt P).

Around 76% of the imported P went to the agriculture, of which 58% is used in crop production and animal production 18%. About 86% of exports are processed foods. Almost half (54%) of the total losses of P were conducted from the retail sector, mainly in the sludge of sewage and organic waste. More than one quarter (28%) was lost by the food-processing sector, from the incineration of meat and bone meal from slaughtering.

The total of primary import of P was 1.777 kt P, which corresponds to 74% of the total import of the system. To around 78% of this primary P imports is destined to the production of mineral fertilizers. Another 22% of the primary import of P went to the production of feed for animals (no pets) inorganic additives (14%), the production of detergents (6%), and the production of additives of inorganic P for human consumption (1%).

The stock of P from the soil of the EU in the farmland and pasture in 2005 was estimated at 150.802 kt P. This data is based on the annual agricultural P balances accumulated estimates for Member States, since 1961. The P stock on live cattle in 2005 is estimated at approximately 534 kt P, in domestic animals living in around 11 Gg P and in the human population was estimated at around 322 kt P.

P from crop uptake was 2.317 kt P in 2005, equivalent to 4,9 kg of P per capita and 12,6 P kg per hectare. The total amount of P to livestock feed was 2.369 kt P, including the organic feed (2.119 kt) and inorganic (250 kt) feed additives. On average, 26% was retained by cattle in animal products, mainly as corpses of animals, milk, eggs and products of aquaculture (553 kt P). In addition, 5 kt P was exported as live animals. The other 74% is excreted as manure, which allocated almost in its entirety to agricultural land (1.749 kt P), which represents the main way of reuse of P in the system.

The food-processing sector had a total input of 1732 kt P/yr, of which 80% (1394 kt P) originated from the crop and animal production, and 20% (122 P kt) of the imported crops, foodstuffs (including fish) and inorganic food additives. All of this entry went to food processing for their consumption 594 kt P, equivalent to 1.21 kg P/ca, including 0.06 kg P/ca in inorganic additives-food.

In this sense, the EU Member States show a great variation in food supply ranging from 0,92 to 1,36 kg P/ca. The contribution of P from vegetable and animal for the food supply of the EU-27 was, on average, 67% (0,75 kg P/ca) and 33% (0,4 kg P/ca), respectively. In addition, 79 kt P from residues from the processing sector of food (mainly of the sacrifice) was used as food ingredients for pets.

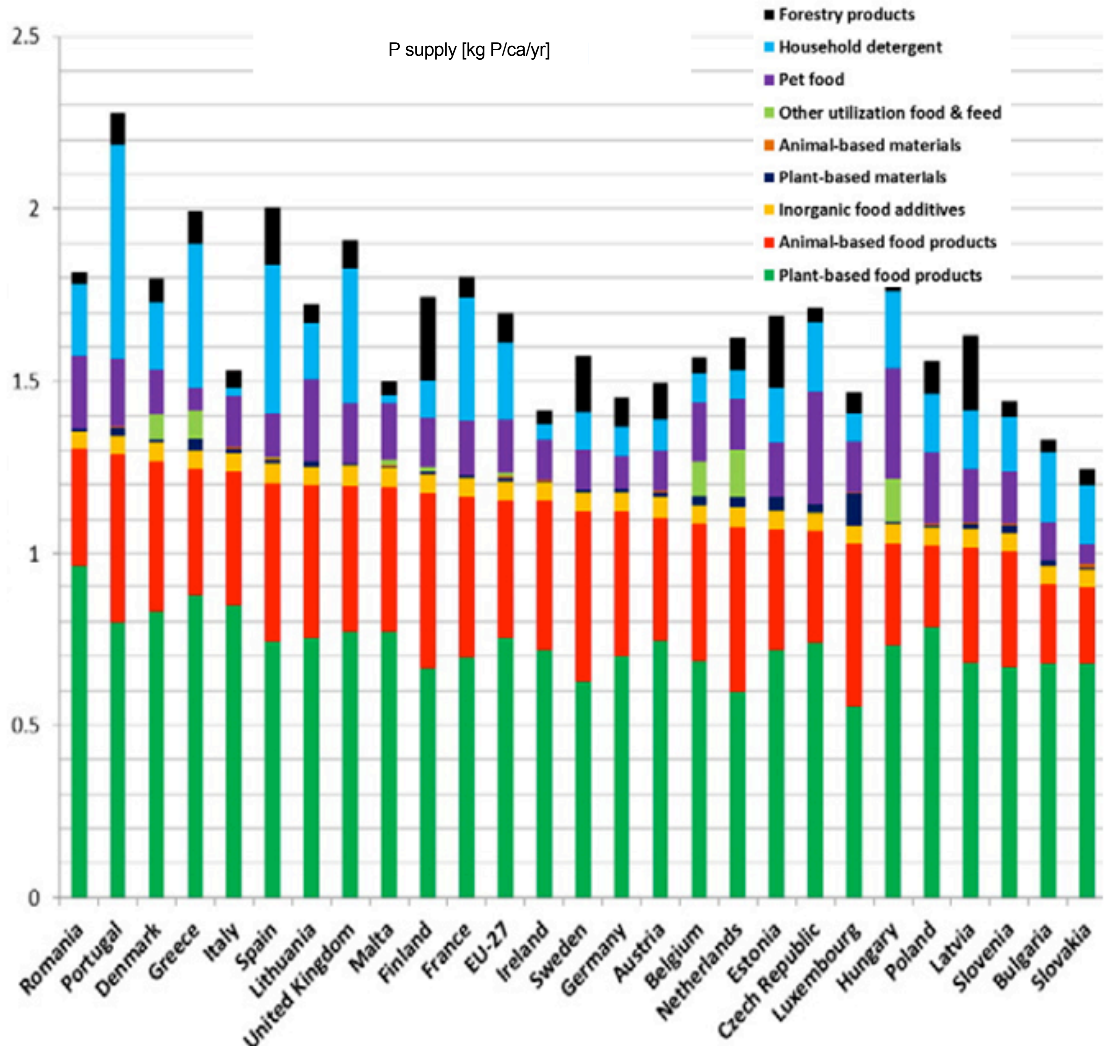


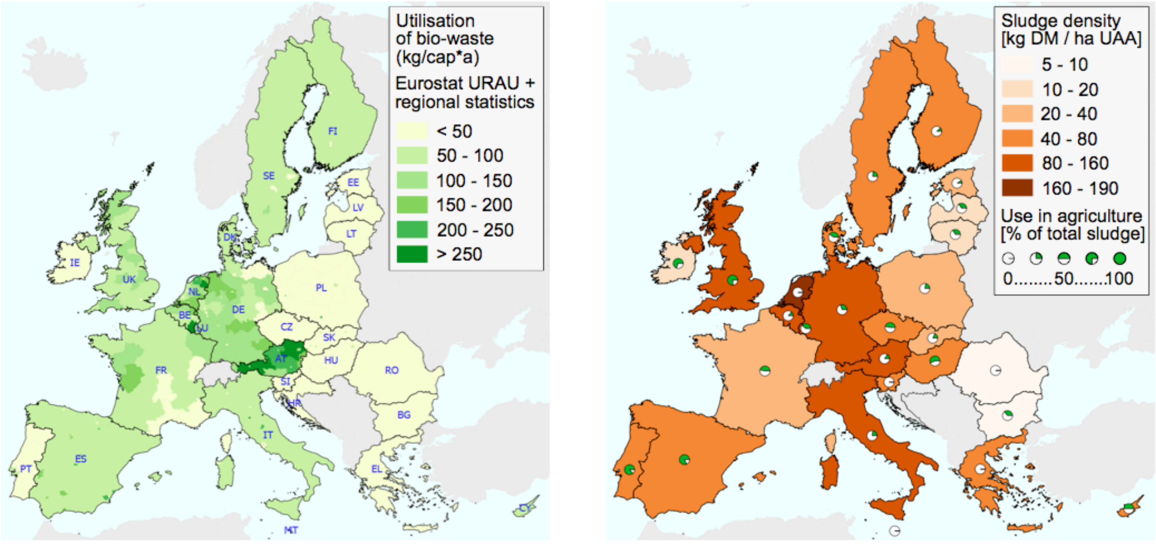
Figure 22 Phosphorus (P) quantities in products supplied to the consumption sector for the EU-27 and its Member States in 2005 [kg P/ca/yr]; sorted by total plant and animal based food product P quantity. Source: (Van Dijk, Lesschen, & Oenema, 2016)

The non-food sector supplied 238 kt P to the consumer sector, including 75 kt in pet food (0,15 kg P/ca), 109 kt in detergents (0,22 kg P/ca), 41 kt in forest products (0,08 kg P/ca), and 13 kt in other non-food products, such as tobacco, fibers and materials (0,03 kg P/ca).

The total entry to the consumer sector was 832 kt P for the EU-27. This entry of P in food and non-food products was equivalent to 1,7 kg kg P/ca/yr, varying between 1,24 and 2,28 kg P/ca among the Member States. After consumption, the food and non-food products P was discarded following several waste streams, of which only 177 kt P was reused and 655 kt P (79%) was lost from the system. The main fraction was lost through the sewage system with 41% in sewage sludge (0,46 kg P/ca) and in effluent (0,08 kg P/ca) from centralized systems (urban) of wastewater treatment, and 14% in other communal wastewater flows (0,19 kg P/ca).

Other considerable losses occurred through the system of solid waste with 26% of the total losses from the consumption sector in food waste from households, retail and other services of supply (e.g., restaurants, catering), and 11% via pet excreta to public spaces, gardens and the solid waste system.

The losses of P in the UE27 (1.217 kt P) in 2005 are produced through the ashes from the incineration of waste (34% of the total), landfills (5%), municipal solid waste (18%), including incineration and landfill deposit as possible final destinations, emissions to the hydrosphere (17%), and the lithosphere (6%), and the undefined destinations (21%). Notably, the incineration of waste from slaughterhouses in the processing of food (72% of the total) and sludge of sewage treatment plants in the production sector to food (26%) generated ash with high content of P.



(a) (b)

Figure 23 Bio-waste and sewage sludge utilization in the EU-28 (data from Eurostat [trf]). (a) Bio-waste utilization in kg per capita and year based on Eurostat Urban Audit and regional statistics; (b) Amount of sewage sludge in kg dry matter in relation to hectare utilized area; and agricultural sludge use. Source: (Meyer-Kohlstock, Schmitz, & Kraft, Organic waste for compost and biochar in the EU: mobilizing the potential, 2015)

The management of waste with high content of P as the sludge from wastewater treatment plants varies widely within the EU. Each Member State manages this waste differently depending mainly of their respective laws, as shown in Figure 24.

The results of the study show that in general, the contribution of each sector, P that is used in the production of crops is collected over 70% with crops. In animal production, 24% is retained in animals, milk and eggs. In food processing, 52% came to foodstuffs. In the non-food industry 76% became non-food products and with respect to the consumption (homes, restaurants, etc.), 21% is recycled after use. There is an inherent inefficiency due to the inevitable accumulation and diffuse losses in all sectors. On average, for the EU-27 in 2005, 4,0 kg P is required to produce 1 kg of P in foods and additives supplied to the consumer sector.

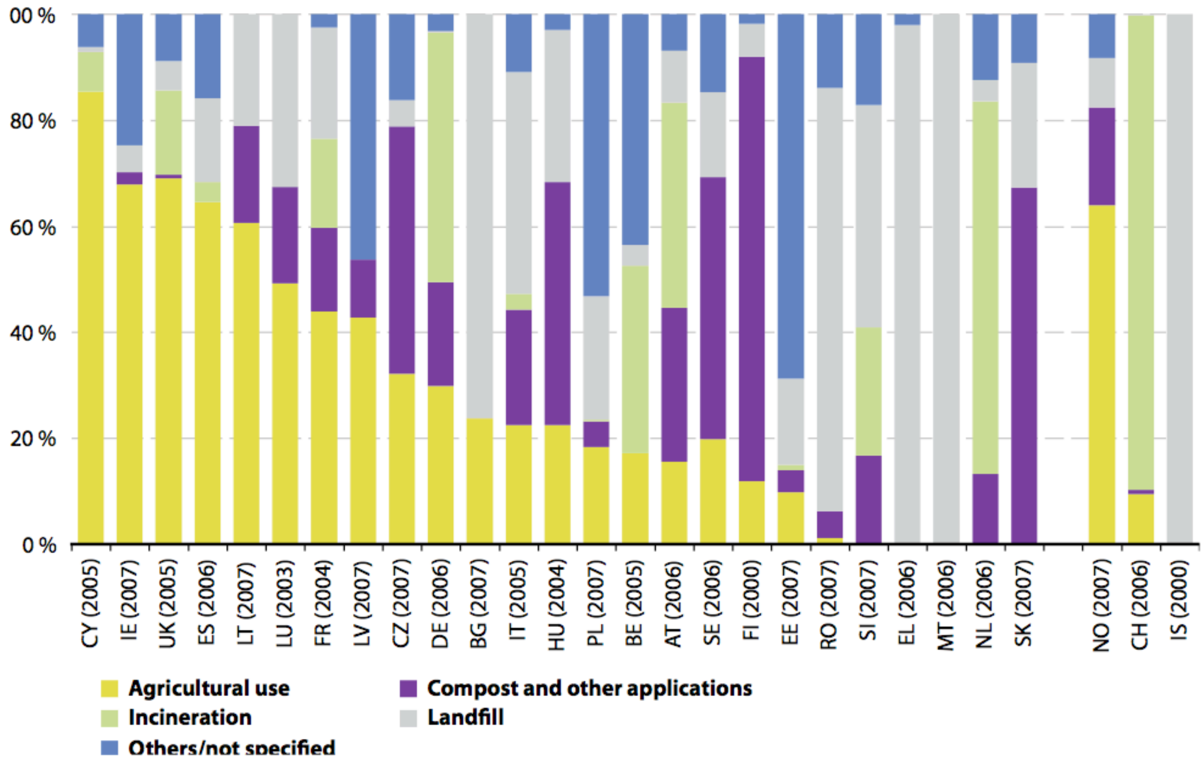


Figure 24 Total sludge by type of disposal, 2007 (% of total sludge treated).(data from Eurostat [trf]).

The P balance of agriculture in the EU-27 recorded a surplus of 924 kt P in 2005, equivalent to a surplus of 4,9 kg P/ha and 1,9 kg P/ca. P input in the production of crops for the EU-27 averaged 17,4 kg P/ha, including the application of 9,2 kg of P in manure (53%), 7,3 kg of P in mineral fertilizers (42%), 0,7 kg of P in the sludge of sewage treatment plant (4%), and the remaining 1% divided between the compost, fertilizers made from slaughterhouse waste deposition, pesticides, and seeds/planting material.

P balances showed wide variation among Members States of the EU-27 with high surplus (positive balances) in most of the countries of Western Europe, as Belgium (23,2 kg P/ha/yr) and the Netherlands (21,9 kg P/ha/yr), and the deficit (negative balances) in many countries of central Europe and East as Slovakia (-2,8 kg P/ha/yr) and Czech Republic (-2,1 kg P/ha/yr). There are also countries with near-zero, as Romania balances (-0,3 kg P/ha/yr), Bulgaria (-0,1 kg P/ha/yr), Austria (-0,1 kg P/ha/yr) and Sweden (0,5 kg P/ha/yr).

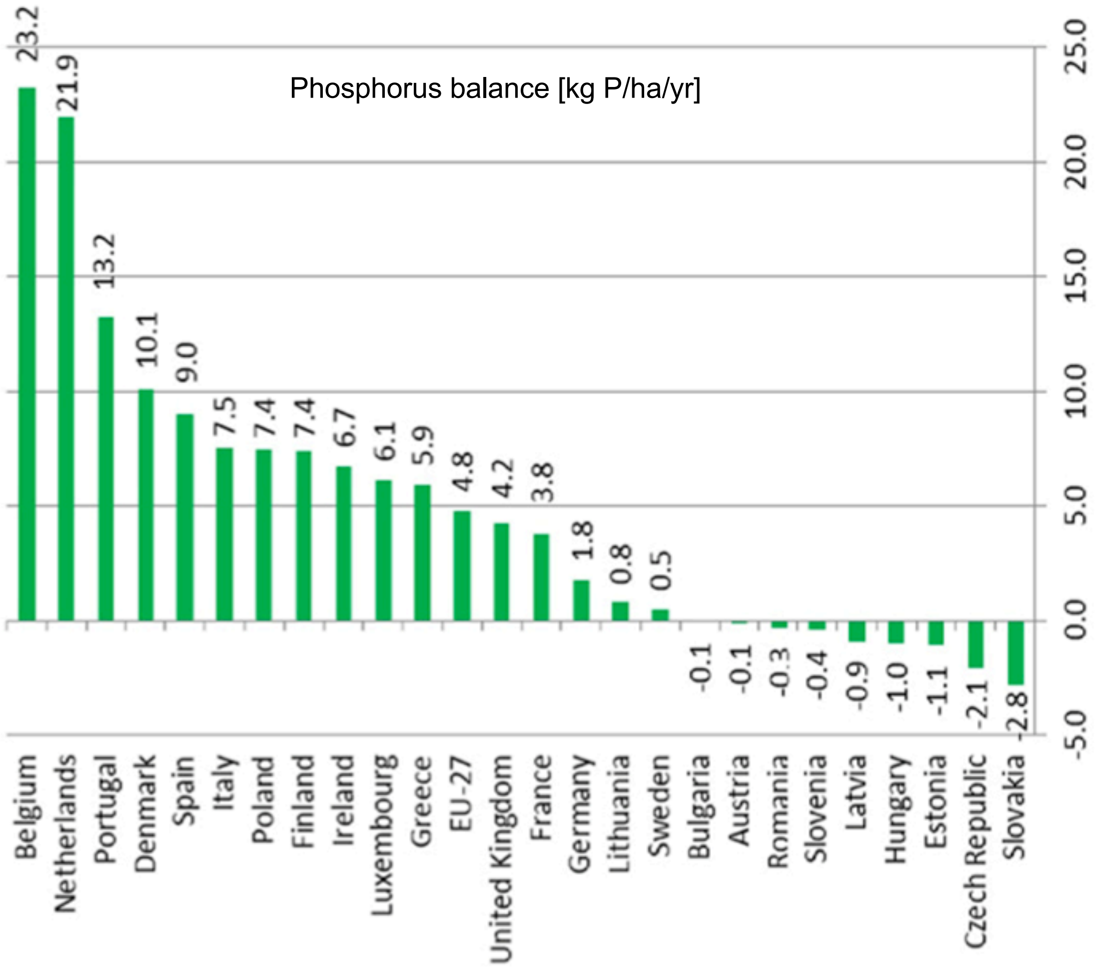


Figure 25 National phosphorus (P) balances for agriculture in the EU-27 and its Member States for the year 2005 (kg P/ha/yr); a positive annul balance represents a net accumulation in the soil, whereas a negative balance means soil P depletion. data from Eurostat [trf]), Source: (Van Dijk, Lesschen, & Oenema, 2016)

As European Sustainable Phosphorus Platform SCOPE Newsletter nº117 describes, phosphorus use in EU-27 was characterized by “5 Ls”:

1. Large dependency on (primary) imports,
2. Long-term accumulation in agricultural soils, especially in west European countries,
3. Leaky losses throughout entire society, especially emissions to the environment and sequestered waste,
4. Little recycling with the exception of manure, and sewage sludge.
5. Low use efficiencies, because of aforementioned issues, providing ample opportunities for improvement.

4.4. Japan SFA

A P flow analysis for Japan was made by Matsubae (Matsubae, Kajiyama, Hikari, & Nagasaka, 2011), phosphorus flow was evaluated partly with reference to the data from previous studies from 2002 to 2010. According to the P flow analysis by (Matsubae, Kajiyama, Hikari, & Nagasaka, 2011) (Figure 26), the total P import into Japan is estimated to be approximately 630 (kt P/yr).

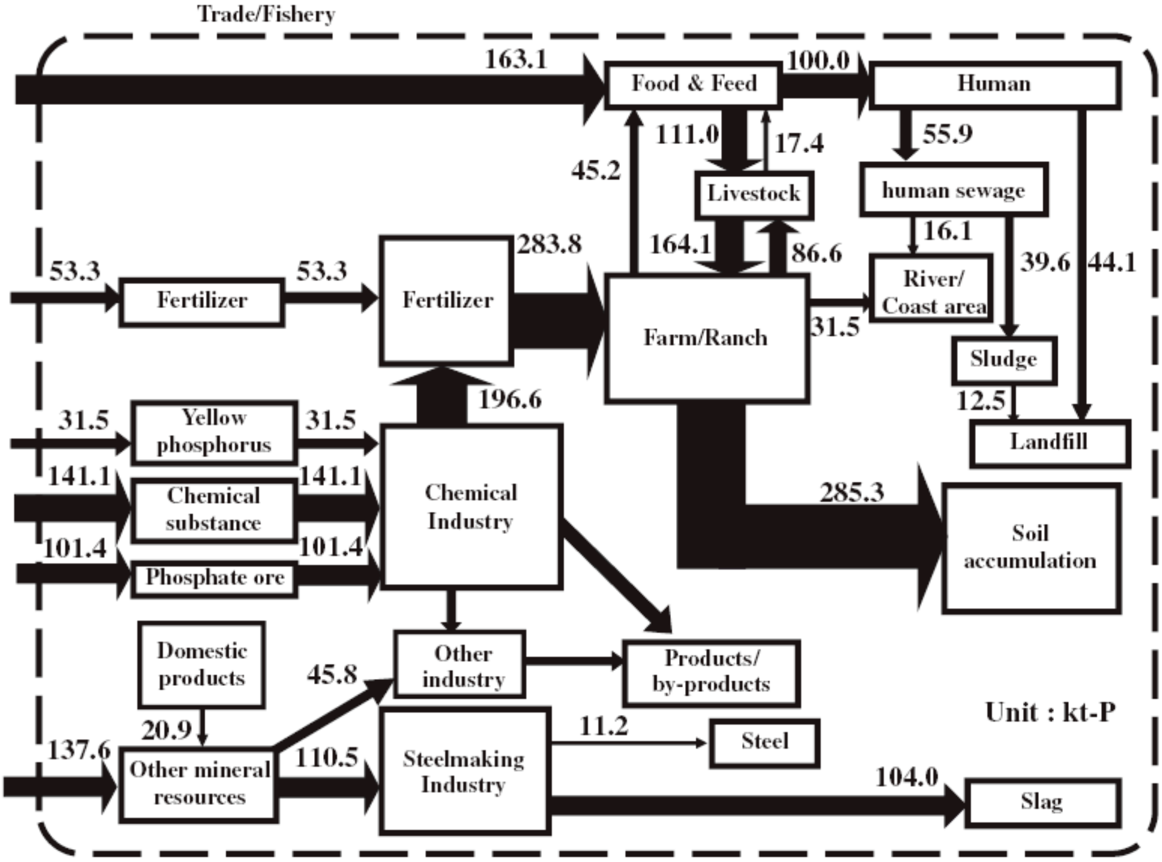


Figure 26 Substance flow of phosphorus in Japan (2005) by Matsubae et al. (2011). Source: (Ohtake & Okano, 2015)

The phosphorus flow into the chemical industry from foreign countries is mainly in three forms: phosphate rock, phosphorus compounds, and yellow phosphorus (Figure 27). In this sector, phosphorus flows are related to industrial activity, particularly in chemical industries, that are the main suppliers of phosphorus fertilizer (222,3 kt P/yr).

From the input, 46% (283,8 kt P/yr) is used as fertilizer, and 26% (163,1 kt kt P/yr) is consumed by humankind and livestock. The largest input flow in the entire phosphorus flow was 284 kt P/yr, which was applied annually to farms and ranches in the form of fertilizer.

The amount of phosphorus accumulated in the soil (285,3 kt P/yr) is nearly equal to input from fertilizer to farms and ranches.

Input flows to food and feed sectors also have large values. They flow in mainly from world imports and marine resources (163,1 kt P/yr) and domestic crop production from farmlands (45,2 kt). This phosphorus is mainly consumed by human and livestock (97,6 and 111,0 kt P/yr) and finally ends up either in the soil or water.

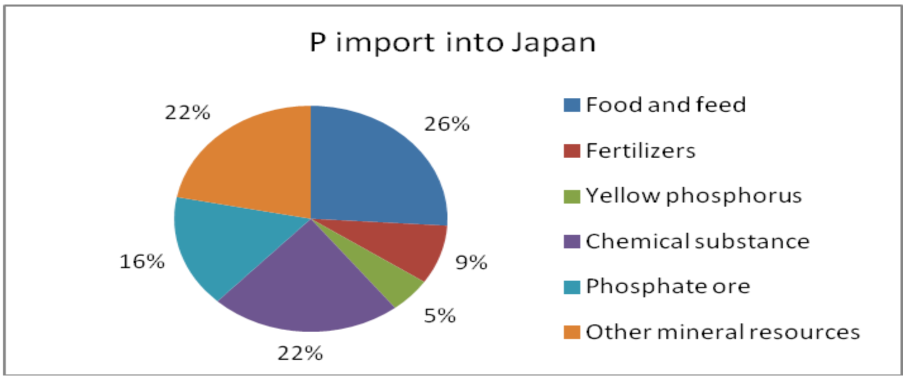


Figure 27 P import into Japan in 2005 according to Matsubae, Kajiyama, Hikari, & Nagasaka, 2011.

Approximately 140 kt P/yr is related to the importation of mineral resources such as iron ore and coal for the iron and steel industry. That's flows account for about 22% of the total P import into Japan. In addition, 17% (110,5 kt P/yr) flow into the steel industry as mineral resources, most of which is condensed in steelmaking slag (104,0 kt P/yr).

Accumulations and losses to water bodies in Japan represent a total of 493,5 kt P/yr (Figure 28). The accumulation generated by human consumption was 56,6 kt P/yr, which comes from waste (44,1 kt P/yr) and sewage sludge (12,5 kt P/yr) that were landfill. Regarding the agricultural sector, as has already been seen, some 285 kt P/yr accumulate in agricultural soils, which is practically all of mineral fertilizers applied to the soil. Losses to water come in part from the wastewater treatment (16,1 kt P/yr) and from erosion of agricultural soils (31,5 kt P/yr). Finally, another great accumulation present in Japan is the slag generated by the metallurgical industry, which represents a 104,0 kt P/yr.

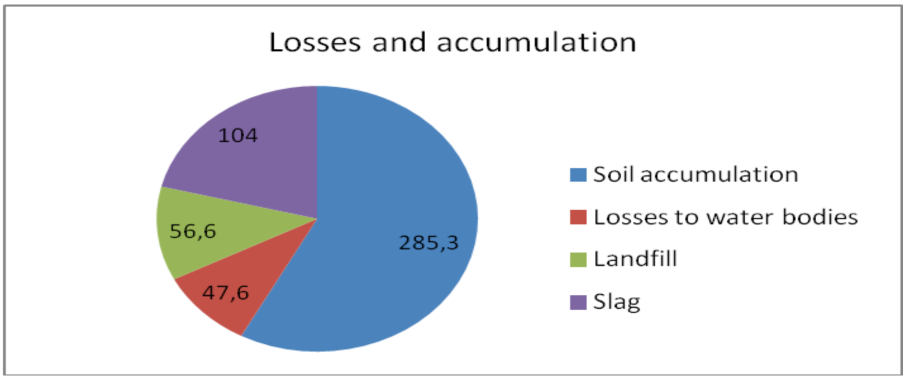


Figure 28 Losses and accumulation in Japan, values in kt P/yr according to Matsubae, Kajiyama, Hikari, & Nagasaka, 2011.

4.5. SFA comparison between countries

Most of the results from this SFA have been presented using total quantities of P (in kt P), these allow to identify major flows and losses, and monitoring changes over time within a country, but is less suited for comparisons with other countries that have different population sizes and agricultural areas. To compare data obtained from SFA, data were normalized by either population kg P/cap or land area kg P/ha or estimates of efficiency can be calculated.

The development of indicators of sustainable phosphorus practices would be useful to monitor changes over time, to set targets to work towards, and to compare one country's performance to another. Examples of such indicators were described by Cooper & Carliell-Marquet, 2013 and (Li, Boiarkina, Young, & Yu, 2016. These indicators are summarizedin Table 7.

Table 7 Definition of P flow indicators (Cooper & Carliell-Marquet, 2013) and (Li, Boiarkina, Young, & Yu, 2016).

Indicator	**Definition**	**Units**
Fertilizer application	P fertilizer application on agricultural land	kg/ha
Mineral fertilizer application	Ratio p mineral fertilizer and total P fertilizer applied on agricultural land	%
Human consumption	P utilization from food and non-food commodities	kg/cap
WWTP effluent	Average P discharged in wastewater treatment plant	kg/cap
Total input	Average total input to the country per person	kg/cap
Total output	Average total output from the country per person	kg/cap
Exported food	Average P export through food per person	kg/cap
Landfill	Average P being landfilled in the country	kg/cap
Manure application	Animal manure applied to agriculture land	kg/ha
Agriculture loss	P loss from agriculture land to streams	kg/ha
Land accumulation	P accumulated in agricultural land	kg/ha
Soil in	P input to agricultural land	kg/ha
Soil out	P output from agricultural land	kg/ha
Agricultural efficiency	Ratio P input and output in agriculture	%
P recovery	P recovered from sewage in WWTP	%

In the Table 8 can be seen as the efficiency of recovery of P is for all countries minor of 0,5 and in some case zero, as in New Zealand. This information has a lot of interest since it is the best indicator of the use of the principal secondary source of P in power identified in all reviewed SFA. In Spain the obtained ratio (0,44) overcomes the average of EU27 (0,38) as UK with 0,41, on the other hand France with 0,28 does not come to 0,30. This is mainly due to the different legislation present in the EU27 member states regarding the agricultural use of sludge from sewage treatment plants.

Table 8 P flows and ratios in different countries

Indicator	**Units**	**Spain**[a]	**France**[b]	**UK**[c]	**Finland**[d]	**EU27**[e]	**Japanf**	**NZ**[g]	**Australia**[h]	**USA**[i]
Fertilizer application	kg/ha	22,89	10,00	4,00	14,90	6,75	87,00	18,00	1,00	4,00
Mineral fertilizer application	%	0,52	0,37	0,27	0,61	0,42	0,73	0,57	0,43	0,81
Human consumption	kg/cap	1,56	1,80	0,80	1,00	1,54	0,80	2,30	2,10	1,20
WWTP effluent	kg/cap	1,68	0,70	0,40	0,10	0,24	0,10	0,90	0,50	2,60
Total input	kg/cap	6,88	7,50	2,20	41,20	4,87	5,70	54,70	25,90	25,30
Total output	kg/cap	2,33	2,70	0,40	3,10	2,99	0,00	20,30	6,90	17,60
Exported food	kg/cap	0,54	2,10	0,30	0,50	0,49	0,00	10,40	5,20	1,30
Landfill	kg/cap	0,35	0,80	0,30	0,50	1,56	0,70	8,60	0,60	1,60
Manure application	kg/ha	9,72	10,60	9,70	8,60	9,17	31,60	13,20	1,20	1,00
Agriculture loss	kg/ha	0,89	1,60	0,80	1,10	0,44	8,60	4,70	0,10	2,00
Land accumulation	kg/ha	3,06	5,80	2,20	12,70	4,85	81,10	85,60	1,70	1,60
Soil in	kg/ha	25,60	26,70	15,60	24,90	17,45	118,80	31,40	2,20	7,80
Soil out	kg/ha	21,65	20,90	13,40	12,20	12,16	37,00	24,00	0,50	6,10
Agricultural efficiency	%	0,85	0,70	0,80	0,50	0,70	0,30	0,70	0,10	0,80
P recovery	%	0,44	0,28	0,41	0,24	0,38	0,47	0,00	0,33	0,30
Year		**2012**	**2002-6**	**2009**	**1995-9**	**2005**	**2005**	**2012-4**	**2001**	**2007**

a According to SFA, b(Senthilkumar, Mollier, Delmas, Pellerin, & Nesme, 2014), c(Cooper & Carliell-Marquet, 2013), d(Antikainen, y otros, 2005), e(Ott & Rechberger, 2012), f(Matsubae, Kajiyama, Hikari, & Nagasaka, 2011), g(Li, Boiarkina, Young, & Yu, 2016), h(Cordell, White, & Moore, 2010), i(Suh & Yee, 2011).

Figure 23(b) provides the annual sludge potential from municipal wastewater treatment in kg dry matter per hectare of utilized agricultural area. Therefore, it represents the theoretical recycling potential of sewage sludge in agriculture. The actual utilization is given in percentage of the total annual amount. For most member states corresponding data are available for 2008 or 2009.

It can be seen that Portugal, Spain and UK are countries with the highest proportion of sludge applied to agriculture which justifies its recovery rate is higher than average in EU27, while you can see that France and Finland make less use of sludge, namely 50% and 25% respectively, which is also reflected in lower average ratios obtained.

In Figure 24 clear heterogeneity between destinations that each member state gives EU27 sludge from sewage treatment plants is appreciated. Basically, there are only five possible destinations for sludge, but each member state distributes sludge in different proportions. Regarding the destination of the sludge, we can say that there are three major trends depending on the sludge disposal. In Table 9 these three trends, countries that develop and pros and cons of these destinations are collected.

4.6. Circular economy applied to the phosphorus cycle

If there is applied the strategy established by the circular economy to the P cycle it is possible to reduce the demand of phosphorus managing to cover it only with secondary sources, it if applying before the tertiary sources as Figure 29 shows.

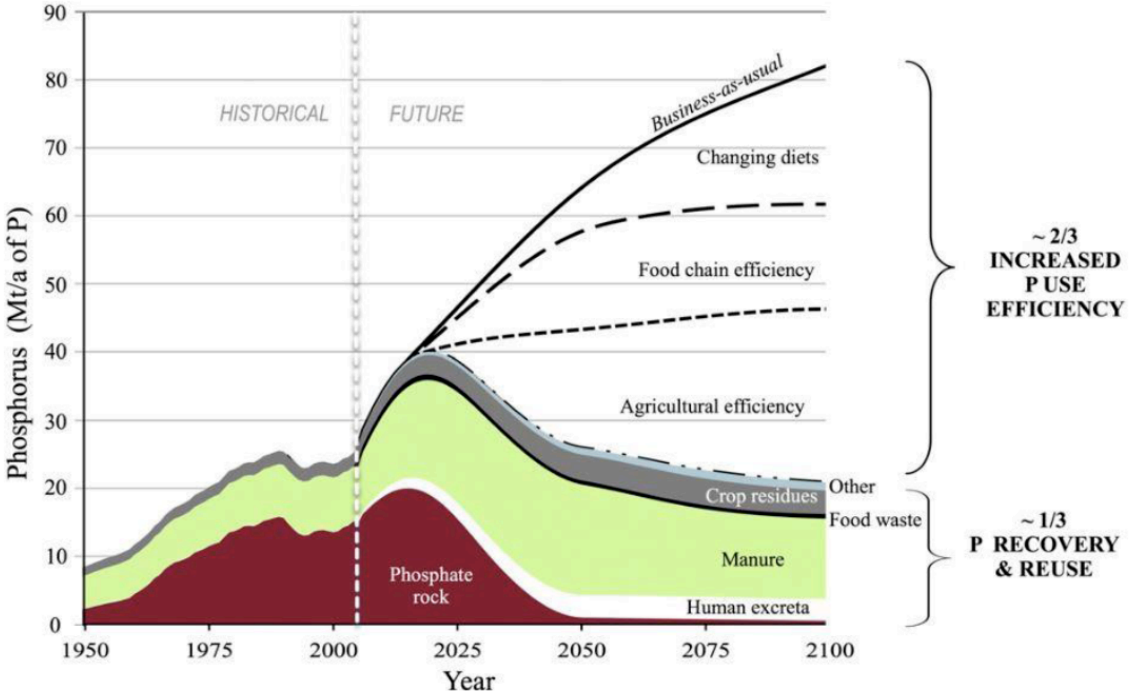


Figure 29 A sustainable scenario for meeting long-term future phosphorusdemand through phosphorus use efficiency and recovery (Cordell et al. 2011)

One of the most valued utilities from the analyses of the cycle of phosphorus, realized for Spain and presented for EU27 and Japan, is to identify and to quantify across flows, the primary, secondary and tertiary sources presented in circular economy model. By means of these analyses we can determine the losses of the system, previous and necessary step to study how to reduce or re-use them as secondary sources. Across the results also we can determine the performances of the different processes presents in the cycle of P to locate potentials improvements and reductions of consumption, that is, to detect possible tertiary sources. In Table 9, primary, secondary and tertiary sources from cycles P of Spain, EU27 and Japan are collected according to Spain SFA (Ohtake & Okano, 2015) and (Van Dijk, Lesschen, & Oenema, 2016).

From secondary sources shown in Table 10, sludge treatment plants is one of the most recurrent in all cycles of P analyzed and reviewed in this paper and on which more work is being done because of its potential as a source of P.

Secondary sources such as effluent from WWTPs, also have a considerable magnitude, but this magnitude is due to the large volume of treated water containing a very low concentration of P, about 2-10 mg/L P. This makes more costly to reduce P concentration in plants that already have a tertiary treatment. Furthermore, the volume of sludge generated is less than the treated water, while the P concentration is up to 5 degrees in order of magnitude greater than that of water, about 19237 mg/Kg P (Ministerio de Medio Ambiente y Medio Rural y Marino, 2009).

Table 9 Primary, secondary and tertiary sources from cycles P of Spain, EU27 and Japan

Country /Region	**Primary sources**		**Secondary sources**		**Tertiary sources**
	Flow	*Kt P/yr*	*Flow*	*Kt P/yr*	
Spain	1.Phosphate rock and Mineral fertilizers 2.Food an feed import 3.Non food import	214,77 54,82 55,80	1.Sewage sludge 2.WWTP effluent 3.Organic waste 4.Agricultural losses to water	47,75 31,72 34,83 12,29	1.Improve the ratio of removal of P in WWTP that do not have tertiary treatment 2.Improve agricultural production performance 3.Waste less food, reducing food consumption and waste generation
EU27	1.Phosphate rock and Mineral fertilizers 2.Food an feed import 3.Non food import	1389,43 778,00 215,00	1.Sewage sludge 2.WWTP effluent 3.Organic waste 4.Agricultural losses to water 5.Food processing waste	394,27 128,89 255,10 84,49 389,95	1.Improve the ratio of removal of P in WwTP that do not have tertiary treatment 1.Improve agricultural production performance 2.Waste less food, reducing food consumption and waste generation
Japan	1.Phosphate rock, phosphorus compounds, yellow phosphorus 2.Mineral fertilizers 3.Food an feed import 4.Others minerals resources	274,00 53,30 163,10 274,00	1.Sewage sludge 2.WWTP effluent 3.Organic waste 4.Agricultural losses to water 5.Slag	39,60 16,10 44,10 31,50 104,00	1.Improve the ratio of removal of P in WWTP that do not have tertiary treatment 2.Improve agricultural production performance 3.Waste less food, reducing food consumption and waste generation

This does not mean you should not improve the average P removal performance of the waters of a territory. You can always improve this media implementing tertiary treatment in plants that are not yet have, or increase the capacity of treatment plants if they hold but are saturated. By modifying yields elimination of P, already we are working on so-called tertiary sources and this is not the purpose of this paper.

In the case of Spain, the annual flow of P from wastewater treatment plant sludge is 47,75 kt. The generation of this sludge is located near urban centers and is proportional to the capacity of the wastewater treatment plant, which is expressed in population equivalent (P.E.). In Spain there are about 2.500 wastewater treatment plants, which in 2009 stripped a load of 68.777.103 P.E.of a total of 2.320 urban agglomerations (National Plan for Water Quality: Sanitation and Treatment 2007-2015).

5. Phosphorus cycle in the Barcelona Metropolitan Area (BMA) and phosphorus recovery prospects from WWTP streams

5.1. Barcelona Metropolitan Area (BMA)

This study has been focused on the second largest metropolitan area in Spain and the eighth of EU27, the BMA. Its territory includes the agricultural areas of the Llobregat Delta, the fully urbanised areas of the Barcelona plain and the large green areas of the Garraf massifs and Collserola and Marina mountain range.

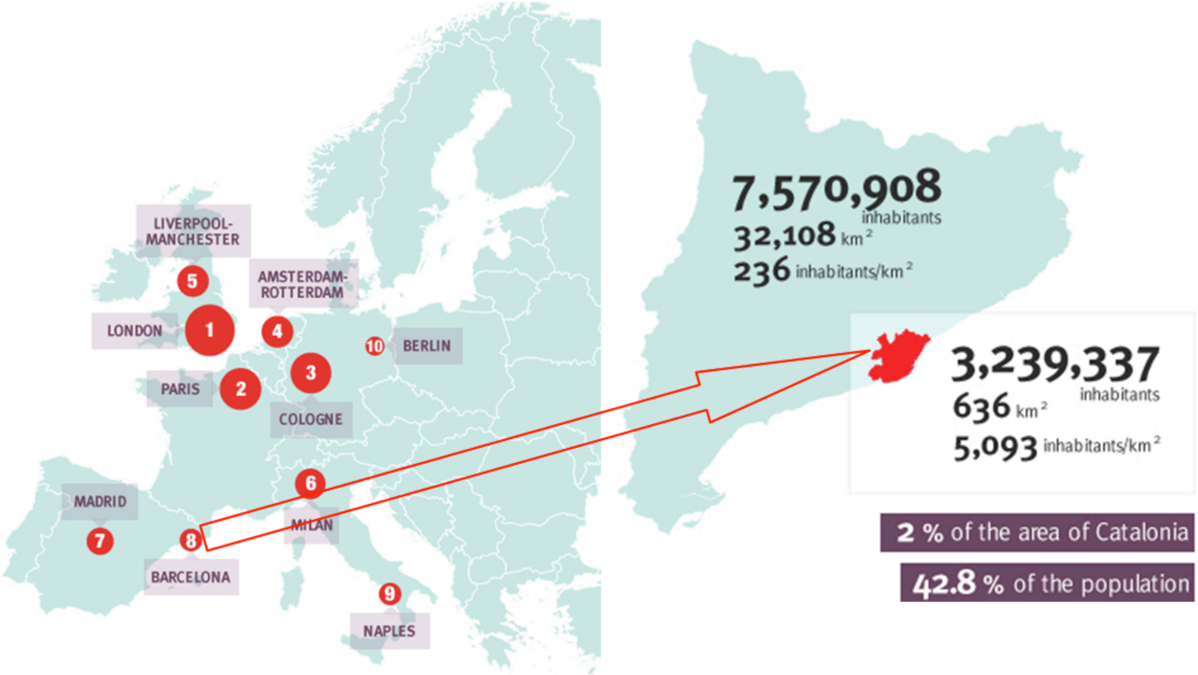


Figure 30 Largest metropolitan areas in Europe and Metropolitan Area of Barcelona. Source: Eurostat: metropolitan regions. Eurostat, 2012.

In the BMA 3.239.337 people live in an area of 636 km^2 (INE, 2016). In other words, 48% of the population of Catalonia is concentrated in 2% of its territory Figure 30. In this area there are seven sewage treatment plants with a total treatment capacity of 5.763.000 P.E. Figure 32 and Table 10, which generated 57.673 t dm of sewage sludge in 2012. The P present in these sludge amounts to 1.743 t P (see Table C2, Annex C). This is 3,65% of the potentially most important secondary source of P in Spain. P flows through the BMA wastewater treatment and disposal of sludge in 2012 are shown in Figure 31.

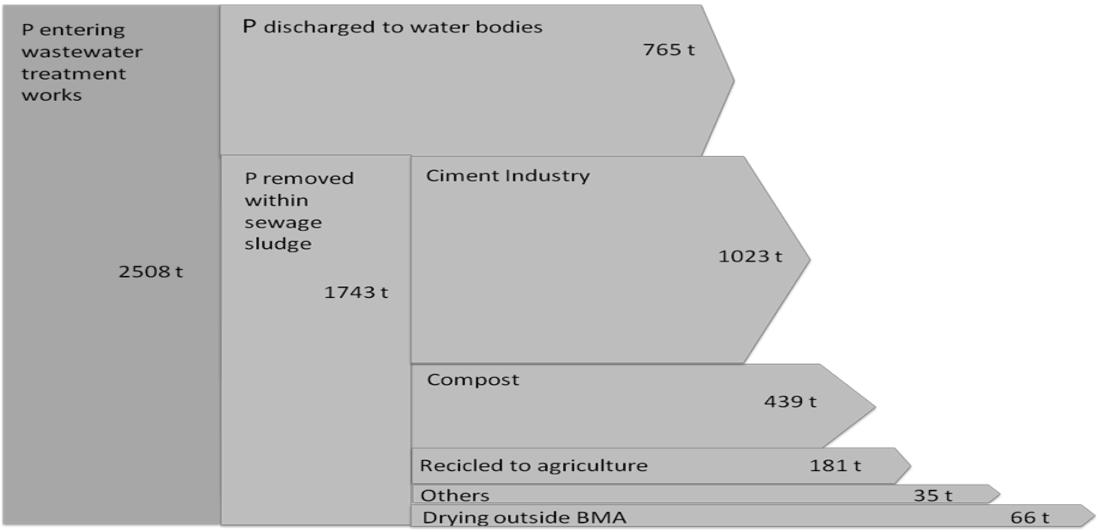


Figure 31 Phosphorous flows through BMA WWTPs in 2012.

5.2. Wastewater treatment system in the BMA

In the BMA there are seven WWTP with different treatments and capacities (see Table 10 and Figure 31). Sludge produced in these plants is treated by different ways in function of the WWTP so that the characteristics of these are different, Table 11 shows the types of treatments of each plant and the dry matter of the sludge generated in them.

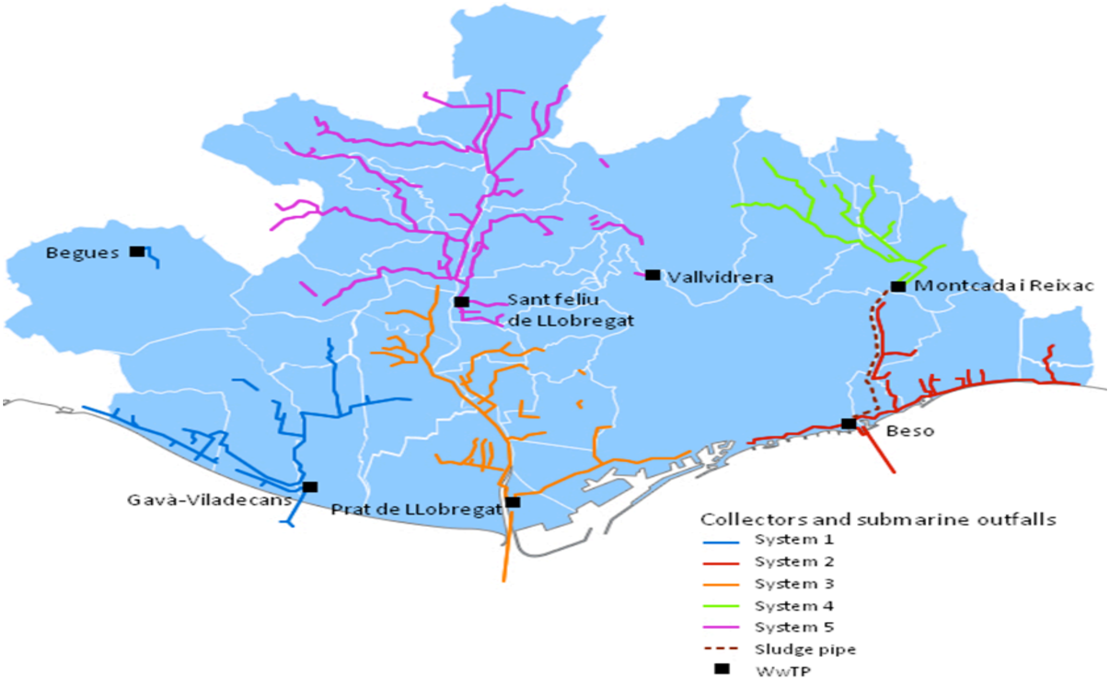


Figure 32 WWTP in BMA and its collectors and outfalls.

Table 10 Details of type of treatment and nominal capacity (m^3/d and PE) of the Wastewater Treatment Plants in the BMA.

Wastewater Treatment Plant	**Capacity design**		**Type of Treatment**
	m^3 / d	*P.E.*	
Sant Adrià de Bèsos	525000	2.850.000	Biological
El Prat de Llobregat	315000	1.710.000	Biological , nutrients and regeneration
Montcada i Reixac	72600	430.000	Biological
Sant feliu de Llobregat	64000	380.000	Biological , nutrients and regeneration
Gavà, Viladecans	64000	380.000	Biological , nutrients and regeneration
Begues	1200	7.000	Biological , nutrients and regeneration
Vallvidrera	1100	6.000	Biological , nutrients and regeneration
Total capacity		5.763.000	

Table 11 Average Dry mater content (% dm) content of sludge generated and type of sludge treatment in every WWTP from the BMA

WWTP	**% Dry substance (dm)**					**Sludge Treatment type**
	2011	*2012*	*2013*	*2014*	*2015*	
Sant Adrià de Bèsos	31/92	29/94	29/95	30	29	Thickening and treatment in Metrofang
El Prat de Llobregat	23/87	22/87	22/88	23/88	23/88	Thickening, anaerobic digestion with CHP, dehydration and thermal drying
Montcada i Reixac	2	2	2	2	2	Thickening, pumping to Besos WWTP and treatment in Metrofang
Sant feliu de Llobregat	25	24	25	25	24	Thickening, anaerobic digestion with CHP and dehydration
Gavà-Viladecans	23	22	21	21	20	Thickening, anaerobic digestion with CHP and dehydration
Begues	16	2/15	2	2	2	Thickening and dewatering
Vallvidrera	14	2/14	2/12	2/13	2	Thickening and dewatering

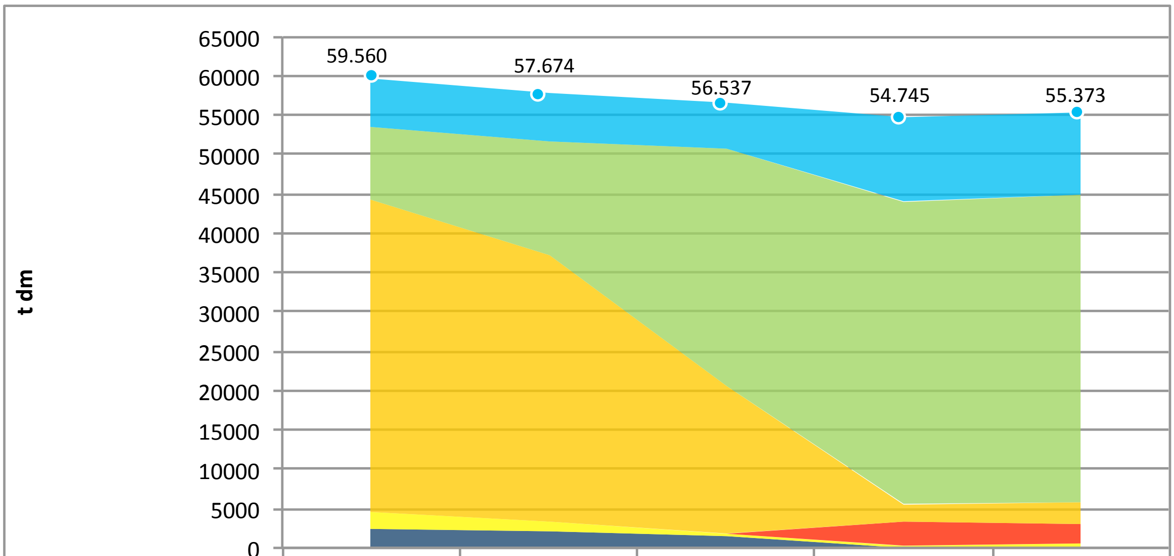
Treatments plants that appear with more than one value use sludge drying systems at different levels, thickening (≈ 2-5 dm), dewatering (≈ 10-30 dm) and drying (≈ 75-95 dm).

For energy efficiency criteria, wet sludge from WWTP Vallvidrera and Begues are anaerobically digested in WWTP Gavà-digesters Viladecans and Sant Feliu de Llobregat, respectively. Sludge generated in WWTP of Montcada i Reixac are sent to the WWTP of Sant Adria de Besos where they mix to send to the thermal drying plant Metrofang. This plant is contracted by BMAuntil 2016; it dried sludge through the STC process at low temperature thermal drying. Metrofang is located next to WWTP of Sant Adria de Besos.

5.3. Evolution of generation and disposal of sewage sludge in the BMA during period 2011-2015

During the period 2011-2015 WWTPs of the BMA generated an annual average of 56.778 tons of DM sludge. The sludge disposal routeswere: direct application in agriculture, composting, energy recovery as fuel for cement industry, anaerobic digestion, BMA external drying and others. Figure 33 shows tons of sludge DM that was sent to each of these destinations as well as total generated each year during the period 2011-2015. Between 2011 and 2014 the proportion of sludge sent to these destinations has been changing to stay in 2015.

Sludge generation during these five years has been declining by an average of 2.8% steadily until 2014; in 2015 it increased 1.2%. This decrease is due to the reduction of the industrial activity within the area of BMA caused by the economic crisis in the 2011-2015 years.



	2011	2012	2013	2014	2015
Total	59560	57674	56537	54745	55373
🟦 Agriculture	6071	5979	5676	10681	10482
🟩 Compost	9231	14508	30407	38460	39104
🟨 Ciment	39556	33838	18625	2297	2766
🟥 Anaerobic digestion	0	0	0	3018	2517
🟨 Others	2181	1159	285	240	504
🟦 External drying BMA	2521	2190	1544	49	0

Figure 33 Values of the disposal routes of the sludge generated in BMA between 2011 and 2015 in tons of dry matter

Table 12 Tons Sludge dry matter produced between 2011 and 2015 by WWTP from BMA

WWTP	**Year**				
	2011	*2012*	*2013*	*2014*	*2015*
Sant Adrià de Bèsos	41.697	39.426	38.896	37.204	37.755
El Prat de Llobregat	12.311	12.343	12.024	12.185	12.127
Montcada i Reixac	5.212	4.943	5.464	4.958	5.137
Sant feliu de Llobregat	3.349	3.508	3.327	3.003	3.016
Gavà-Viladecans	2.137	2.377	2.288	2.353	2.475
Begues	51	60	53	48	55
Vallvidrera	27	38	39	41	38

In Table 12 generation of sludge produced in every plant of BMA is shown during the period 2011-2015.

Sludge disposal to Agriculture

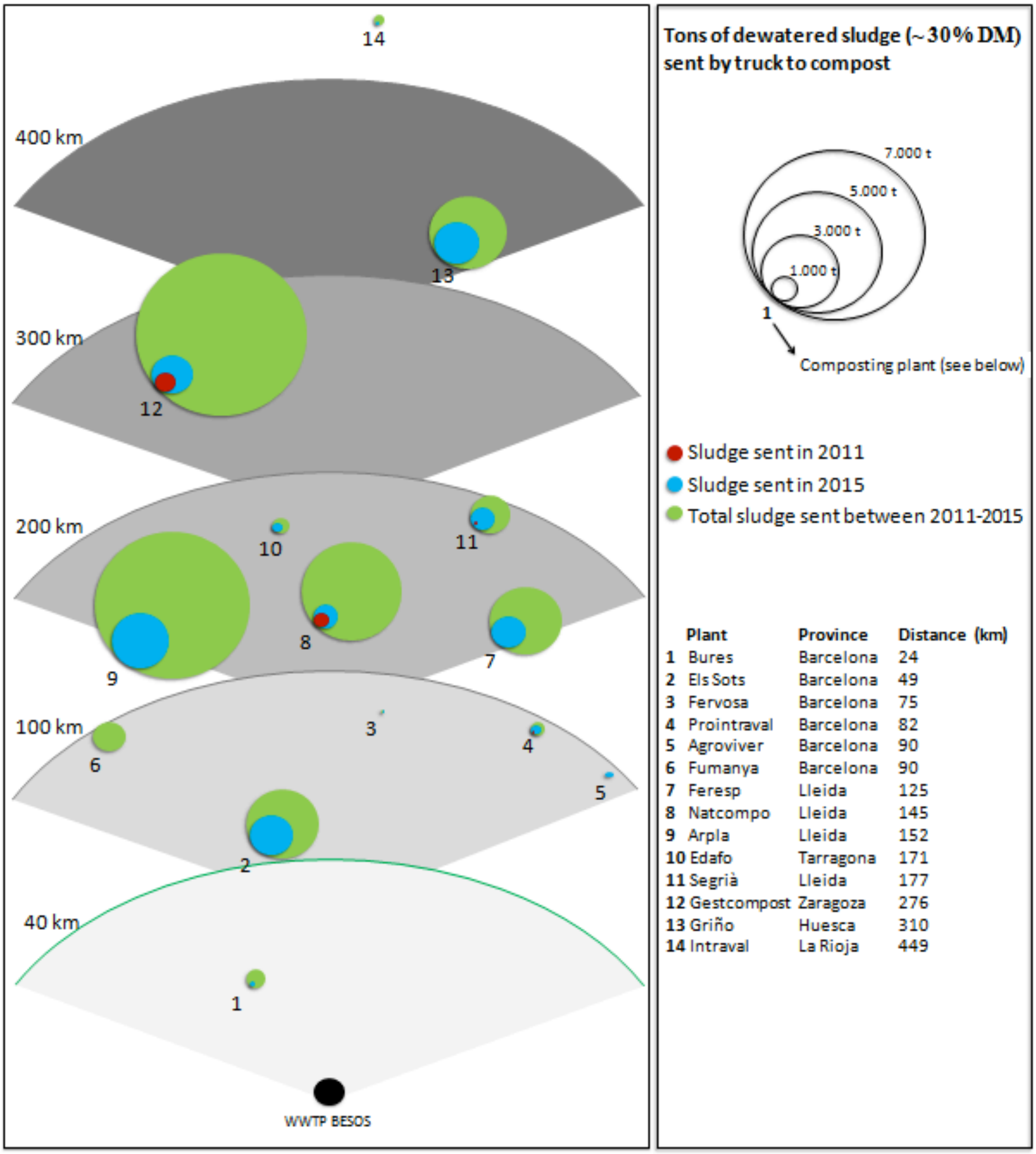
During the first three years of this period they were sent about 6.000 t (dm) of sludge annually to agriculture, from 2014 onwards increased to 10.000 t (dm). Factors limiting in use of sludge in agriculture are available agricultural surface, remoteness of agricultural areas and sludge characteristics such as pH and heavy metal content among others. The use of sludge from sewage treatment plants is regulated by Directive 86/278/CEE on the protection of the environment and in particular soils where sludge is used for agricultural purposes. This directive regulates the conditions of application of sludge to agricultural soils, conditions designed to avoid possible harmful effects on water, soil, vegetation, animals and human health.

According to the last agricultural census conducted for 2009, in the BMA there are 23.089 ha for agricultural use (Idescat, 2009). Spanis regulation, through the Real Decreto 1310/1990 limits the application of sludge in agricultural soils depending on the concentration of heavy metals (Cd, Cu, Ni, Pb, Zn, Hg and Cr), so the amount of sludge that can be sent by this route is very limited depending on the heavy metals present in the target agricultural soil and in the sludge. Another factor to consider when sludge is sent to far-off agricultural areas is the distance to the WWTP. A greater distance causes more environmental and economic impact.

Sludge disposal to Composting

Since 2011, the amount of sludge intended for composting has increased from 9.231 t (dm) to 39.104 t (dm) until 2015. This sharp increase occurs to balance the reduced demand of sludge as fuel for cement industry and have saturated the other alternatives. Note that in the BMA there are only two composting plants, one in Sant Cugat del Vallès and another in

Torrelles de Llobregat, with capacities of 7.600 t/yr and 5.500 t/yr of FORM and a crushing plant (TRV) or pruning respectively, so it is not possible to sent any sludge to these plants and it is inevitable send the sludge to other plants outside the BMA. WWTP of Besos is the main generator plant intended for composting sludge. Figure 34 shows composting plants where sludge from WWTP of Besos is sent, distance of these and tons of dry matter shipped in years 2011 and 2015.



	Plant	Province	Distance (km)
1	Bures	Barcelona	24
2	Els Sots	Barcelona	49
3	Fervosa	Barcelona	75
4	Prointraval	Barcelona	82
5	Agroviver	Barcelona	90
6	Fumanya	Barcelona	90
7	Feresp	Lleida	125
8	Natcompo	Lleida	145
9	Arpla	Lleida	152
10	Edafo	Tarragona	171
11	Segrià	Lleida	177
12	Gestcompost	Zaragoza	276
13	Griño	Huesca	310
14	Intraval	La Rioja	449

Figure 34 Data on dewatered sludge (as tonnes of dm) sent to compost from WWTP of Besos between 2011-2015. Data provided by WWTP of Besos and AMB.

Between 2011 and 2015 WWTP of Besos increased sludge sent to composting from 15.322 tonnes (30% SS) in 2011 to 137.073 tonnes in 2015. This sharp increase in sludge intended for composting has increased the requirements for sending higher amounts of sludge to more distant plants because saturation of the closest. This resulted on the transport of 1.557 t in 2015 to Intraval plant located 449 km away. Figure 34 shows tonnes shipped in 2011, 2015 and the total sent during this period and composting plants destination. The distribution of plants is also shown by their distance from the WWTP of Besos. The major part of the sludge was sent to treatment plants placed between 40 and 200 km of distance. In 2011, 41.147 tonnes were sent to a distance of between 40 and 100 km and 58.930 tons between 100 and 200 km. This supposes 30 and 40 % respectively of the total. Given that sludge sent to composting has 70 % of water (e.g 30% dm) and the quantities transported by truck, it suggests clearly the need for more efficient management of sludge both environmentally and economically.

Sludge disposal to Cement industry

In 2011, 39.556 t (dm) of sludge was sent to cement industry as fuel for co-substitution options. Co-substitution means that a percentage between 5 to 16 of the coque used is substituted by dried sludge. This sludge came from WWTP of Besos and Montcada with about 4% dry matter and was sent to the thermal drying plant Metrofang, next to the Besos WWTP. Metrofang uses dried thermal treatment at low-temperature by means of fossil fuels up to obtaining a 80 % dry matter sludge. From Metrofang the dry sludge was sent to the ciment industries placed in the proximities of BMA Cement plants where dry sludge destined during the period 2011-2014, tons and locations of the same ones are shown in Table 13.

Table 13 Location of cement plant were sludge was sent as fuel and tons of sludge in dry matter (dm)

Plant	**Location**	**Sludge (t dm)**		
		2011	**2012**	**2013**
Cemex	*Alicante*	3334	2235	0
Asland	*Sagunt*	2788	603	967
Asland	*Montcada*	11808	7698	4573
Cemex	*Sant Feliu*	0	1437	1369
Uniland	*Monjos*	1662	4547	8563
Molins	*St Vicent*	1971	8563	2916
Uniland	*Garraf*	13046	7359	0

From 2011 to 2013 it has reduced the amount of sludge sent to cement industry due to reduced activity in the construction sector caused by the crisis in this sector. However, according to the cement industry, the crissis reduced dramatically the amounts of sludge dried and consequently, a reduction of product availability.

Sludge disposal to others

Sludge destined to other three disposal routes reached up to 8 % of the total during the five years period. In most of the cases scarce information about these destinations was available and the the follow-up was impossible to be reported

5.4. Closing the P cycle of seawage sludge in BMA

5.4.1. Actual seawage sludge disposal as example of a non- closed P cycle

There is foreseen a slow but continuous recovery of the sector of the construction in Spain (Euroconstruct. June 2016) and it is assumed that in a future it will turn to a situation similar to the presented one in 2011 for the disposition of sludge. This may encourage the return to the use of sludge as fuel in the cement industry, but although this may lead to a more sustainable option to send the sludge composting plants located more than 100 km (Figure 34), this option may not be performed due the action plans of the EU for circular economy (European Commission, 2015) and the requeriments defined by regulation on Critical Elements where the phosphatic rock has been included (European Commission , 2008).

Since the P present in the sludge can be returned to the soil as fertilizer, reducing the demand for mineral fertilizers in agriculture as well as the impact of manufacturing these, EU provides ban the use of secondary sources of P, including the sewage sludge, in activities that do not involve the closure of the P cycle following the model of a circular economy. Among these are the uses of sludge in the construction industry, either as fuel in cement or component, or other ceramic materials.

Given these new limitations, it is necessary to plan new scenarios in which the requirements set by the EU regarding P cycle while the environmental and economic impact are reduced and consequently met. The different technologies available to recover the P sludge from sewage treatment are key for the new sludge management, which some have been presented in Section 3.3.

5.4.2. Identification and quantification of seawage sludge that do not close the cycle P

To meet the goal of circular economy should be given a new destination for the sludge to the cement industry. Since 2011 was the year when more tonnes were directed for the cement industry, this is taken as a reference to calculate the alternatives.

Acording with data provided by WWTPs of BMA (See Annex B), in 2011 there were destined a total of 39.556 tons (dm) of sludge from WWTPs of BMA to cement, that was 79 % of sludge generated in this year (Figure 33). The average content of P of this sludge was 20.648 mgP/kg dm (See ANNEX C), and consequently 715 tons (dm) of P were sent out of the cycle of P, the equivalent to 8.631 t of mineral fertilizer (super phosphate simple).

This sludge was generated in WWTP of El Prat, Besos and Montcada. Because of different treatments used (see Table 10) their characteristics differ. In Table 14 quantities, dry matter, concentration of P and total P of sludge disposal to cement in 2011 are collected.

Table 14 Sludge generated in WWTP of Prat, Besos and Montcada sent to cement in 2011. (Data provided by the plants shown in ANNEX B. ** Concentration of P was calculated following the method shown in ANNEX C from data provided by the plants.*

	WWTP	
	Besos and Montcada	**El Prat**
Sludge (t)	103.977	8.686
*% dm**	30,75	87,30
*t (dm)**	34.753	7.583
*mg P/kg dm***	13.363	38.069
P (t)	427	288

The main differences between the sludge generated by WWTP of Prat and Besos are the dry matter content and the stabilization treatment carried-out by the anaerobic sludge digestion stage in –El Prat WWTP.

5.4.3. Identification of new and alternatve disposal routes to promote P-cycle clossing

There are several ways to manage sludge that close the cycle P in the BMA.

- *Direct use in agriculture:* this pathway is saturated unable to allocate more sludge to agricultural areas of the BMA due to the limit for heavy metals established by the RD 1310/1990.

- *Composting:* is one of the most sustainable alternatives but should avoid sending the sludge composting plants which are located more than 40 km because of the high environmental and economic impact it entails.

- *Sludge leaching:* is other alternative to recover P from sludge digested, this alternative have performed technologies at full scale and large pilot (See Table 16).

- *Incineration and ash processing:* this option also closes the P cycle and at the same time it revalues the sludge energetically. As seen above, there are different technologies and tested on an industrial scale and have been evaluated by P-Rex Project.

Considering the studies by Garrido et al. (Garrido-Baserba, Molinos-Senante, Abelleria-Pereira, Fdez-Güelfo, Poch, & Fernandez_Sancho, 2015) and Kersti L. et al. (Linderholm, Tillman, & Mattsson, 2012), in which it is concluded that after direct use in agriculture, the option of composting is the one that generates fewer CO_2 emissions (for a transport lower than 40km) and at the same time as an economic return generates based in the commercialization of the generated compost. This route will be one of the alternatives studied in this study.The other alternative is selected based on the Life Cycle Assesment (LCA) study performed by P-Rex and discussed in section 5.5. The development of an specifiic LCA analysis was outside the timeframe of this project.

5.5. Scenarios to close the cycle P of seawage sludge in BMA

5.5.1. Selected technologies

P-Rex project made an LCA study for all technologies that have been presented in Section 3.3. The results of the set of technologieshas filed in the report "Life Cycle Assessment of selected processes for P recovery from sewage sludge, sludge liquor, or ash "(C. Remy, 2015). A summary of the main results are shown in Figures 35 to 44. The indicators for LCA impact assessment are collected in Table 15.

Table 15 Indicators for impact assessment from P-Rex LCA study according to(Remy & Jossa, 2015.

Indicator	Unit	Main contributors
Cumulative energy demand (fossil)	MJ	Fossil fuels (lignite, hard coal, natural gas, oil)
Cumulative energy demand (nuclear)	MJ	Nuclear fuels (uranium)
Metal depletion potential	Kg Fe-eq	Metals, inorganic resources
Global warming potential (100a)	Kg CO_2-eq	CO_2 (fossil), N_2O, CH_4
Terrestrial acidification potential (100a)	Kg SO_2-eq	SO_2, NO_x, NH_3
Freshwater eutrophication potencial	Kg Fe-eq	P emissions in water and soil
Marine eutrophication	Kg N-eq	N emissions in air, water and soil
Ecotoxicity (freshwater)	CTUe	Heavy metals, organic pollutants
Human toxicity	CTUh	Heavy metals, organic pollutants

In Table 16 are shown processess assessed by P-Rex, its descriptions and technologies aviables and the state of these technologies.

Table 16 List of processess assessed by P-Rex project Remy & Jossa, 2015.

Prossess	**Description**	**Process name**	**Data quality**
Sludge precipitation	Precipitation of struvite with Mg dosing in sludge before dewatering, pH adjustment via aireation	AirprexTM	Full-scale
Liquor precipitation 1	Precipitation of struvite with Mg dosing in sludge liquor after dewatering, pH adjustment via NaOH	Pearl (R)	Full-scale
Liquor precipitation 2	Precipitation of struvite with Mg dosing in sludge liquor after dewatering, pH adjustment via NaOH	StruviaTM	Large pilot
Sludge leaching 1	Leaching of digested sludge, dewatering and P recovery in liquor after dewatering by pH increase and Mg dosing, simultaneous precipitation of metals with Na_2S	Gifhorn process	Full-scale
Sludge leaching 2	Leaching of digested sludge, dewatering and P recovery in liquor after dewatering by pH increase and Mg dosing, metal complexation with citric acid	Stuttgarter process	Large pilot
Sludge metallurgic	Thermal treatment of dried sludge in a shaft furnace (1'450°C) with coke addition and energy recovery via off-gas burning	Mephrec (R)	Model
Sludge metallurgic (integrated in MSWI)	Thermal treatment of dried sludge in a shaft furnace (1'450°C) with coke addition and energy recovery via burning of off-gas in municipal solid waste incinerator	Mephrec (R)	Model
Ash metallurgic	Thermal treatment of ash in a shaft furnace (1'450°C) with coke addition	Mephrec (R)	Model
Ahs leaching 1	Leaching of ash with H_2SO_4, solid-liquid separation, pH increase and precipitation of CaP with Ca(OH)2	LeachPhos	Large pilot
Ahs leaching 2	Leaching of ash with recycled H_3PO_4, metal separation via staged ion exchange, production of H_3PO_4	Ecophos	Full–scale planing
Ash thermo-chemical	Thermochemical treatment of cold ash in rotary kiln (950°C), addition of Na and dried sewage sludge as reducing agent to remove metals via off-gas	Ash Dec	Pilot / Model
Ash thermo-chemical (integr. In mono-inc)	Thermochemical treatment of hot ash from mono-incineration in rotary kiln (950°C), addition of Na and dried sewage sludge as reducing agent to remove metals via off-gas	Ash Dec	Pilot / Model

As shown in Figures 35 and 36 processes with higher performance, lower cumulative energy demand and P recovery, are the processes that treat ash from mono sludge incineration (with the exception of metallurgic Ash). Negative values presented are due to energy credits generated by replacing mineral fertilizers by products obtained in each process and energy recovery from off-gas.

Fossil energy demand of ash leaching 1 of ChemP ash (Leachphos) is dominated by chemical demand for leaching and product precipitation. This energy demand is partly neutralized by fertilizer credits, leaving a final energy demand of 2.7 10^6 MJ/yr for this option. In comparison, the Ecophos process (ash leaching 2) needs higher amounts of energy mainly for steam production, but this is completely neutralized by credits for fertilizer and by-products, resulting in net energy savings for this process (-6.1 10^6 MJ/yr) (Remy & Jossa, 2015).

Thermo-chemical treatment of ash needs energy for chemicals (mainly Na_2SO_4) and heating of ash and rotary kiln, plus some energy for drying of sludge as reducing agent. Overall, fertilizer credits and avoided disposal of ash leads to an overall negative energy demand (-8.1 10^6 MJ/yr) which can be further decreased by integration into an existing mono-incineration plant, saving on natural gas for ash pre-heating (-12.1 10^6 MJ/yr).

From the energy point of view, processes Ahs Thermo-chemical integrated, Ash Thermo-chemical and Ash Leaching 2 are those that in this order have better recovery of P and lower energy demands. The other processes have lower efficiencies in the recovery of P or higher energy demands.

For the other parameters evaluated, Ash Leaching 2 process is the best results obtained by what is considered the least environmental impact (Figures 37 to 44). Noteworthy is the large difference in Human Toxicity and Ecotoxicity, between the three technologies that process sludge ashes. The Ash Leaching 2 technology test negative values (-8) compared to 549 of the other two processes (Figures 43 and 44), this is due to the heavy metals present in the products of these processes and can reach the soils.

Legend for Figures 35 to 44

◇ Sludge precipitation
◇ Liquor precipitation 1
◇ Liquor precipitation 2
◇ Sludge leaching 1
◆ Sludge leaching 2
● Ash leaching 1

● Sludge metallurgic
● Sludge metallurgic integrated
● Ash metallurgic
○ Ash thermo-chemical
○ Ash thermo-chemical integrated
○ Ash leaching 2

■ Infrastructure
▦ Energy Credit
■ Off-gas treatment
■ Disposal of ash
■ Transport and mono-incineration
■ Chemicals
■ By-products
■ Heavy metals to soil (secondary P)
■ Heavy metals to soil (mineral P)

■ Substitution of mineral N fertilizer
■ Substitution of mineral P fertilizer
■ Treatment of return load
■ Drying of sludge
■ Heat for product drying
■ Electricity demand
■ Dewatering
■ Digestor and CHP

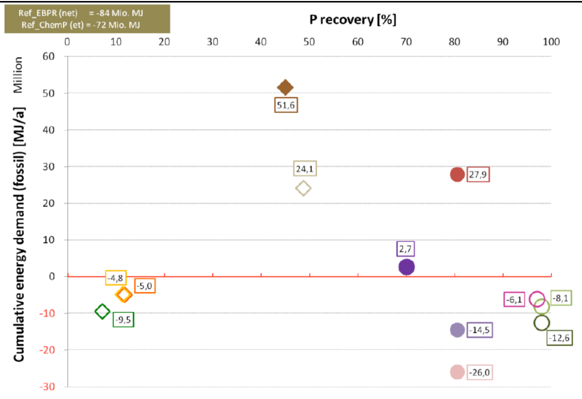


Figure 35 Total cumulative demand (fossil) related to P recovery potential

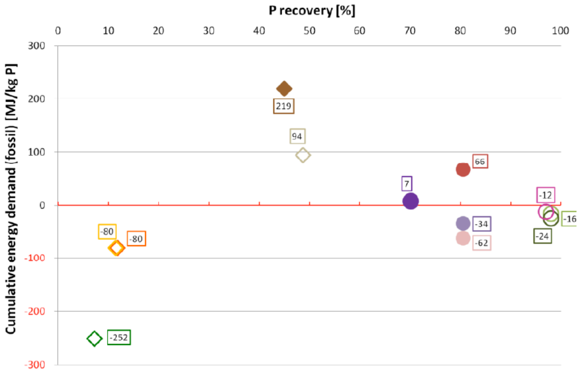


Figure 36 Total cumulative energy demand (fossil) per kg P recovery potential

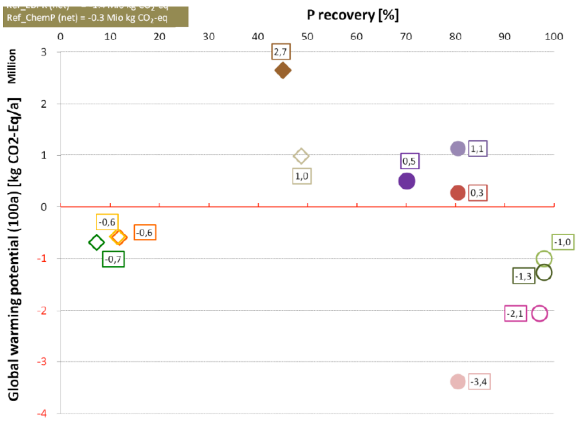


Figure 37 Total global warming potential (100a) related to P recovery potential

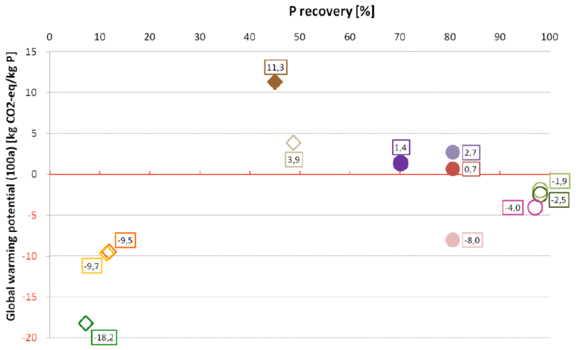


Figure 38 Global warming potential (100a) per kg P related to P recovery potential

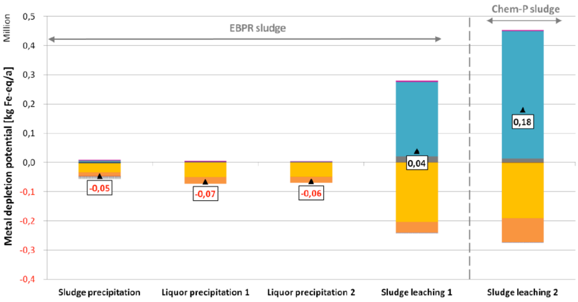


Figure 39 Total metal depletion potential of P recovery from sludge or liquor

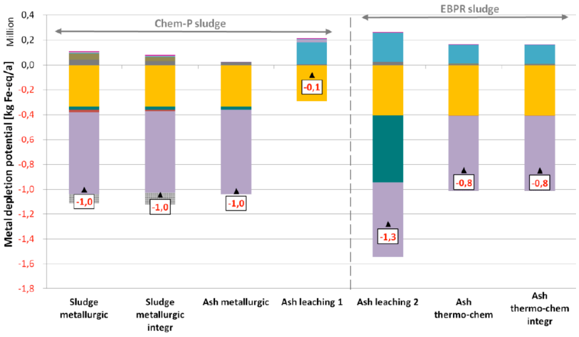


Figure 40 Total metal depletion potential of P recovery from dried sludge or ash

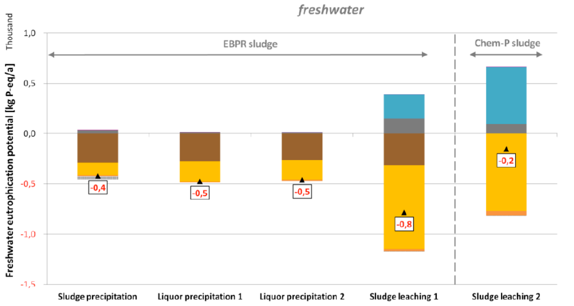


Figure 41 Total freshwater eutrophication potential for P recovery from sludge or liquor

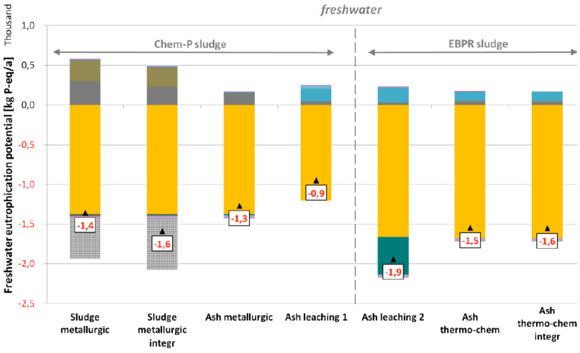


Figure 42 Total freshwater eutrophication potential for P recovery from dried sludge or ash

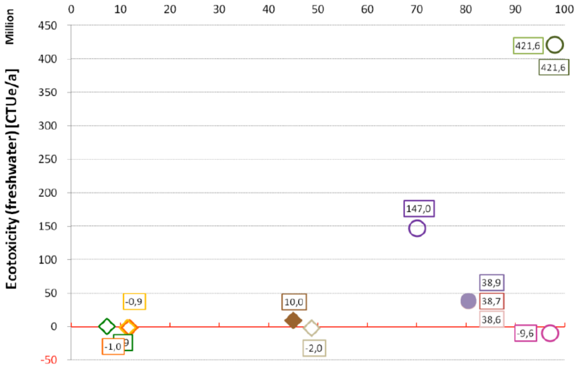


Figure 43 Total ecotoxicity (freshwater) related to P recovery potential

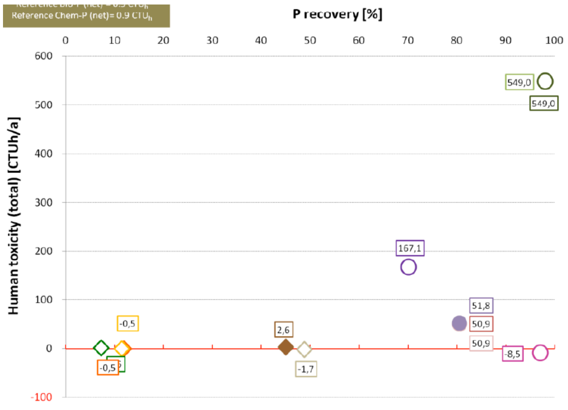


Figure 44 Total human toxicity related to P recovery potential

In Table 17 results of the indicators evaluated for each process according P-Rex are collected.

Table 17 Results of indicators evaluated in LCA made by P-Rex Project (Remy & Jossa, 2015).

Pathways	P yield[1] [%]	Fossil Energy Demand [10^6 MJ]	Global Warming [kt CO_2-eq]	Eutro-phication freshwater [t P-eq]	Ecotoxicity [10^6CTUe]	Human Toxicity [CTUh]
Sludge precipitation	7[2]	-9,5[3]	-0,7[3]	-0,4	0,9	1,6
Liquor precipitation 1	12[2]	-0,5	-0,6	-0,5	-1,0	-0,5
Liquor precipitation 2	11[2]	-4,8	-0,6	-0,5	-0,9	-0,5
Sludge leaching 1	49	24,1	1,0	-0,8	-2,0	-1,7
Sludge leaching 1	45	51,6	2,7	-0,2	10,0	2,6
Sludge metallurgic	81	27,9	0,3	-1,4	38,7	50,9
Sludgemetallurgic (integrated in MSWI)	81	-26,0	-3,4	-1,6	38,6	50,9
Ash metallurgic	81	-14,5	1,1	-1,3	38,9	51,8
Ahs leaching 1	70	2,7	0,5	-0,9	147,0	167,1
Ahs leaching 2	97	-6,1	-2,1	-1,9	-9,6	-8,5
Ash thermo-chemical	98	-8,1	-1,0	-1,5	421,6	549,0
Ashthermo-chemical (integr. In mono-inc)	98	-12,6	-1,3	-1,6	421,6	549,0

[1] related to total P load in raw mixed sludge = 100%

[2] depending on dissolved PO_4-P concentration in digested sludge, reference is 200 mg/L PO_4-P

[3] depending oe effects on sludge dewaterability, refernce is +2% DM

Given these results, it has been determined that the best technology proposed for P-Rex Project that can be applied in sludge management of BMA is Ecophos (Ash Leaching 2).

The EcoPhos process was originally developed by the phosphate industry to process low-grade P input material (e.g. P rock with high contamination of heavy metals) into a high-quality P product (phosphoric acid in feed-grade quality). Recently, it has been modified and tested for mono-incineration ash as input material.

The Ecophos process is based on the digestion of ash into a large excess of H_3PO_4 (Figure 45), which is recycled from the product side. After digestion, insoluble residues are removed via filtration and disposed as inert material. The liquid solution contains a high amount of H_3PO_4 and dissolved impurities from the ash. This solution is purified by a multi-stage ion exchange (IEX) process, thus removing divalent salts (Mg, Ca), metals (Fe, Al), and other impurities such as heavy metals. Ion exchange resins are regenerated with HCl, thus introducing the acid equivalents into the process which are required for ash digestion. The different regeneration solutions of the IEX are valuable by-products of the process, which can be valorized as Ca/Mg solution or Al/Fe solution, whereas other impurities are disposed as wastewater.

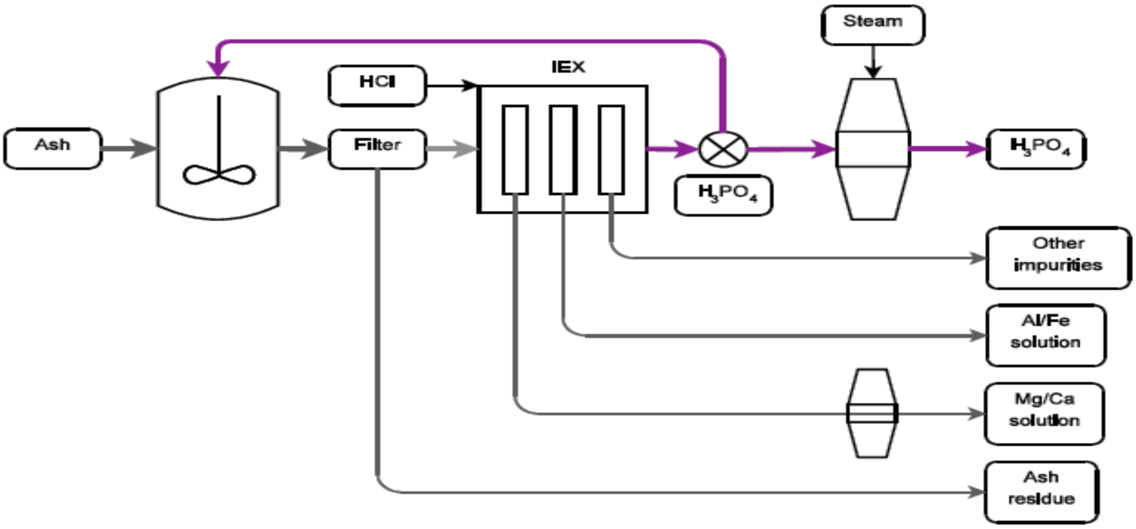


Figure 45 Ecophos Scheme Process (Remy & Jossa, 2015)

After purification of the solution, a part of the H_3PO_4 is recycled back to the ash digestion, whereas another part is recovered as H_3PO_4 product and is further concentrated using steam. The final product is a H_3PO_4 solution with high concentration and low impurities.
Energy demand for steam concentration of product and chemical demand for IEX regeneration are relatively high, but are completely off-set by credits for substituted mineral P fertilizer and other valuable by-products ($CaCl_2$, $FeCl_3$) of the purification process. The Ecophos process can recover up to 97% of total P load in ashes with credits in all environmental indicators. Based on this technology will be made the different scenarios presented below.

5.5.2. Definition of Scenarios to promote P-cycle closing actions

Given the quantities and characteristics of the sludge to manage (Table 14) and present alternatives to close the cycle P (Sections 5.4.3 and 5.5.1), the following scenarios are proposed in Table 18.

Table 18 Proposed scenarios to promote P-cycle closing actions at the BMA.

Scenario	Description
1	Anaerobic digestion and dewatering of sludge from WWTP Besos, mixing with sludge from WWTP Prat, incineration and ash treatment process by Ecophos
2	Mixing sludge from Besos dehydrated in Metrofang and sludge from WWTP Prat, incineration and ash treatment process by Ecophos
3	Mixing sludge from Besos dehydrated in Metrofang and sludge from WWTP Prat and composting
4	Anaerobic digestion and dehydration of sludge from WWTP Besos, mixing with sludge from WWTP Prat and composting

Scenarios that arise in this study are different combinations of processes listed in Table 19, whose characteristics are described below and summarized in Table 20.

Table 19 Processes involved in proposed scenarios to promote P-cycle closing actions at the BMA

	Processes	Resource
P1	Anaerobic digestion with CHP Plant	P-Rex (Remy & Jossa, 2015)
P2	Dewatering by centrifugation	P-Rex (Remy & Jossa, 2015)
P3	Mono incineration in fluidized-bed incinerator	P-Rex (Remy & Jossa, 2015)
P4	Ecophos	P-Rex (Remy & Jossa, 2015)
P5	Composting	(Garrido-Baserba, Molinos-Senante, Abelleria-Pereira, Fdez-Güelfo, Poch, & Fernandez_Sancho, 2015)
P6	Transport by truck	(Linderholm, Tillman, & Mattsson, 2012)

P1 Anaerobic digestion with CHP Plant

The digestor is a mesophilic digestion process at 35-37°C with typical retention times of 15-20d. During the digestion process, 55% of volatile solids (VS) are degraded and converted into biogas (463 NL/kg VS_{in}) with a methane content of 61 Vol-% CH_4. The degradation and gas yield are in the upper range of typical values for mesophilic digestion, assuming optimium operation. Electricity demand for the entire digestor (mainly for mixing and pumping of sludge) is estimated with 3 kWh/m^3 input sludge (MUNLV 1999), whereas thermal energy demand for digestor heating is assumed to 30 kWh/m^3 input sludge (MUNLV 1999). Digested sludge contains dissolved methane, assuming 100% saturation (18 mg/L CH_4 at 30°C). This methane is stripped in the downstream dewatering.

Valorisation of biogas in the CHP plant is assumed to produce electricity and heat, assuming an electrical efficiency of 42% and thermal efficiency of 38% for a modern CHP unit. Electricity demand for CHP operation and gas cleaning is assumed with 0.1 kWh/m^3 biogas. Emissions are taken from M. Garrido et al. 2014.

P2 Dewatering by centrifugation

Digested sludge is dewatered in a centrifuge (decanter), using polymer as flocculant to improve dewaterability results. The dewatered sludge has a final DM content of 25%, thus being in the medium range of dewaterability of mixed sludge (20-30% DM). Electricity demand of the centrifuge is assumed to 2.5 kWh/m^3 (MUNLV 1999). Polymer demand is estimated 12 g/kg DM, which is in the medium range for mixed digested sludge (5-20 g/kg DM).

P3 Mono incineration in fluidized-bed incinerator

Dewatered sludge is transported by truck (40km) to a dedicated mono-incineration plant (fluidized-bed incinerator) where sludges are mixed. Process data for the mono-incineration plant in terms of energy balance and material demand for operation is based on a BAT mono-incineration plant and provided by Outotec (Orth, 2015). Based on the lower heating value (LHV) of the input sludge, efficiency of the steam turbine is estimated with 14% of LHV as generated electricity, while 73% of LHV are supplied in form of district heating or predry system. Electricity demand of the incinerator is estimated with 0.23 kWh/kg DM, assuming autothermal incineration of sludge with internal pre-drying. Fluidized bed is realized by sand addition (0.7 g/kg DM).

Off-gas cleaning of mono-incineration requires additives (0.3 g coke, 5 g lime/kg DM, 16.5 g NaOH (30%), and 12.1 g NH_3 (25%) per kg input DM) and produces waste (42 g gipsum) for disposal. Off-gas emissions are estimated based on M. Garrido et al. 2014. Heavy metals are completely bound in ash or off-gas cleaning, but a transfer of 10% of Hg load into the air is assumed. The resulting ash is transported by truck (40 km) to Ecophos plant.

P4 Ecophos

Data is based on previous experience of Ecophos with mono-incineration ashes and represents planning data of a full-scale plant. Demand for electricity, steam (for product concentration), and HCl are based on Ecophos estimates, while ion exchange resin is changed every 2 years. By-products of the purification process are accounted as $CaCl_2$ and $FeCl_3$ solution.

P5 Composting

Composting process lasts for nine months, with a reduction in volume and weight of 70 and 60% respectively. The final compost has a 60% dry substance with 100% of P present at the start of the process, since it is estimated that no P losses by leaching. Energy consumption is 30 kWh/t DM and direct emissions of GHG 153,1 kg CO_2-eq/t DM, taken from M. Garrido et al. (Garrido-Baserba, Molinos-Senante, Abelleria-Pereira, Fdez-Güelfo, Poch, & Fernandez_Sancho, 2015).

P6 Transport by truck

The transport is realized by truck with capacity of load of 35 tons for sludge and 24 for rest of loads. The distance of transport is estimated in 40 km both for sludge and for ashes and 200 km for the necessary reagents in other processes. The consumptions of diesel and emissions are based on the information from K. Linderholm et al. 2012 and MAGRAMA respectively.

Table 20 data common to processess according to (Garrido-Baserba, Molinos-Senante, Abelleria-Pereira, Fdez-Güelfo, Poch, & Fernandez_Sancho, 2015), (Orth, 2015) and (Remy and Jossa, 2015).

	Amount	Reference
Anaerobic digestion with CHP Plant		
Degradation of volatile solids	55 %	P-Prex
Conversion to biogas	463 NL/kg VS_{in}	P-Prex
Methane content in biogas	61 % vol	P-Prex
Methane LHV	8900 kcal/Nm^3 CH_4	Moran, Shapiro,2006
Direct emissions of GHG	50,0 kg CO_2-eq/t DM	M. Garrido et al. 2014
Electricity demand	3,1 kWh/m^3	P-Prex
Thermal energy demand	30 kWh/m^3	P-Prex
Electrical eficiency	42 %	P-Prex
Thermal eficiency	38 %	P-Prex
Dewatering by centrifugation		
Electricity demand	2,5 kWh/m^3	P-Prex
Polymer demand	12 g/kg DM	P-Prex
Mono incineration in fluidized-bed incinerator		
Transport to mono-incinerator plant	40 km	Estimated
LHV of imput sulge (30 % DM)	1,61 kWh/kg DM	Outotec
LHV of imput sulge (34 % DM)	2,17 kWh/kg DM	Outotec
Steam turbine Electrical eficiency	14 % of LHV	Outotec
Steam turbine Thermal eficiency	73 % of LHV	Outotec
Electricity demand	0,23 kWh/kg DM	Outotec
Sand adition	0,7 g/kg DM	Outotec
Direct emissions of GHG	450,64 kg CO_2-eq/t DM	M. Garrido et al. 2014
Ash generation	43,2 kg ash /kg DM	Outotec
Ecophos		
P recovery	97 %	Ecophos
Electricity demand	0,03 kWh/kg	Ecophos
Thermal energy demand	30 kWh/m^3	Ecophos
Steam	3 kg/kg	Ecophos
HCl (37%) consumption	0,9 L/kg	Ecophos
Ion exchange resin consumption	0,29 g/kg	Ecophos
$CaCl_2$ (100%) production	0,67 kg/kg	Ecophos
$FeCl_3$ (40%) production	0,41 kg/kg	Ecophos
Composting		
Transport to composting plant	40 km	Estimated
P recovery	100 %	Estimated
Composting time	9 moths	Estimated
Mass reduction after composting time	60 %	Soliva M. Et al. 2004
Final moisture	40 %	Average from catalonian compost marked
Direct emissions of GHG	153,10 kg CO_2-eq/t DM	M. Garrido et al. 2014
Electricity demand	30 kWh/t DM	M. Garrido et al. 2014
Transport by truck		
Fuel Energy content	9,82 kWh/L	Linderholm et al.,2012
Lorry capacity for sludge full load	35 t	Linderholm et al.,2012
Lorry capacity for others full load	24 t	Linderholm et al.,2012
Fuel consumption full load	0,48 L/km	Linderholm et al.,2012
Fuel consumption empty	0,33 L/km	Linderholm et al.,2012
GHG emissions	2,471 kg CO_2-eq/kWh	Carbonfoodprint

5.5.3. Scenario 1. Anaerobic digestion and dewatering of sludge from WWTP Besos, mixing with sludge from WWTP Prat, incineration and ash treatment process by Ecophos

In this scenario it is proposed to stabilize the sludge from WWTP Besòs undewatered (DM = 4.8%) by anaerobic digestion. The biogas generated will be recovered in the CHP plant where electrical and thermal energy are produced. Subsequently, the digested sludge is dewatered by centrifugation. The overflow is returned to the WWTP of Besòs and dewatered sludge will be transported by lorry to the mono-incineration plant where previously mixed with dry sludge from WWTP of El Prat, which have also been trucked. The mono-incineration plant arises locate within 40 km of the two WWTPs. The process of mono-incineration includes a pre-drying through recovery of flue gases, is why a LHV is applied based on the dry substance of the mixture of sludge (the LHV is reduced according to the DM). In the mono-incineration electric power is generated by a steam turbine and heat energy, both from combustion gases. Subsequently, the ash generated will be moved by lorry to the plant Ecophos, located 40 km away, where fly ash will be treated to recover the P in the form of phosphoric acid in industrial grade (85%). In the process of Ecophos calcium and ferric chloride were also generated. In this study the management of waste generated in the process of Ecophos is not included. The flowchart of this scenario presented in Figure 46.

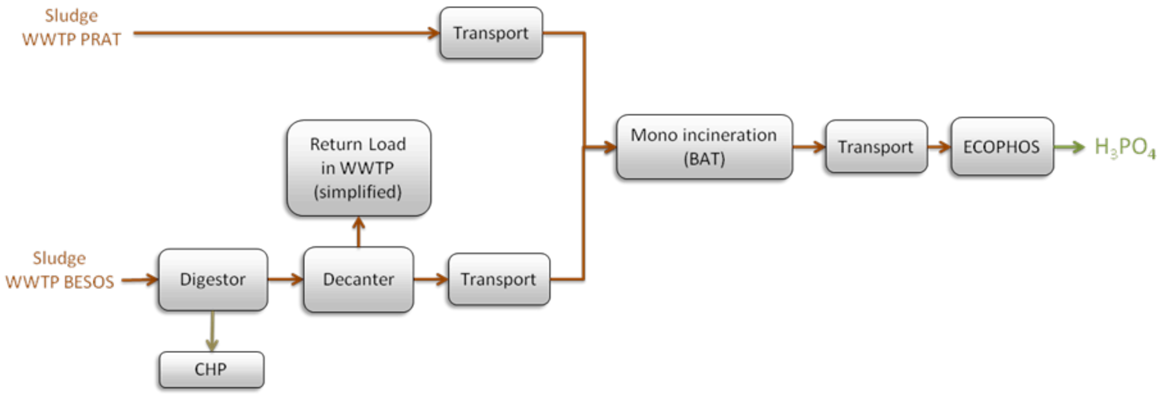


Figure 46 Process scheme for scenario 1

5.5.4. Scenario 2. Mixing sludge from Besos dehydrated in Metrofang and sludge from WWTP Prat, incineration and ash treatment process by Ecophos

In this scenario it is proposed to truck the sludge from WWTP of Besòs, which have been dewatered in the plant Metrofang, to the mono-incineration plant where previously will be mixed with the dry sludge from the WWTP of El Prat, which have also been trucked. The mono-incineration plant arises locate within 40 km of the two WWTPs. The process of mono-incineration includes a pre-drying through recovery of flue gases, is why a LHV is applied based on the dry substance of the mixture of sludge (the LHV is reduced according to the

DM). In the mono-incineration electric power is generated by a steam turbine and heat energy, both from combustion gases. Subsequently, the ash generated will be moved by lorry to the plant Ecophos, located 40 km away, where fly ash will be treated to recover the P in the form of phosphoric acid in industrial grade (85%). In the process of Ecophos calcium and ferric chloride were also generated. In this study the management of waste generated in the process of Ecophos is not included. The flowchart of this scenario presented in Figure 47.

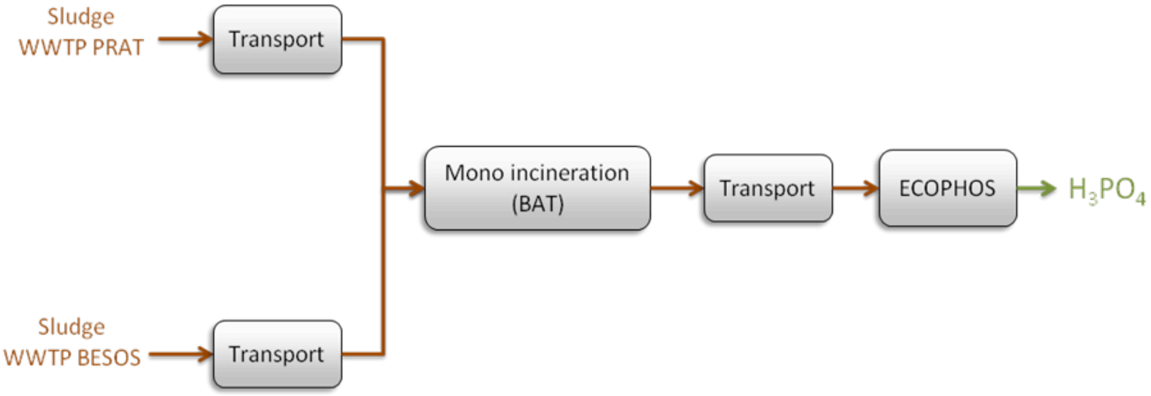


Figure 47 Process scheme for scenario 2

5.5.5. Scenario 3. Mixing sludge from Besos dehydrated in Metrofang and sludge from WWTP Prat and composting

In this scenario it is proposed to truck the sludge from WWTP of Besòs, which have been dewatered in the plant Metrofang, to the composting plant where previously will be mixed with the dry sludge from the WWTP of El Prat, which have also been trucked. The composting plant arises locate within 40 km of the two treatment plants. The composting process arises, lasts about 9 months and generates compost, which will be sold. The flowchart of this scenario presented in Figure 48.

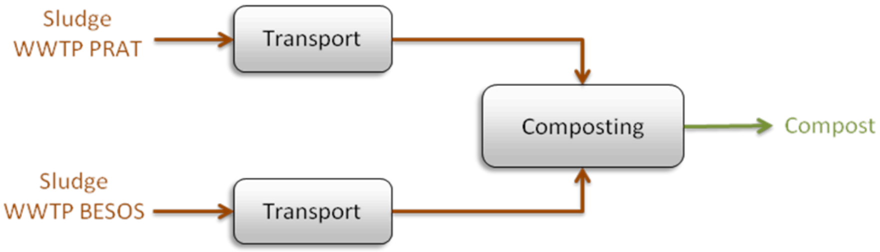


Figure 48 Process schem for scenario 3

5.5.6. Scenario 4 Anaerobic digestion and dehydration of sludge from WWTP Besos, mixing with sludge from WWTP Prat and composting

In this scenario it is proposed to stabilize the sludge from WWTP Besòs undewatered (DM = 4.8%) by anaerobic digestion. The biogas generated will be recovered in the CHP plant where electrical and thermal energy are produced. Subsequently, the digested sludge is dewatered by centrifugation. The overflow is returned to the WWTP of Besòs and dewatered sludge will be transported by lorry to the composting plant where previously mixed with dry sludge from WWTP of El Prat, which have also been trucked. The composting plant arises locate within 40 km of the two treatment plants. The composting process arises, lasts about 9 months and generates compost, which will be sold. The flowchart of this scenario presented in Figure 49.

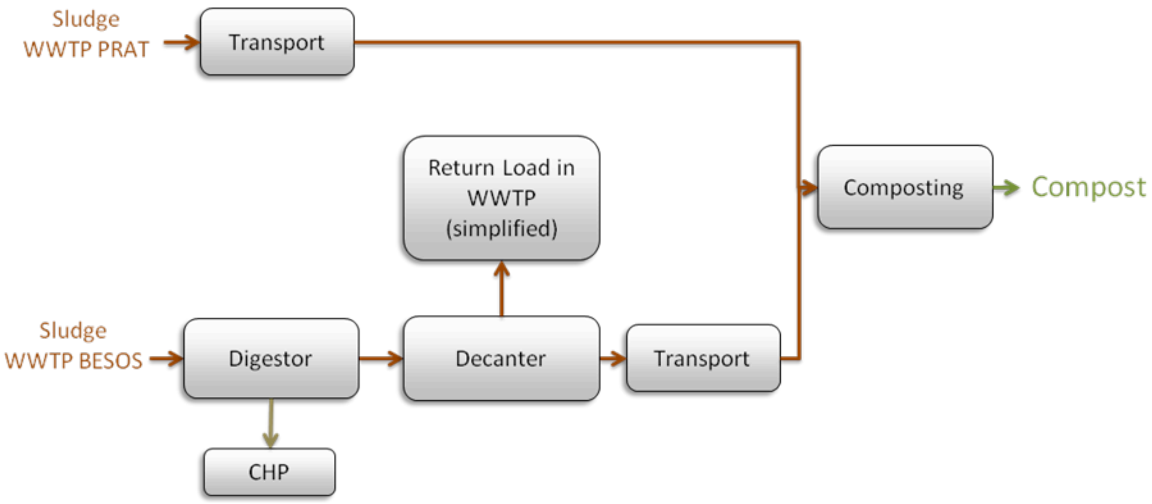


Figure 49 Process schem for scenario 4.

5.6. Methodological approaches of mass and energy balances

5.6.1. Mass and energy balances

In this study we were performed P, energy, emissions and economic balances. These balances are based on data provided by the BMA for each plant (see Annex C), calculated (see Annex D) and the parameters of each process presented in the report of the LCA conducted by the P-Rex project.

The methodology for calculating balances made is in the form of generic algorithm for each of the six processes that are combined in the four scenarios. These algorithms have to be applied following the diagram of each stage (Figures 46 to 49). The algorithms are shown schematically in figures 50-54.

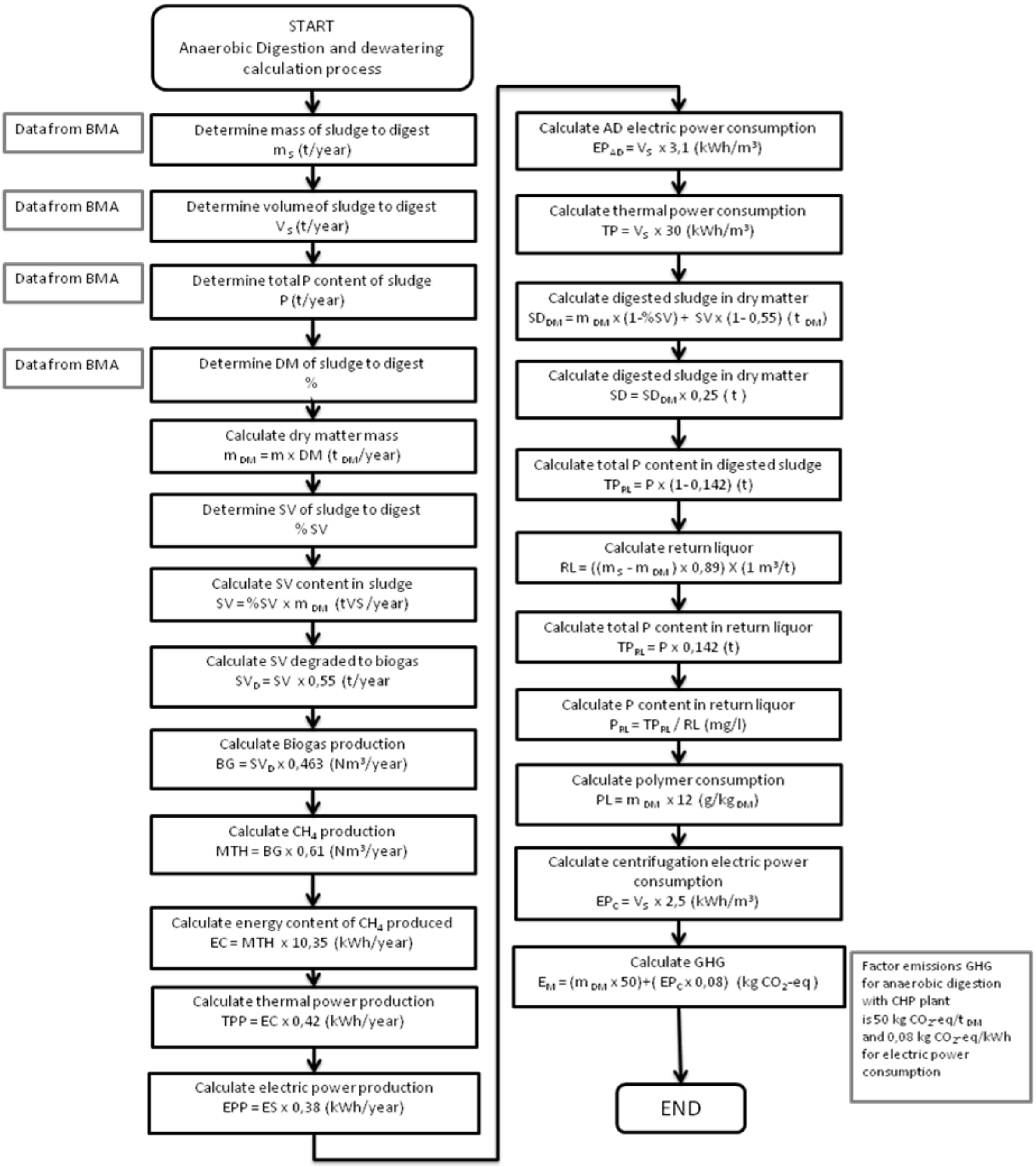


Figure 50 Algorithm for Anaerobic digestion with CHP Plant (P1 Anaerobic digestion with CHP Plant and Dewatering by centrifugation (P2) processess

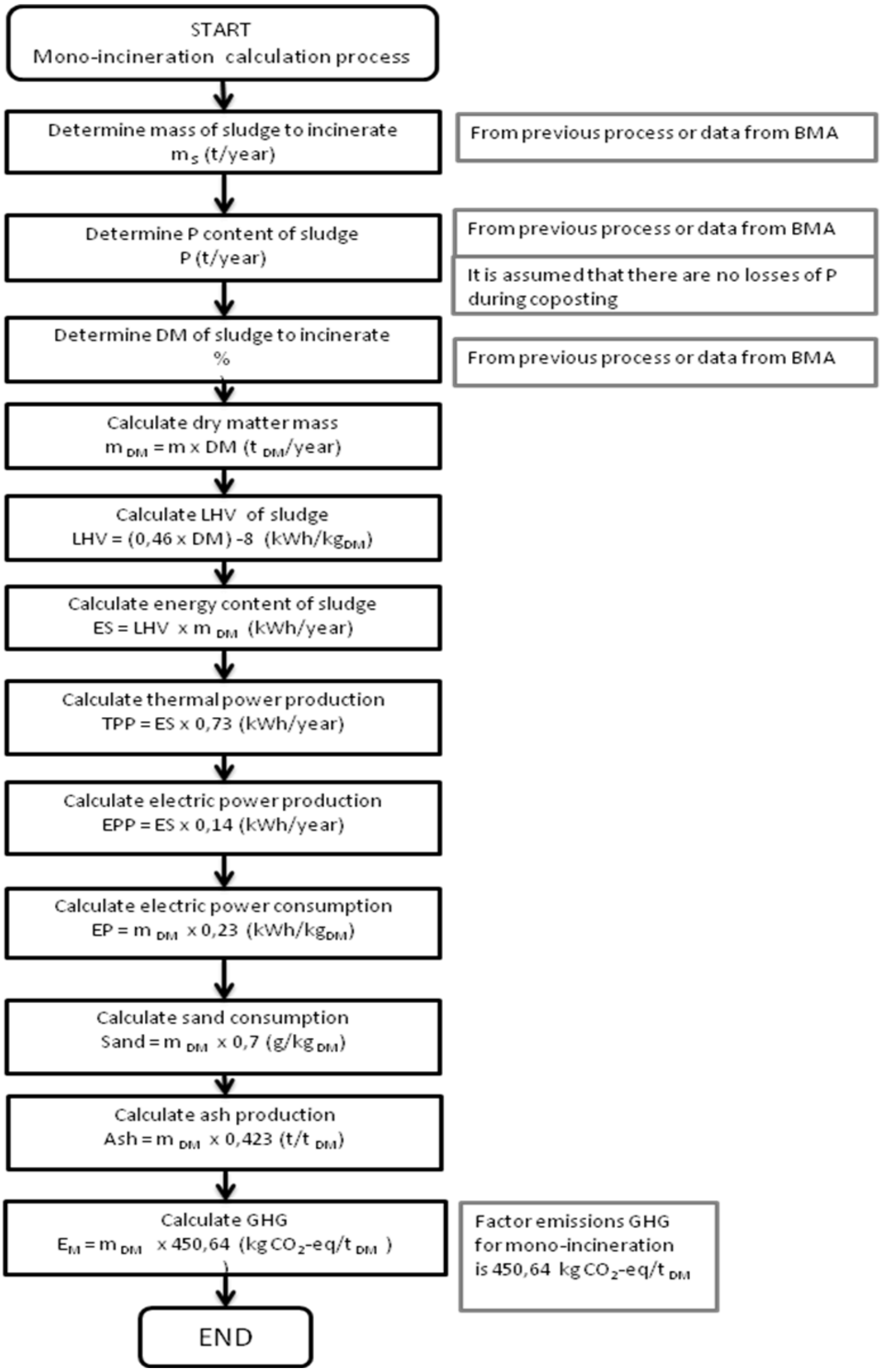


Figure 51 Algorithm for Mono incineration in fluidized-bed incinerator (P3) process

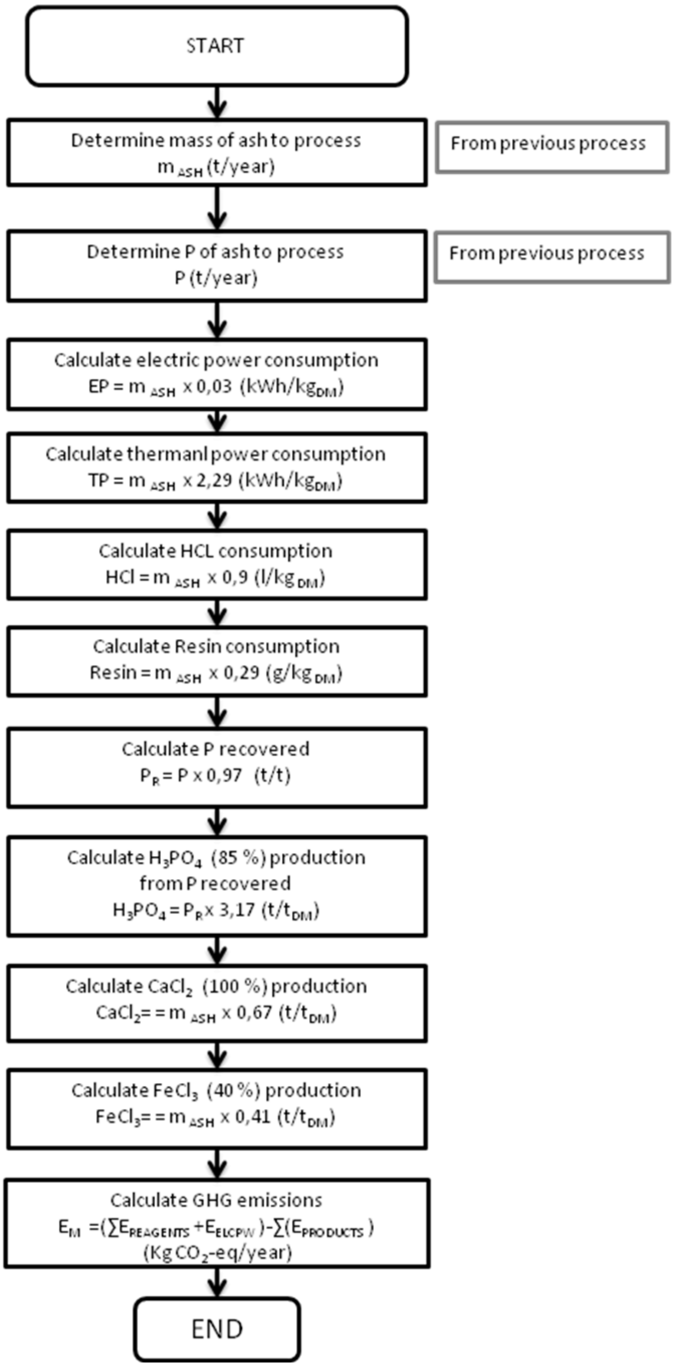


Figure 52 Algorithm for Ecophos (P4) process

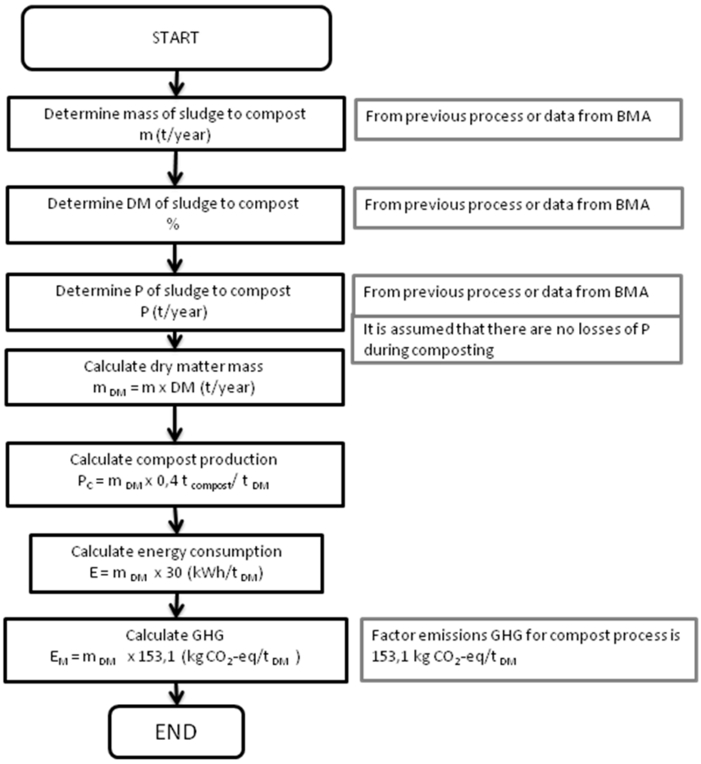


Figure 53 Algorithm for Composting (P5) process

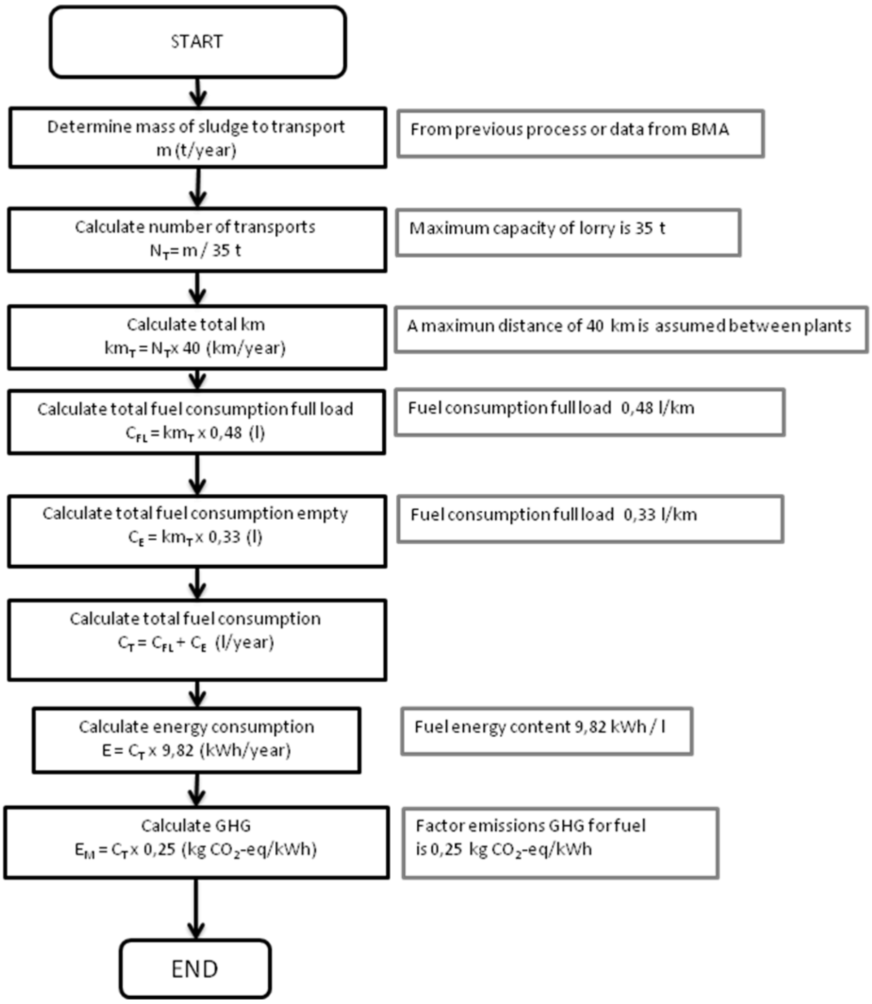


Figure 54 Algorithm for Transport by truck (P6) process

5.6.2. P recovery

P balance is based on the initial content of the sludge P calculated using the methodology shown in Annex D and P recovery factors of each process, which are summarized in Table 21. To perform the balance in each scenario the following assumptions have been made:

- During anaerobic digestion there is no loss of P, so the P content is constant throughout the process.

- In centrifugation of digested sludge, the P which is returned to the treatment plant is present in the soluble compounds.

- The assumptions made in the models presented by the P-Rex project for the LCA, which is returned as 14.2% of total P with water removed with centrifugation of digested sludge which is accepted by 89% the initial volume.

- During the mono-incineration there is no loss of P, so the P content is constant throughout the process.

- During composting no loss of P, whereas no leaching of compounds wherein the P is present, so the P content is constant throughout the process.

Table 21 P recovery yields of processess

	Processes	**P recovery**	**Resource**
P1	Anaerobic digestion with CHP Plant	1,00	P-Rex (Remy & Jossa, 2015)
P2	Dewatering by centrifugation	0,86	P-Rex (Remy & Jossa, 2015)
P3	Mono incineration in fluidized-bed incinerator	1,00	P-Rex (Remy & Jossa, 2015)
P4	Ecophos	0,97	P-Rex (Remy & Jossa, 2015)
P5	Composting	1,00	Estimated
P6	Transport by truck	1,00	Estimated

5.6.3. GWP balance

The balance of GWP emissions is made by applying emission factors of CO_2-eq found in the literature for each process or product. These factors are shown in Table 22.

Table 22 GWP factor emissions

Process/product	**Factor**	**Units**	**Source**
Anaerobic digestion with CHP plant	50,00	kgCO_2-eq/t dm	M. Garrido et al. (2015)
Incineration	450,64	kgCO_2-eq/t dm	M. Garrido et al. (2015)
Fuel	0,26	kgCO_2-eq/kWh	MAGRAMA
Electricity	0,08	kgCO_2-eq/kWh	MAGRAMA
Steam	0,78	kgCO_2-eq/kWh	MAGRAMA
HCl (35%)	1,20	kgCO_2-eq/kg	Carbonfoodprint
Resin	0,53	kgCO_2-eq/kg	Carbonfoodprint
$CaCl_2$ (100%)	0,89	kgCO_2-eq/kg	Carbonfoodprint
$FeCl_3$ (40%)	0,18	kgCO_2-eq/kg	Carbonfoodprint
H_3PO_4 (85%)	1,45	kgCO_2-eq/kg	Carbonfoodprint
Polymer	2,2	kgCO_2-eq/kg	Carbonfoodprint

The energy and consumed products are given a positive factor since emissions are generated. The energy and products generated are given a negative factor when considered as emissions savings by substituting other energy sources or products generated by other technologies. The final balance will result from the sum of all emissions generated or saved for each scenario.

5.6.4. Econimic balance

To make a detailed economic analysis, it was necessary to find cost values that will influence all processes of each of the scenarios, whether on energy demand, costs of materials and market price of the products arising from recovery treatment phosphorus sludge. It has also a need on searching data for investment costs and maintenance of various technologies involved in each stage. For that reason different sources literature, EU projects and reports from WWTP or those provided by Catalan and Spanish Waste Management Regulators. Table 23 show data found and their sources.

Table 23 Values of the Investments Costs(IC) and Operationand Maintenance Costs(OMC), chemical, material and energy prices

Process	IC	Units	OMC	Units	Source
An. Digestion	y=x·494·x^(-0,2)/mon	y [€] x [m3/d]* mon [1,1233 $/€]	95-105	€/t dm	*(Garrido Baserba et al., 2015)*
Incineration	1500	€/t dm	250-300	€/t dm	*(Garrido Baserba et al., 2015)*
Centrifugation	62,09	€/t dm	45,67	€/t dm	*Estimation (GEA Westfalia Separator)*
Composting	220-500	€/t dm	60-140	€/t dm	*(Garrido Baserba et al., 2015)*
Ecophos	**Price**				
HCl (37%)	75	€/t			*ICIS Pricing Europe, 2014*
Resin	9,8	€/L			*Estimated by market*
Personnel	0,53	€/kg P			*P-REX (Nättorp & Remmen, 2015)*
CaCl2 (100%)	1,1	€/Kg			*Estimated by market*
FeCl3 (40%)	0,81	€/Kg			*Estimated by market*
H3PO4 (85%)	7,02	€/Kg			*Estimated by market*
Energy	**Price**				
Electricity (Sale)	0,06022	€/kWh			*(Operador del Mercado Ibérico de la Energía, 2011)*
Thermal (Sale)	0,045	€/kWh			*(Agencia Andaluza de la Energía, 2011)*
Fuel	1	€/L			*Estimated by market*
Others	**Price**				
Polymer Centr.	3	€/Kg			*Estimated by market*
Compost (Sale)	27,98	€/t m			*COGERSA S.A.*
Compost (Saving)	21-40	€/t m			*(Herrero Chamorro, 2013)*

*x[m^3/d] is the flow of treated water in WWTP

Selection of cost values used for the economic evaluation some assumptions have been made:

1. It has been decided to take the highest values of Investment Cost (IC) and Operation and Maintenance Costs (OMC) of each process to analyze the worst situation.
2. It is assumed that the selling price of electricity is what makes the “Operador de Mercado Ibérico de Energia” (OMIE) for 2011. Values of 2011 were used as a large portion of the data collected for other concepts were from references or reports in the same period.

3. For Sale by thermal energy it has followed the approach of the Andalusian Energy Agency, which says that the price at which thermal energy is supplied by biomass must be equal or less than the minimum to the estimated price of conventional fuels. Table 24 shows this prices of conventional fuels.

*Table 24 Energy prices **(€/kWh)** for differents fuels. (Agencia Andaluza de la Energía, 2011)*

Fuel	Energy price (€/kWh)
Diesel Oil	From 0,062 to 0,070
Propane	From 0,06 to 0,076
Natural Gas	From 0,045 to 0,08

4. It has been assumed that fuel price for transport of sludge and ash is 1 €/L due to variability in the market.
5. To calculate the savings of not sending the sludge to the composting plants outside the BMA, it has been assumed the lowest value that the “Depuración de aguas del Mediterráneo” provides, under estimation. This price is about 21€ per ton of sludge. (Herrero Chamorro, 2013)

5.7. Results on energy and mass balances on P-cycle closing scenarios in the BMA

Results are being summarized directly through the scenario flow chart, figures include details on the process involved and the inpits and outputs of each process step in terms of mass and energy needs and by-products production

5.7.1. Overview results of Scenario 1

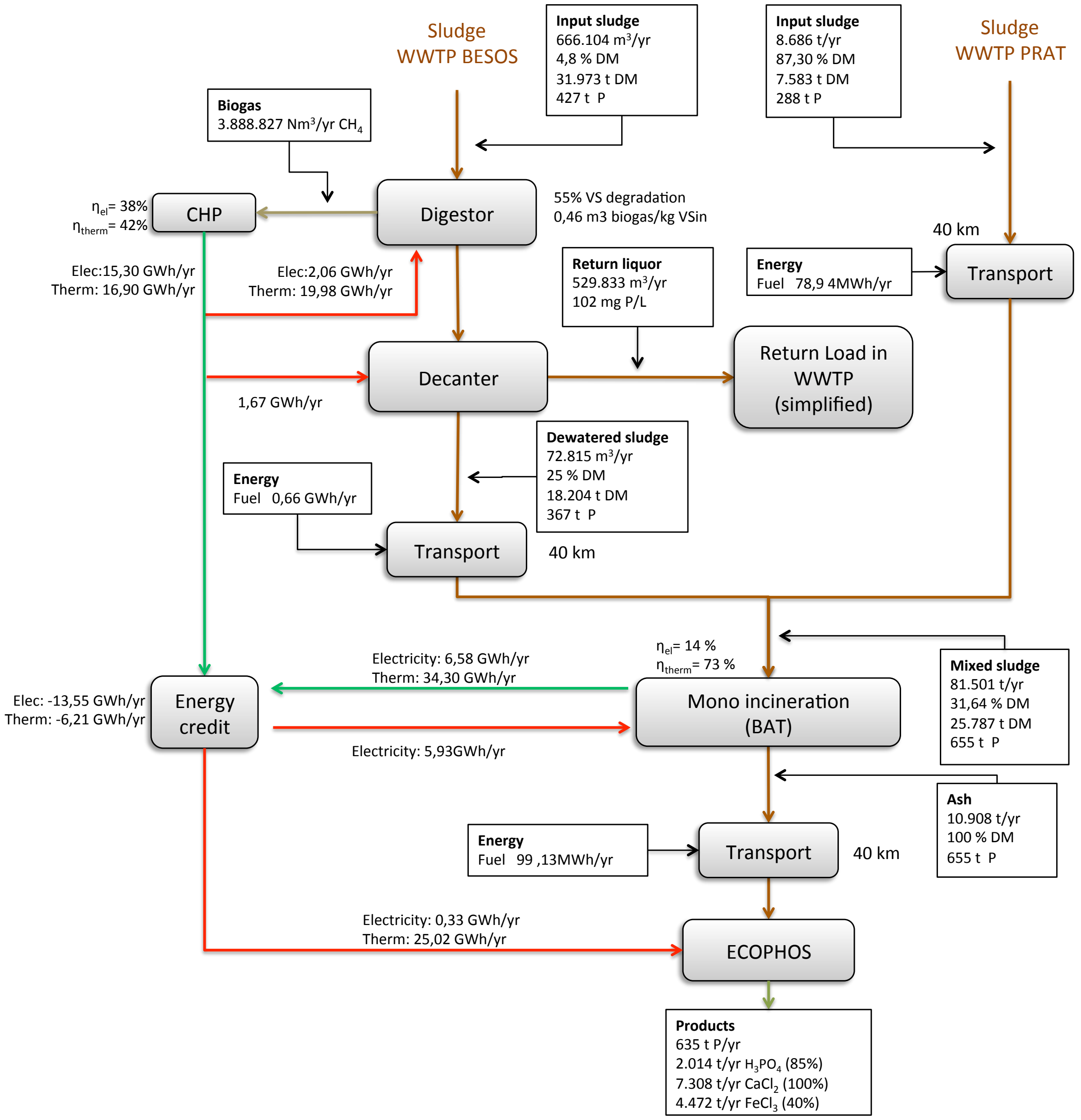


Figure 55 Process scheme with energy and P balance results for scenario 1 for P-cycle closing options at BMA

In this scenario it has taken into account the initial energy savings of not dewater sludge from WWTP of Besòs in the plant Metrofang. This saving is estimated at 16.70 GWh/y. Anaerobic digestion of sludge from WWTP of Besòs generate 15,30 and 16,90 GWh/y of electricity and thermal energy respectively. The power generation meets the demand of the digester, which is estimated at 2,06 GWh/y but not the heat demand of thermal energy, which would be 19,98 GWH/y. Centrifugation of digested sludge has a power consumption of 1,67 GWh/y, which also comes from the cogeneration plant. Digested and dewatered sludge from WWTP of Besos and from El Prat would be transported to the mono-incineration plant by truck to an estimated distance of 40 km in both cases. This represents an estimated consumption of 0,66 and 0,79 GWh/yr respectively.

Due to the pre-drying of sludge mixture in the mono-incineration plant, energy recovery is limited to the dry substance of the sludge. In this scenario, the mono-incineration are obtained 6,58 and 34,30 GWh/y of electricity and thermal energy respectively. In this case also it covers power generation demand, which is estimated at 5,93 GWh/y. Fly ash generated would be transported to the plant Ecophos, which arises placing it at a distance of 40 km. This transport is an energy expenditure of 0,10 GWh/yr in fuel. The treatment of the ashes requires electrical and thermal energy, estimated at 0,33 and 25,02 GWh/y respectively. Both demands are covered by excess generation of the above processes, leaving the final energy balance in -18,92 GWh/yr, of which -13,55 GWh/yr is electricity and -6,21 GWh/yr thermal (see Figure 55). Negative values represent an energy surplus that could be sold in the electrical and thermal networks. In Annex D results are collected.

5.7.2. Overview results of Scenario 2

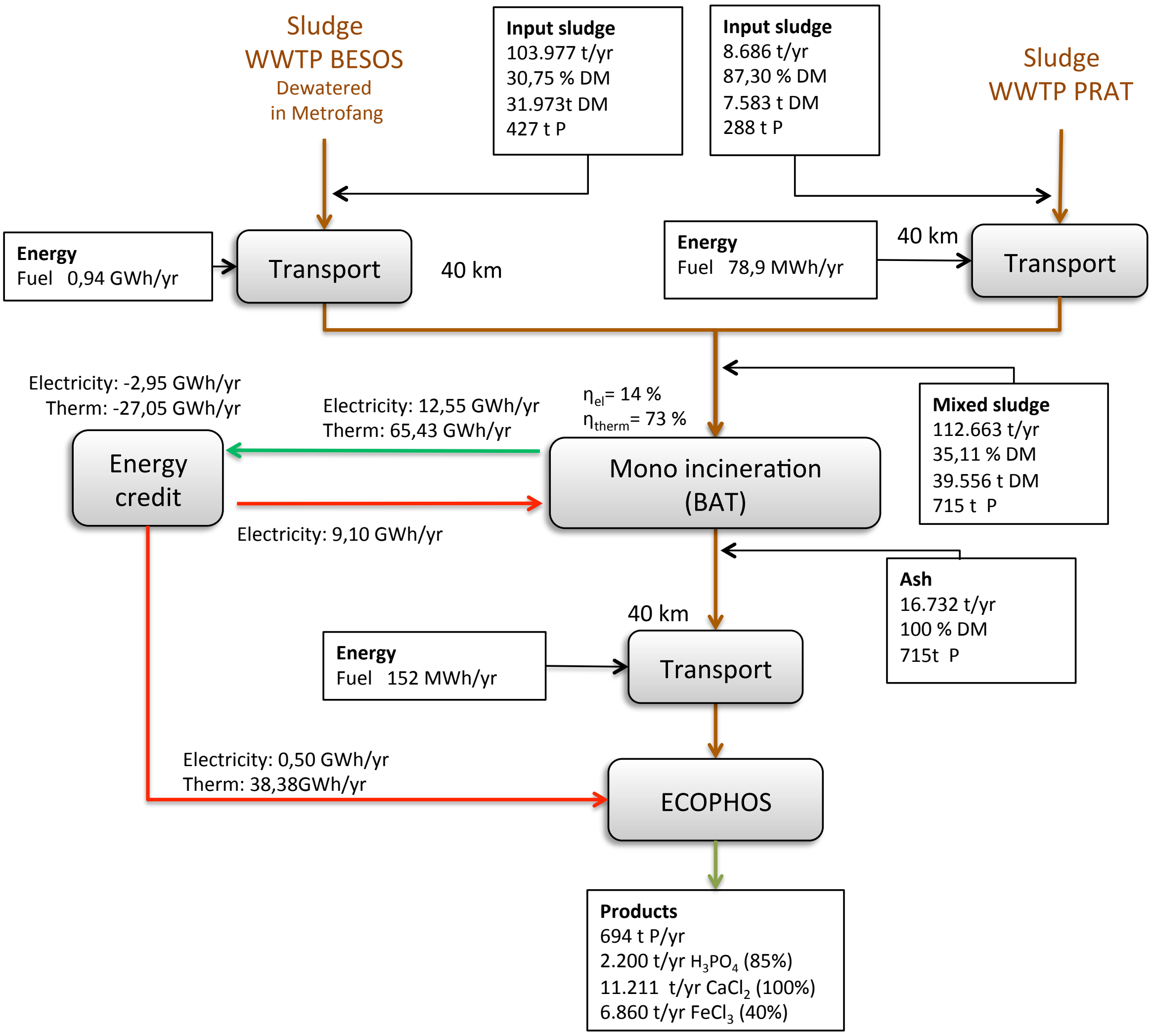


Figure 56 Process scheme with energy and P balance results for scenario 2 for P-cycle closing options at BMA

In this scenario dewatered sludge from WWTP of Besòs (dewatered in Metrofang) and dry sludge from WWTP El Prat would be transported to the mono-incineration plant by truck to an estimated distance of 40 km in both cases. This represents a power consumption estimated in 0,94 and 0,79 GWh/yr respectively.

Due to the pre-drying of sludge mixture in the mono-incineration plant, energy recovery is limited to the dry substance of the sludge. In this scenario, in the mono-incineration are obtained 12,55 and 65,43 GWh/yr of electricity and thermal energy respectively. Electricity generation also covers the demand, which is estimated at 9,10 GWh/y for the mono-incineration. Generated fly ashes are transported to the plant of Ecophos, which arises to place it at a distance of 40 km. This transport represents expenditure energy of 0,15 GWh/yr to in fuel. The demand for electric and thermal energy of the treatment of ashes is estimated at 0,50 and 38,38 GWh/yr respectively. Both demands are covered by the surplus of generation from mono-incineration, being the final energy balance in -28,82 GWh/yr, of which -2.95 are electric power and -27.05 GWh/yr thermal energy. It has to add fuel consumption of transport (1,18 GWh/yr) to close de balance . Negative values represent a surplus of energy that it could sell in the thermal and electrical networks. Annex D refers to the results.

5.7.3. Overview results of Scenario 3

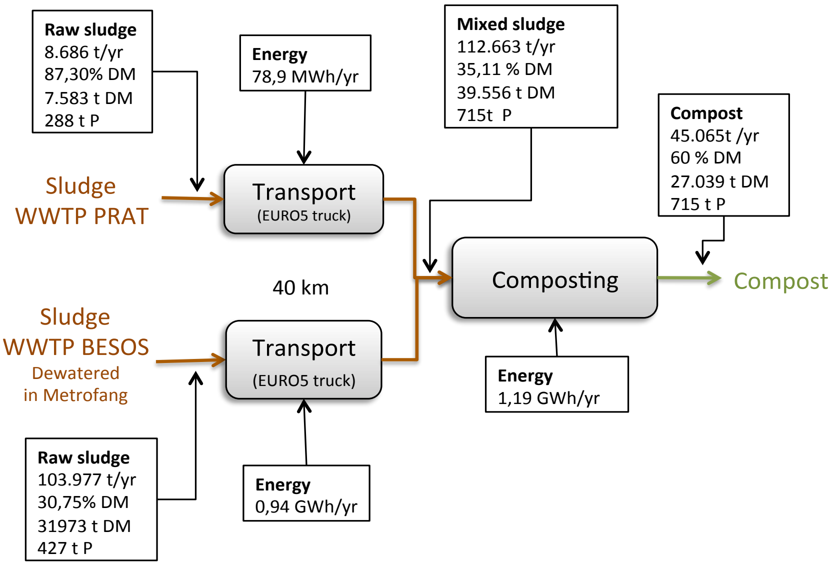


Figure 57 Process scheme with energy and P balance results for scenario 3 for P-cycle closing options at BMA

In this scenario dewatered sludge from WWTP of Besòs (dewatered in Metrofang) and dry sludge from WWTP El Prat would be transported to the mono-incineration plant by truck to an estimated distance of 40 km in both cases. This represents a power consumption estimated in 0,94 and 0,79 GWh/y respectively.

The demand for electricity of the composting of sludge is estimated at 1.19 GWh/yr. Because there is not generation of energy in this scenario, the final balance of energy is 2.21 GWh/yr, which implies a net consumption.

5.7.4. Overview results of Scenario 4

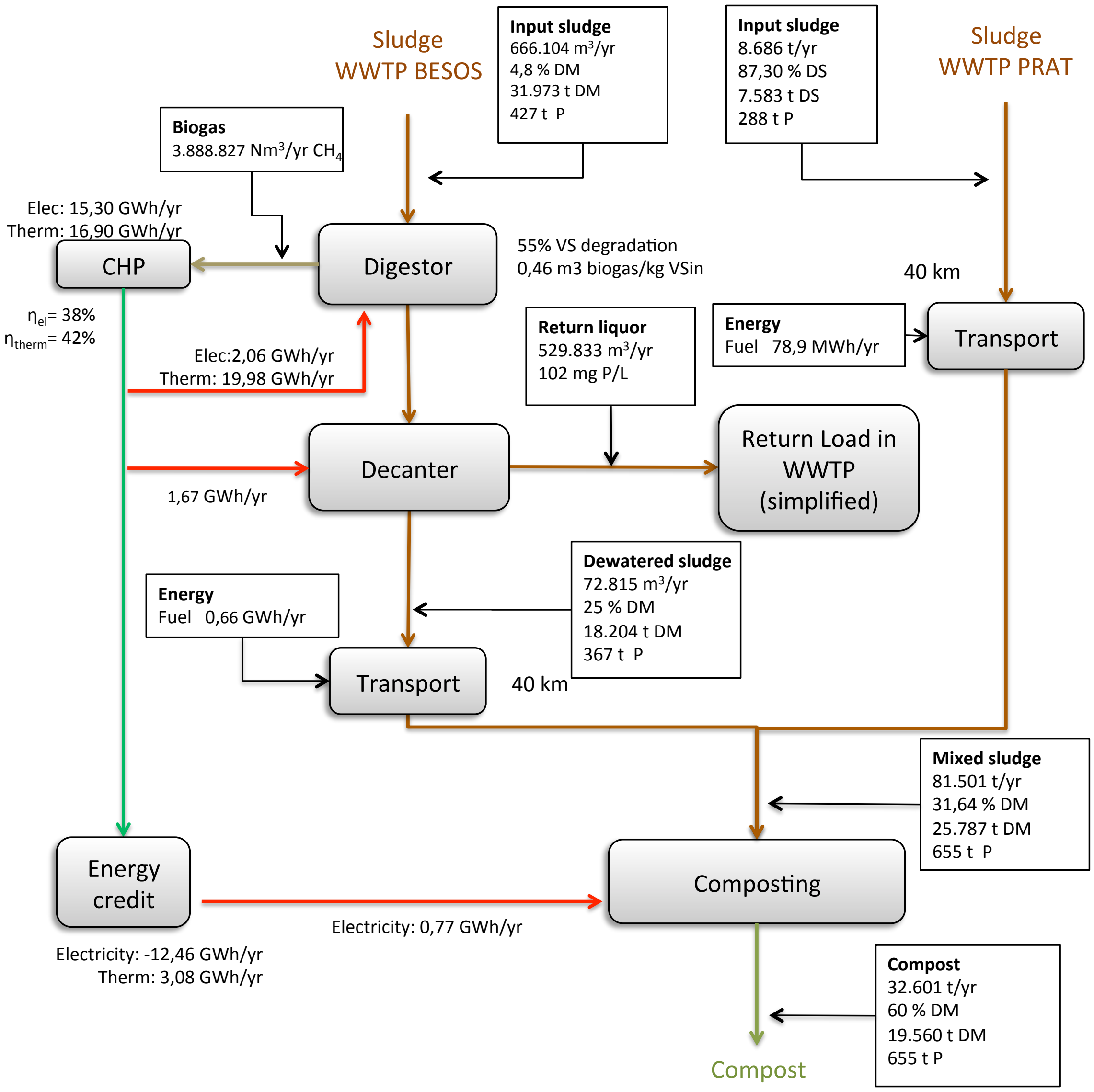


Figure 58 Process scheme with energy and P balance results for scenario 4 for P-cycle closing options at BMA

In this scenario it has also taken into account the initial energy savings of not dewater sludge from Besòs in Metrofang. This saving is estimated at 16.70 Gwh/y. The anaerobic digestion of sludge from WWTP of Besòs would generate 15,30 and 16,90 GWh/yr of electric power and thermal respectively. The generation of electricity meets the demand of the digester, which is estimated at 2,65 GWh/yr but not the thermal demand, which would be 19,98 GWh/yr. The centrifugation of digested sludge supposed a consumption of 1,67 GWh/yr of electric energy, which also comes from CHP plant. Both, sludge digested and dewatered and dry sludge from WWTP of El Prat, are transported to the compost plant by lorry to a distance estimated of 40 km in both cases. This assumes consumption energy of 0,66 and 0,79

GWh/yr for sludge transported from Besòs and El Prat respectively.

The demand of electricity to compost the mixed sludge is estimated in 0.77 GWh/yr which is covered by the surplus of electricity generation in CHP plant. Final energy balance is estimated at - 8.64 GWh/yr of electric power. Negative values represent a surplus of energy that I could sell in the electrical networks. It should be noted that the final balance of thermal power in this case is positive indicating a demand of this energy along with the fuel. Annex D refers to the results.

5.7.5. Energy analysis results

As energy is a key component on the P-cycle closing an analysis on the energy needs and types has been carried out. Generations and demands of the three types of energy involved in each scenario are detailed in Annex D and presented in Figures 59 and 60.

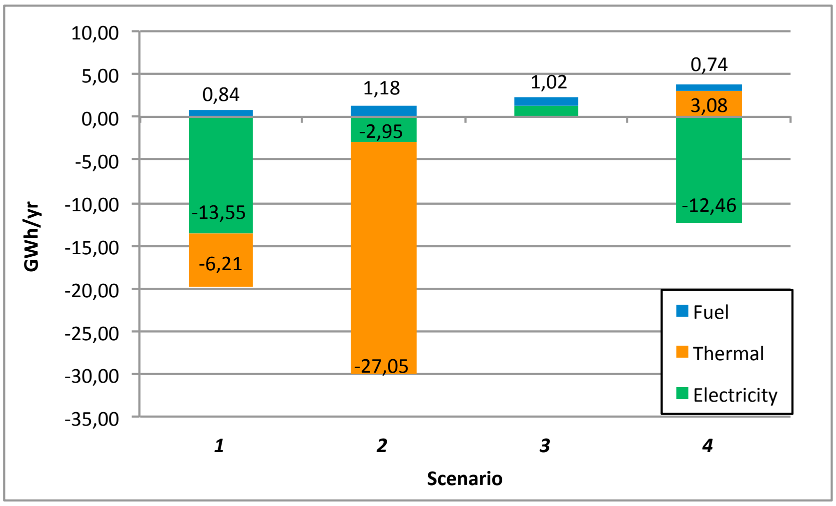


Figure 59 Demand and generation of energy (Gwh/yr) by type of energía and scenarios on P-cycle closing options at BMA. negative values are surplus generation and positive demand

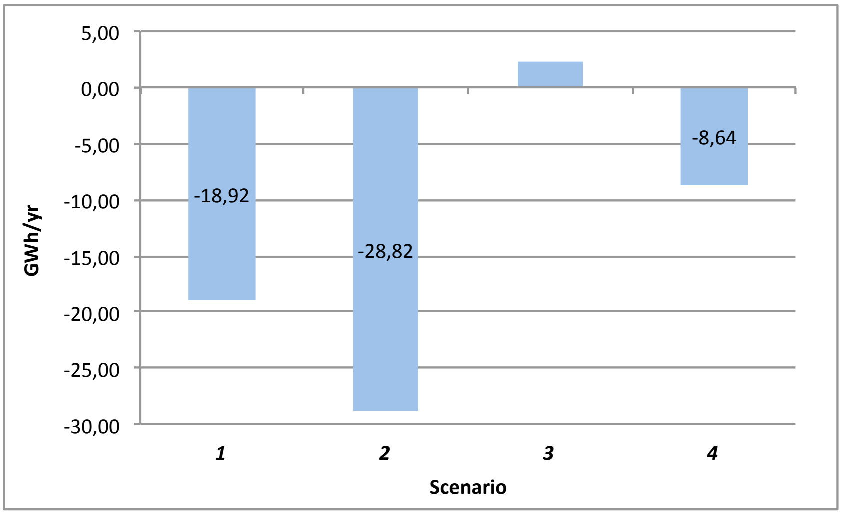


Figure 60 Net energy balance (Gwh/yr) for the scenarios on P-cycle closing options at BMA

Figure 59 shows the generations (negative values) and net demands (positive values) of each type of energy for each scenario. As shown this figure, in the four scenarios there is fossil fuel demand due to transport between plants. As seen above, Scenario 3 is the only in which there are not revaluation energy of sludge, is why the energy balance is positive (Figure 60). Scenarios 1, 2 and 4 generate energy but their balance sheets have different characteristics. In scenario 1 is generated an energy surplus -18.92 GWh/yr which is most electrical and easy distribution via the mains power. However in scenario 2, which has a higher energy surplus (-28.85 GWh/yr), most of the surplus is thermal energy (-27.05 GWh/yr), which can be delivered to a heat distribution network. The difficulty is that such networks are not usual in the area of BMA. That is why the use of this surplus heat would be subject to distribution. Finally in Scenario 3, in which there are power generation, the surplus is fully electric (-12.46 GWh/yr) and easy distribution. Unlike scenarios 1 and 2, in this there is demand for thermal energy (3.08 GWh/yr) from the digester, which can not supply itself with this kind of energy since their generation is not enough.

5.7.6. Global Warning Potential (GWP)results

Emissions and credits of GWP of the each scenario are detailed in Annex E and presented in Figures 61 and 62.

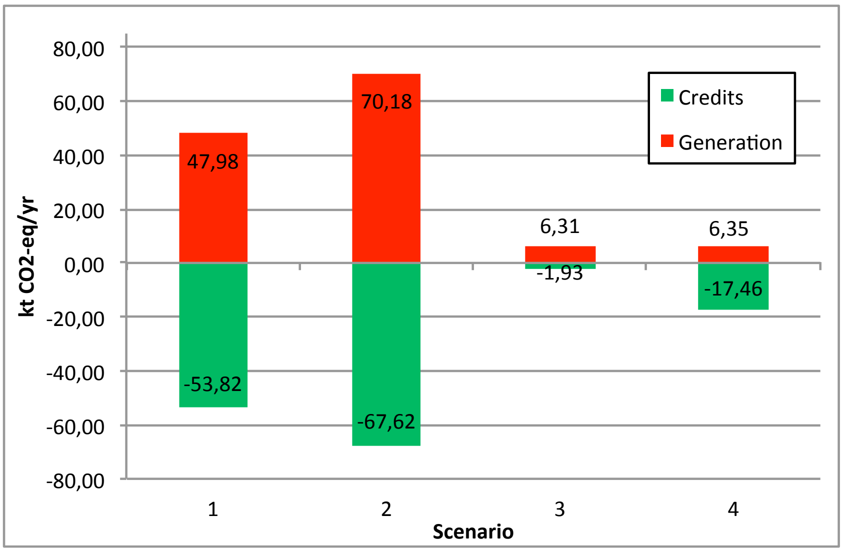


Figure 61 Emissions and credits of GWP for scenarios on P-cycle closing options at BMA

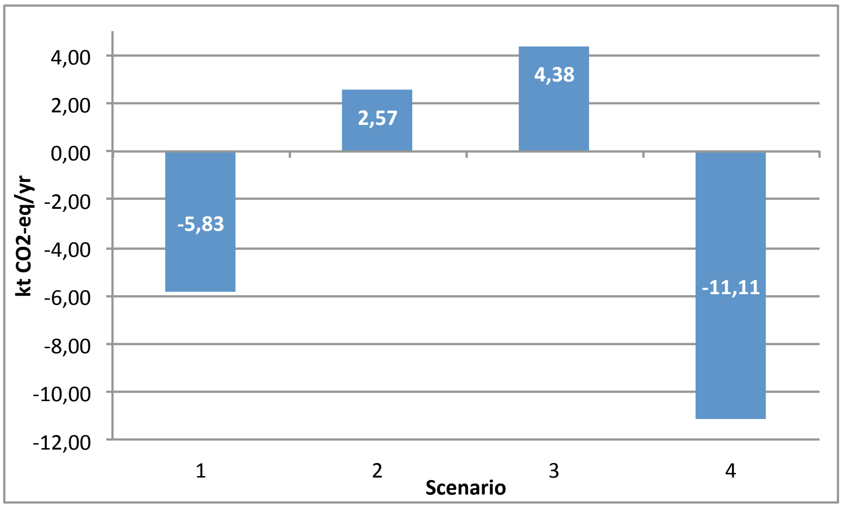


Figure 62 Net GWP of each scenarios on P-cycle closing options at BMA

Net GWP for al scenarios shows a variation between -11,11 and 4,38 kt CO_2-eq/yr. In scenario 1, energy recovery from sludge in the cogeneration plant and incinerator, generate a lot of emissions, to which must be added those generated by the use of diesel fuel for transportation and power consumption of the processes. So the emissions in this scenario are 47.98 kt CO2-eq/yr (Figure 61). These emissions are offset by the substitution of products and energy generated in every process of the scenario. The energy surplus in this scenario means savings in emissions of 42.7 kt CO_2-eq/yr and the production of phosphoric acid, calcium chloride and ferric represent a saving of 10.23 kt CO_2-eq/yr. To these must be added the savings in reduced polymer consumption in centrifugation not dehydrate in Metrofang. Thus the net balance for this scenario is -5.83 as shown in Figure 62.

In Scenario 2, the increase of sludge incinerated generates increased emissions in addition to reducing energy generated because there is no digester and CHP plant, leaving a positive balance of 2.57 kt CO_2-eq/yr. In this scenario, reducing emissions from the substitution of the products generated in the ahs processing (-14.40 kt CO_2-eq/yr) along with the savings from energy surplus (-52.21 kt CO_2-eq/yr) do not compensate the already mentioned high emission of 70.18 kt CO_2-eq/yr.

The scenario 3 and 4 are the least GWP issued. Scenario 3 becomes a positive balance of 4.38 kt CO_2-eq/yr because the emissions in transport (0.24 kt CO_2-eq/yr) and composting sludge (6.06 kt CO_2-eq/yr) are not compensated by the savings of 1,93 kt CO_2-eq/yr from compost generated that replaces chemical fertilizers consumption. However, in scenario 4, reducing emissions from energy surplus from CHP plant (-14.74 kt CO_2-eq/yr), reducing energy consumption and polymer in Metrofang (-0.98 kt CO_2-ev/yr) and compost generated (-1.77 kt CO_2-eq/yr), offset emissions. Leaving a negative balance of -11.11 kt CO_2-eq/yr.

5.7.7. Economic analysis results on the evaluation of for P-cycle closing options at BMA

Figure 63 shows the economic balance of each scenario. In this balance, the annual Investment Costs (IC), maintenance costs (OMC), product sales, energy produced and energy saving or materials savings, such as saving the polymer used in the centrifugation coming from Metrofang, are shown. The costs and profits are referenced in € per kg P recovered, so it can compare better the results. For IC it has supposed a lifetime of technologies used for 20 years, so the costs and profits are referenced by € per year. Positive values indicate the costs and negative imply earnings. The results are detailed in Annex F.

Scenarios 1 and 2 have the major expenses of IC and OMC, with very similar values around 4.5 € kg $P_{recovered}^{-1}$ yr^{-1} for IC and 23 € kg $P_{recovered}^{-1}$ yr^{-1} for OMC. Instead scenarios 3 and 4 have a lower cost around 2 € kg $P_{recovered}^{-1}$ yr^{-1} and 7-11 € kg $P_{recovered}^{-1}$ yr^{-1} respectively. This is due, basically, for costs generated by the implementation of the sludge mono-incinerator needed in scenarios 1 and 2 for management. Instead stages 3 and 4 need only a composting plant and in the case of 4, an anaerobic digester is needed as well. All this leads to lower costs IC and OMC.

In contrast, scenarios 3 and 4 do not generate enough profit to cover the project because the OMC are high, and profits by selling the compost (according to the market study) are not sufficient to cover them. This would entail a cost to the taxpayer would be reflected in taxes. If we look at scenarios 1 and 2 we see that profits are very high, around 70 € kg $P_{recovered}^{-1}$ yr^{-1}. This is due thanks to the sale of energy (electricity and heat) produced in anaerobic digester and mono-incineration plant, but especially the sale of products that are generated from the management of the ashes through the Ecophos process, in particular phosphoric acid H_3PO_4 that have a market value about 7 € kg^{-1}.

In Figure 64 the annual global balance of each scenarios is shown. It reflects what is discussed above as benefits, in scenarios 1 and 2, and as losses in scenarios 3 and 4. This values are 40 € per kg P recovered benefit in scenarios 1 and 2 approximately, and 5 € per kg P recovered losses for scenarios 3 and 4. The results of this balance are detailed in Annex G.

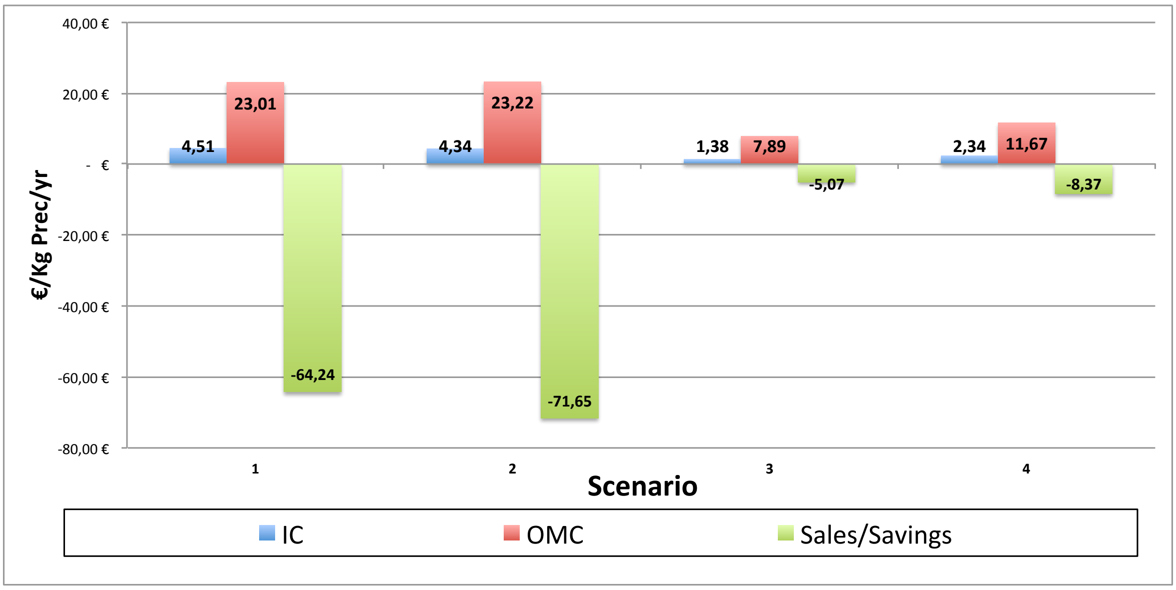


Figure 63 Representation of the IC and OMC costs and the profits of the Sales and Savings of each scenario for P-cycle closing options at BMA

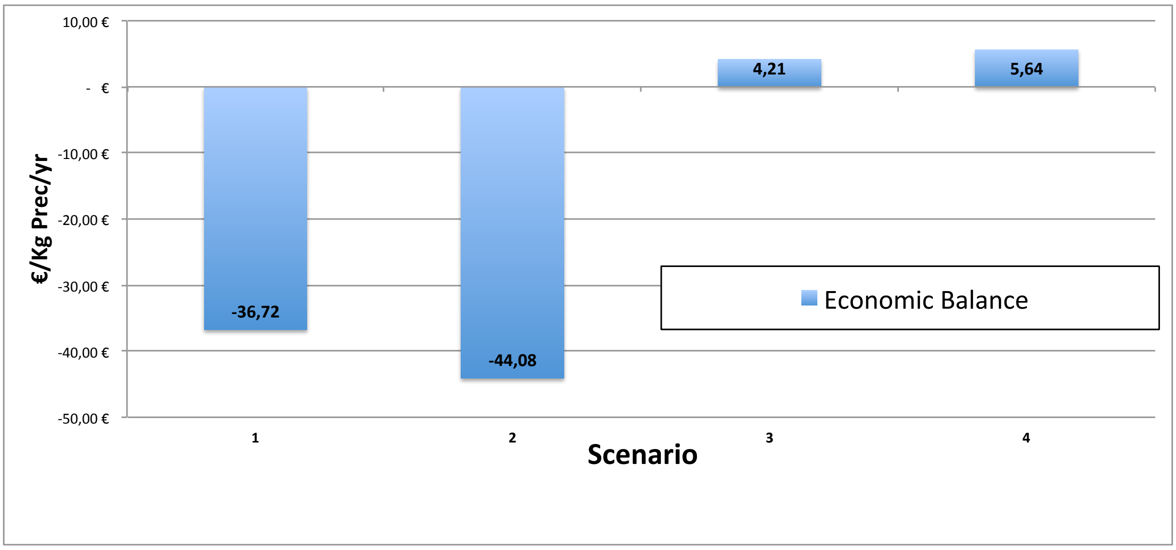


Figure 64 Economic balance of each scenario for P-cycle closing options at BMA

5.7.8. P recovery analysis results for P-cycle closing options at BMA

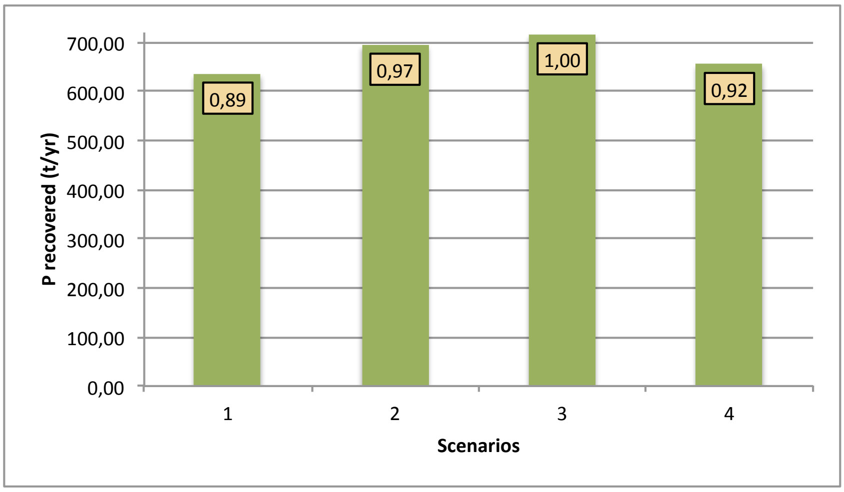


Figure 65 Tonnes of P recovered and P recovery of each scenario

The recovery yield of P in scenarios is between 0.89 and 1.00. In tonnes, this is equal to a recovery of between 635 and 715 tons of P per year from initial 715 t. This variation in yields is not significant for tons recover proposed in this study (P intended to cement in 2011). But will be significant if it is increased the P to recover. For example, in 2012 it would be 190 tons a difference between scenarios.

The yields of Scenarios 1 and 4 are reduced by the return of P with sludge liquor. This does not involve the loss of this P, it can be applied other technologies to recover this P such as Struvia or Gifhorn.

5.7.9. Global overview results

In Figure 66 are plotted the values analyzed in this project for each scenario:

i. *Energy balance*

ii. *CO2 emissions*

iii. *P recovery*

iv. *Economic Balance*

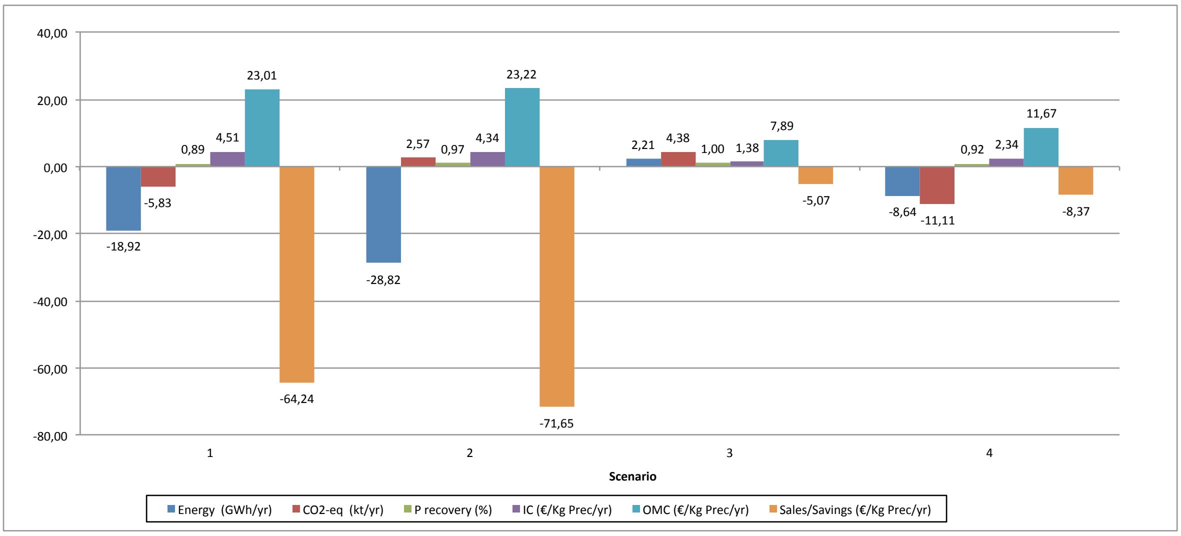


Figure 66 Overall analysis of the interesting values for P-cycle closing options at BMA

The overall assessment of each scenario depends on the preference assigned to the economic impact, environmental or closure of the phosphorus cycle. This assessment does not fall within the objectives of this project; simply it is presented a detailed study.

6. Economic assessment of the project

In Table 26 the executed expenses of the development of the present are collected. The main cost was associated to personnel resources (two persons with a qualification of junior enginners and based on the time spent (see Table 25 and Figure 67) and interprofessional median salary for technical specialists in Barcelona (http: //www.experteer .com / salary_calculator). The total remuneration is estimated at 21,000 €.

Table 25 Time spent in every process of the Project.

Process		**Description**	**Time spent * (days)**
Initial study	Step 1	Literature data collection	2
	Step 2	study of the global P situation	3
	Step 3	study of P situation in Europe	3
Study of the art	Step 4	Technical data collection about P recovery technologies	2
	Step 5	Study of P recovery technologies	6
Spain SFA	Step 6	Study of P situation in Spain	3
	Step 7	Data collection	15
	Step 8	Calculation of Spain SFA	7
	Step 9	Analysis of results	3
P assessment in BMA	Step 10	Data collection	7
	Step 11	Study of P situation in BMA	6
	Step 12	Review of available technologies	3
	Step 13	Study of possible new scenarios in AMB	3
	Step 14	Calculation of the proposed scenarios for AMB	18
	Step 15	Analysis of results	4
Memory	Step 16	Compilation of information	3
	Step 17	Compilation of results	3
	Step 18	Drafting of the memory	10
	Step 19	Drafting conclusions	3
	Step 20	Environmental impact assessment study	1
	Step 21	Cost evaluation study	1
Final revision	Step 22		2
Total time spent			**108**

*Every day means 10 hours of work time

Figure 67 Gantt Chart of the Project with the estimated time spent.

Table 26 Estimated total cost of the study.

Concept	Units		Cost		Cost (€)
Electric power	4753	kWh	0,13	€/kWh	636,88
Fuel	114	l	1,00	€/l	114,00
Paper	3	kg	1,48	€/g	4,43
Printer ink	2	ud	10,00	€/g	20,00
CDs	2	ud	0,14	€/g	0,28
			Total		**775,59**

Thus the total cost of this study is estimated at € 21.731,59.

7. Enviromental impact of the project

This report has been made in the office of the authors. The study was made entirely by computer. There have been no analytical in laboratories or visits to plants. The transfers have been made in private vehicles, from the office to the facilities of the UPC in Av. Diagonal. The information obtained to develop this study, such as analytical, statistical and cost data were obtained through literature or directly to entities or companies concerned consultation. To determine the environmental impact of this project the carbon footprint generated is calculated. The calculation is performed according to ISO 14064-1 UNE (MAGRAMA). Then the data for calculating the carbon footprint presented.

Time limit: project implementation period 11.30.2015 to 23.09.2016

Limit of the organization: the working group has two people (the authors), a work center and two cars.

Operating Limit: scope of the study 1 + 2 + 3 (MAGRAMA)

Indication of the sources of GHG emissions in the organization:

Scope 1:
- Two cars

Scope 2:
- Electricity consumption: 2 portable, lighting, electric heater, printer and modem

Scope 3:
- Paper consumption
- Ink consumption
- Consumption CD

The results are shown in Table 27:

Table 27 Emissions to produce this project

Concept		**Units**	**Factor**		**Emissions (kgCO2-ep)**
Electric power	4753	kWh	0,08	kgCO2-ep/kWh	380,22
Fuel	114	l	2,79	kgCO2-ep/l	318,06
Paper	2,994	kg	2,42	kgCO2-ep/kg	7,25
Printer ink	30	ml	1,87	kgCO2-ep/ml	56,10
CDs	0,032	kg	2,70	kgCO2-ep/kg	0,09
			Total		**761,72**

8. Conclusions

In 2014 the EU declared P, as phosphatic rock, critical raw material since it is a necessary and non-renewable resource, in addition to the poor distribution of the existing reserves. In this project it has been tried to present the main available technologies to close the P cycle taking advantage of secondary sources that in most developed countries are mainly sludge from WWTP and the organic fraction of municipal solid waste. However it is also recalled that tertiary sources help to reduce the loss of P. These sources would be the reduction of P present in the effluent from sewage treatment plants, a better management of P in agricultural soils and a reduction of organic waste, followed by a reduction of waste food and effective disintegration of these that allows applying new technologies to recover P present in them.

In order to identify the secondary and tertiary sources in Spain, it has made the SFA of P in the Spanish territory using the best of reliable and documented at 2012. The SFA carried for Spain is the first study according to review of the state of the art. The SFA performed for n Spain estimates that 66.1% of P entered was accumulated. This accumulation occurred in the water bodies, soils and stocks of different markets. In the SFA have been identified secondary sources of P, of which the largest number that has already developed technologies are the sludge from sewage treatment plants. In the analysis have been identified secondary sources of P, which, sludge from sewage treatment plants is the one that has the largest number of technologies already developed. In Spain it is estimated that in 2012 came out of the WWTP 47.75 kt of P, of which 32.89 kt were for agricultural use closing the P cycle. This represents a recovery of 68.9% of P from this source secondary, but this figure corresponds to the national level. The management of sludge varies depending on the territory. For example, in the BMA in 2012, 58.7% of sludge generated was disposed to cement, a destination that does not close the cycle of P and the EU plans to ban. In 2011 it was sent to cement 66.4% of the sludge.

In 2015, 89.5% of the sludge produced in the BMA were sent to disposals that close the cycle P. 39.104 t dm of sludge were specifically sent to composting, but due to the lack of processing capacity of compost plants close to the BMA, this sludge was distributed in other plants located up to 400 km away. This could make the situation unsustainable.

In this project it has been carried out a second assessment devoted to analyze alternatives to improve the management of sludge generated in the BMA to recover the maximum of P with the least environmental and economic impact. For this it has been postulated and raised four scenarios for closing the P-cycle in which each scenario was defined by using a combination of various processes. In the proposed scenarios, two technologies for the recovery of P (Ecophos and composting) are combined with alternatives for energy recovery of sludge. Alternatives for the energy recovery are anaerobic digestion and combustion of the biogas with CHP plant, and mono-incineration with electricity and heat generation by steam turbine. Selection of processes to recover P has been supported on the LCA made by the P-Rex EU project in the evaluation of technologies available. After studying the LCA, it is selected technology Ecophos by having the third best performance recovery of P (97%) and reduced environmental impact. With this technology, P is extracted from the ash of the mono-incineration of sludge by leaching with phosphoric acid. P is obtained as phosphoric acid, which are extracted heavy metals by ion exchange resins. Finally the acid is concentrated by evaporation to obtain industrial grade phosphoric acid.

The other selected process to recover the P is composting, which according to the literature appears to be the option that has less environmental impact after the direct use of sludge in agriculture.

Thus, they were proposed Scenario 1: anaerobic digestion, mono-incineration and Ecophos; Scenario 2: mono-incineration and Ecophos; Scenario 3: composting; and Scenario 4: anaerobic digestion and composting.

From the four proposed scenarios the balance of mass, P, energy, economic, and environmental impacts were calculated. For the calculations, it has been considering as hypothesis the use of the processing of sludge ratios used allocated for the cement industry in 2011 with their characteristics and amounts. It has been selected 2011 as reference taking into account that it was the year when more sludge was send to the cement industry before the initiation of the last world economic crisis. The use of dried sludge in the cement industry is based on their used as co-substitution of coque on the cement kilner.

The results obtained in the four scenarios concludes, that all of them would receive a minimum recovery of 87% of P, but the others balances vary widely among the four. The scenario that generates a greater surplus of thermal energy is Scenario 2. On the other hand, Scenario 1 is the one that generates greater surplus electricity. Regarding cost, Scenario 2 obtains the highest yields, followed by Scenario 1. In both cases it is due to the sale of energy surplus and especially the phosphoric acid produced. Finally, in the assessment of the environmental impact, scenario 4 is that lower GWP emissions would have. With these results, it cannot be assessed that scenario would be the most suitable option to improve the P-cycle closing in the BAM without considering the prioritization between the environmental impact and economic fact that escapes from the study.

Thanks

We want to thank José Luis Cortina and Cesar Alberto Valderrama for his help in the elaboration of this project, above all the patience they had with us in addition to the information that they have provided for the development of this.

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A. Calculations, assumptions, uncertainties and final results for Spain SFA

The calculation methodology followed to perform the SFA P for Spain is included in the algorithm shown in Figure A1. Calculations, assumptions, sources and final results are shown in Table A1.

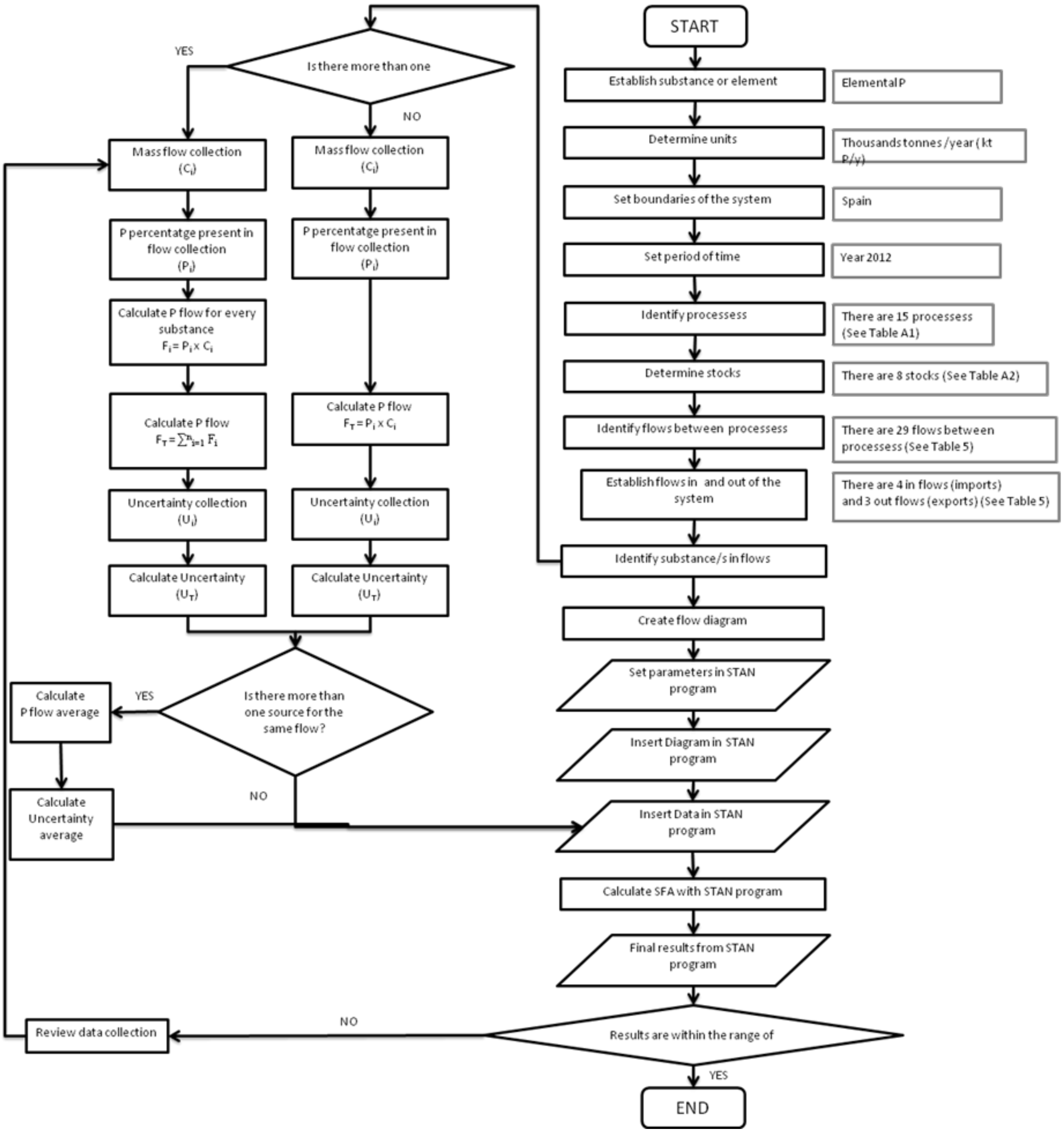

Figure A 1 Algorithm to develop a SFA

Table A 1 Process list

Process	**Name**
P1	Fertilizer industry
P2	Fertilizer marcket
P3	Non-food market
P4	Food and feed market
P5	Human
P6	Waste
P7	WWTP
P8	Back ground
P9	Incineration
P10	Land fill
P11	Compost and others disposals
P12	Water bodies
P13	Agricultural land
P14	Crops and fodder
P15	Animals

Table A 2 Stock list

Process	**Name**
S1	Fertilizer marcket
S2	Non-food market
S3	Food and feed market
S4	Incineration
S5	Land fill
S6	Compost and others disposals
S7	Water bodies
S8	Agricultural land

Table A.1 Calculations, assumptions, uncertainties and final results for Spain P flows

Flow Number and name		Description	Calculations, assumptions and references	Pi content	Estimated Amount	Average amount [a]	Stándar desviation	Uncertainty interval[b]	Average confidence[c]	Average confidence interval[d]	Final value[e]	Final confidence[f]	In calculation[g]
					(kt P/yr)	(kt P/yr)				(kt P/yr)	(kt P/yr)	(kt P/yr)	(kt P/yr)
F1	Rock import	Imported P rock, P2O5 and Fosforic ac.	This source include imports of the folow products groups: 2510 Natural calcium phosphates and natural aluminium calcium phosphates, natural and phosphatic chalk (P rock); 280910 P2O5; 280920 Phosphoric acid and polyphosphoric acids. International trade statistics in goods, ITC (2012)	Average of P content was taken from (F. Zapata, R.N. Roy, Utilización de las rocas fosforicas para una agricultura sostenible, FAO, Roma 2007) for P rock. The rest was calculated based on their chemical composition.	118,48	118,48	NA	1,33	1,33	39,10	118,48	15,00	116,62
F2	Non-food import	Imported P in non-food commodities such as detergents, P dosing and industrial applications.	This source include imports of the folow products groups: 2835 Phosphinates "hypophosphites", phosphonates "phosphites" and phosphates; polyphosphates, whether or not chemically defined; 3401 Soap; organic surface-active products and preparations for use as soap; organic surface-active products and preparations for washing the skin,; paper, wadding, felt and nonwovens, impregnated, coated or covered with soap or detergent ; 3402 Organic surface-active agents (excl. soap); surface-active preparations, washing preparations, incl. auxiliary washing preparations, and cleaning preparations, whether or not containing soap. International trade statistics in goods, ITC (2012).	In order to calculate from detergents to P the conversion factor of 0,2527 was used (T. Wind et al., 2007)	50,87	50,87	NA	1,33	1,33	16,79	50,87	16,79	55,80
F3	Fertilizer import	Imported P fertilizer	International trade statistics in goods, ITC (2012)	Pi content was taken from www.tecnologiagricola.es/abonos-compuestos-npk	91,30	98,15	4,58	1,33	1,15	14,72	98,15	14,72	98,15
			MAGRAMA, movimiento de fertilizantes Enero-Diciembre 2012.		100,86			1,10					
			Anuario de Estadistica de 2012. MAGRAMA. 15.2.5. Medios de producción.		100,29			1,10					
			MAGRAMA, movimiento de fertilizantes Enero-Diciembre 2012.		100,16			1,10					
F4	Food and feed import	Imported P in food and feed	*Crops:* estimates for crops imports obtained from International trade statistics in goods, ITC (2012), gives 39,02 kt P/yr. *Animal producs:* live and slaughtered animals, milk, eggs and dairy products from International trade statistics in goods, ITC (2012), containing 3,70 kt P/yr. *Fish:* fish and seafood imported 2.76 kt P / year, from International trade statistics in goods, ITC (2012). Fish and shellfish caught 1,79 kt P/ year, from AE 2012, MAGRAMA. Total: 4,55 kt P/yr. *Processed food:* imports of processed food from ITC (2012) 3,18 kt P/yr. *Animal feed:* imported animal feed (wich excludes unmilled cereals to avoid double counting) from International trade statistics in goods, ITC (2012) gives 4,37 kt P/yr. Total = 39,02+3,70+4,55+3,18+4,37 = 54,82 kt P/year	Pi content was taken from (G. Barril-Cuadrado et al. 2013) and (M. Verdú, 2011)	54,82	54,82	NA	1,33	1,33	18,09	54,82	18,09	54,82
F5	Fertilizer export	Exported P fertilizer	International trade statistics in goods, ITC (2012)	Pi content was taken from www.tecnologiagricola.es/abonos-compuestos-npk	61,66	45,71	13,81	1,33	1,19	8,68	45,71	8,68	45,71
			MAGRAMA, movimiento de fertilizantes Enero-Diciembre 2012.		37,71			1,10					
			MAGRAMA, movimiento de fertilizantes Enero-Diciembre 2012.		37,76			1,10					

Table A.1 (Continued)

Flow Number and name	Description	Calculations, assumptions and references	Pi content	Estimated Amount (kt P/yr)	Average amount [a] (kt P/yr)	Stándar desviation	Uncertainty interval [b]	Average confidence [c]	Average confidence interval [d] (kt P/yr)	Final value [e] (kt P/yr)	Final confidence [f]	In calculation [g]
F6 Non-food export	Exported P in non-food commodities such as detergents, P dosing and industrial applications.	This source include imports of the folow products groups: 2835 Phosphinates "hypophosphites", phosphonates "phosphites" and phosphates; polyphosphates, whether or not chemically defined; 3401 Soap; organic surface-active products and preparations for use as soap; organic surface-active products and preparations for washing the skin,; paper, wadding, felt and nonwovens, impregnated, coated or covered with soap or detergent ; 3402 Organic surface-active agents (excl. soap); surface-active preparations, washing preparations, incl. auxiliary washing preparations, and cleaning preparations, whether or not containing soap. International trade statistics in goods, ITC (2012).	In order to calculate from detergents to P the conversion factor of 0,2527 was used (T. Wind et al., 2007)	39,10	39,10	NA	1,33	1,33	12,90	39,10	12,90	39,10
F7 Food and feed export	Exported P in food and feed	*Crops:* estimates for crops exports obtained from International trade statistics in goods, ITC (2012), gives 12,54 kt P/year. *Animal producs:* live and slaughtered animals, milk, eggs and dairy products from International trade statistics in goods, ITC (2012), containing 6,36 kt P/yr. *Fish:* fish and seafood exported 1,80 kt P /yr, from International trade statistics in goods, ITC (2012). *Processed food:* exports of processed food from ITC (2012) 3,00 kt P/yr. *Animal feed:* exported animal feed (wich excludes unmilled cereals to avoid double counting) from International trade statistics in goods, ITC (2012) gives 1,65 kt P/yr. Total=12,54+6,11+1,47+3,00+1,65 = 25,35 ktP/yr	Pi content was taken from (G. Barril-Cuadrado et al. 2013) and (M. Verdú, 2011)	25,35	25,35	NA	1,33	1,33	8,37	25,35	8,37	25,35
F8 Fertilizer production	Produced P in fertilizers	MAGRAMA, movimiento de fertilizantes Enero-Diciembre 2012.	Pi content was taken from www.tecnologiagricola.es/abonos-compuestos-npk	117,86	116,30	2,69	1,10	1,14	16,28	116,30	15,03	116,62
		Anuario de Estadistica de 2012. MAGRAMA. 15.2.5. Medios de producción.		117,85			1,10					
		Asociación Nacional de Fabricantes de Fertilizantes, ANFFE, 2012		113,20			1,20					
F9 Fertilizer application	Applied P fertilizer to agricultural land	MAGRAMA, movimiento de fertilizantes Enero-Diciembre 2012.	Pi content was taken from www.tecnologiagricola.es/abonos-compuestos-npk	164,34	163,00	2,67	1,10	1,10	16,30	163,00	16,30	163,00
		MAGRAMA, movimiento de fertilizantes Enero-Diciembre 2012.		159,00			1,10					
		Balance de P en la agricultura española 2012, MAGRAMA		164,35			1,10					
		Anuario de Estadistica de 2012. MAGRAMA. 15.2.5. Medios de producción.		164,30			1,10					
F10 Human non-food consumption	P consumed as detergents	The amount of P used in greywater (assumed to be mostly detergents) is estimated at around 0,68 g/day/person (Jönsson et al., 2006), for the population of 47265321 (INE,2012).		11,44	14,80	4,74	1,20	1,20	2,96	14,80	2,83	16,15
		The amount of P used within domestics laundry cleaning products and automatic dishwasher detergents (ADD) is estimated at around 0,384 kg/year/person (T. Wind et al., 2007), for the population of 47265321 (INE,2012).		18,15			1,20					

Table A.1 (Continued)

	Flow Number and name	Description	Calculations, assumptions and references	Pi content	Estimated Amount (kt P/yr)	Average amount ^{a} (kt P/yr)	Stándar desviation	Uncertainty interval^b	Average confidence^c	Average confidence interval^d (kt P/yr)	Final value^e (kt P/yr)	Final confidence^f (kt P/yr)	In calculation^g (kt P/yr)
F11	Non-food commodities	P within food type commodities that have uses other than food, feed or seed (Biodiesel).	*Crop products:* domestic uses for crops are estimated by Defra (2011a). P concentrations for various crops are obtained from Balance de P en la agricultura española 2012, MAGRAMA. In 2012 there were destined 1961, 324, 442 and 5077 tons of beet, sunflower, cartamo and rape respectively for biodiesel production (AE 2012,13.4.2. Cultivos Industriales: Destino de la producción). With a content of P of 0,05 kt P. For other industrial uses there were destined 156797 t of sunflower and 775872 t of diverse oleaginous by a content of 5,08 kt P. Total = 5,13 kt P. *Animal products:* It is estimated Spain consumes around 13,06 kt P/yr within animals (milk and eggs not included,from AE 2012, MAGRAMA), and assuming that around 80% of the body P is found within bones (Withers et al., 2001), around 10,75 kt P/yr is found within the bones of slaughtered animals. The bones have a number of uses, including the production of gelatine, glue, grease and bone meal, although specific data is limited. Of the remaining 10,75 kt P in bone, it is assumed that 75% is used for non-food commodities, containing 8,07 kt P/yr. Total=5,13 + 8,07 = 13,20 ktP/yr		13,20	13,20	NA	1,20	1,20	2,64	13,20	2,64	13,20
F12	Human food consumption	P consumed in domestic food market	Anuario de Estadistica de 2012. Ministerio de Agricultura, Alimentación y Medio Ambiente. Estimates for household and eating out food purchases from Family Food 2009 (Defra, 2010c)	Pi content was taken from (G. Barril-Cuadrado et al. 2013) and (M. Verdú, 2011)	73,76	73,76	NA	1,33	1,33	24,34	73,76	24,34	73,76
F13	Food and feed processing waste	P loss during manufacturing food	Waste collection statistics for Animal and vegetal waste in 2012 was 2363035 t, with a P content of 8221 mg P/kg gives 19,43 kt P/ yr. (EUROSTAT) Waste collection statistics for Vegetal waste in 2012 was 429524 t, with a P content of 8221 mg P/kg gives 3,53 kt P/ yr. (EUROSTAT) Total= 19,43 + 3,53 = 22,96 ktP/yr	Pi content in food manufacturing slugde is 8221 mg P/kg d.m (García-Albacete et al.,2012).	22,96	22,96	NA	1,20	1,20	4,59	22,96	4,59	22,96
F14	Other disposal for human excreta	P within human excreta which is not disposed of to sewers	3 g of P per capita and day is assumed to be contributed from household and small activities into the sewage (C. Ott et al.,2012). The total P load from this source can be calculated by considering the population of 47265321 (INE, 2012) and gives 51,75 kt P/yr. If 98,7% of the Spain population (EUROSTAT) was conected to sewers in 2012, the total charge which is not disposed of to sewers was 0,67 kt P/yr.		0,67	0,52	0,22	1,33	1,33	0,17	0,52	0,17	0,68
			Roughtly 1,6 g of P per capita and day is assumed to be contributed from human urine and feces into the sewage (T. Wind et al., 2007). The total P load from this source can be calculated by considering the population of 47265321 (INE, 2012) and gives 27,60 kt P/yr. If 98,7% of the Spain population (EUROSTAT) was conected to sewers in 2012, the total charge which is not disposed of to sewers was 0,36 kt P/yr.		0,36			1,33					

Table A.1 (Continued)

Flow Number and name		Description	Calculations, assumptions and references	Pi content	Estimated Amount (kt P/yr)	Average amount ^{a} (kt P/yr)	Stándar desviation	Uncertainty interval^b	Average confidence^c	Average confidence interval^d (kt P/yr)	Final value^e (kt P/yr)	Final confidence^f (kt P/yr)	In calculation^g (kt P/yr)
F15	Human excreta to WwTW	Human P waste to treatment facilities	3 g of P per capita and day is assumed to be contributed from household and small activities into the sewage (C. Ott et al.,2012). The total P load from this source can be calculated by considering the population of 47265321 (INE, 2012) and gives 51,75 kt P/yr. If 98,7% of the Spain population (EUROSTAT) was conected to sewers in 2012, the total charge to sewers was 51,08 kt P/yr.		51,08	39,16	16,86	1,20	1,20	7,83	39,16	4,80	65,09
			Roughtly 1,6 g of P per capita and day is assumed to be contributed from human urine and feces into the sewage (T. Wind et al., 2007). The total P load from this source can be calculated by considering the population of 47265321 (INE, 2012) and gives 51,75 kt P/yr. If 98,7% of the Spain population (EUROSTAT) was conected to sewers in 2012, the total charge to sewers was 51,08 kt P/yr.		27,24			1,20					
F16	Waste to sewers	P within human waste to sewers	This value is obtained by mass balance in process Waste	-	-	-	-	-	NA	-	-	8,16	14,38
F17	Human waste	P within human waste food	Waste collection statistics for Animal and mixed food waste in 2012 was 1486057 t, with a P content of 5093 mg P/kg gives 7,57 kt P/ yr. (EUROSTAT)	- The content of P for Municipal Solid Waste was set at 0.5093%, based on the information provided by Dirección General de Calidad y Evaluación Ambiental y Medio Rural (MAGRAMA), the amount of P product was set at 5095 mg/kg	15,40	17,69	3,14	1,20	1,30	5,31	17,69	4,48	24,14
			Waste collection statistics for Household and Similar waste in 2012 was 10298721 t, with a P content of 760 mg P/kg gives 7,83 kt P/ yr. (EUROSTAT)	- Applying P concentrations of similar food types obtained from USDA (2004), suggests that 1 Mt of household food waste contains 0,76 kt P (760 mg P/kg).									
			Total= 7,57 + 7,83 = 15,40 ktP/yr										
			Waste collection statistics for Restaurant and food waste in 2012 was 547564 t, with a P content of 5095 mg P/kg gives 2,80 kt P/ yr. (AE 2012. Residuos)		16,41			1,20					
			Waste collection statistics for Urban waste in 2012 was 17911465 t, with a P content of 760 mg P/kg gives 13,61 kt P/ yr. (AE 2012. Residuos)										
			Total= 2,80 + 13,61 = 16,41 ktP/yr										
			0,45 kg P/ cap/ yr is assumed to be generated from human into urban waste (C. Ott et al. 2012). The total P load from this source can be calculated by considering the population of 47265321 (INE, 2012) and gives 21,27 kt P/yr.		21,27			1,33					
F18	Sewage sludge to incineration	P within sewage sludge	Anuario de Estadistica de 2012. MAGRAMA, 8.9. Producción y destino de lodos, estimate that 75258 t d.m. of sludge was disposed to incineration.	-Average of P content in sludge is 19237 mg P/kg d.m, from Caracterización de Lodos de Depuradoras de España,2012.	2,57	6,19	3,13	1,20	1,20	1,24	6,19	1,24	6,19
			Common sludges diposed to incineration in 2012 was 234184 t d.m. (INE 2012)	-P content in slugde is estimated in 31247 mg P/kg d.m (García-Albacete et al.,2012).	8,00			1,20					
			Common sludges diposed to incineration in 2012 was 234184 t d.m. (EUROSTAT)	- Using the data of the Synthesis Report on the use of sludge in spanish agriculture for 2012 sent to the European Union, prepared by Dirección General de Calidad y Evaluación Ambiental y Medio Rural (MAGRAMA), the amount of P product was set from sewage sludge at 5,199% (51990 mg/kg d.dm.)	8,00			1,20					
				-Total average of P in sluldge= 34158 mg P/kg d.m. (s = 16569)									

Table A.1 (Continued)

Flow Number and name	Description	Calculations, assumptions and references	Pi content	Estimated Amount (kt P/yr)	Average amount[a] (kt P/yr)	Stándar desviation	Uncertainty interval[b]	Average confidence[c]	Average confidence interval[d] (kt P/yr)	Final value[e] (kt P/yr)	Final confidence[f] (kt P/yr)	In calculation[g] (kt P/yr)
F19 Sewage sludge to landfill	P within sewage sludge	Anuario de Estadistica de 2012. MAGRAMA, 8.9. Producción y destino de lodos, estimate that 80490 t d.m. of sludge was disposed to landfill.	-Average of P content in sludge is 19237 mg P/kg d.m, from Caracterización de Lodos de Depuradoras de España,2012.	2,75	5,62	2,48	1,20	1,20	1,12	5,62	1,22	6,62
		Common sludges diposed to landfill in 2012 was 206410 t d.m. (INE 2012)	-P content in slugde is estimated in 31247 mg P/kg d.m (García-Albacete et al.,2012).	7,05			1,20					
		Common sludges diposed to landfill in 2012 was 206410 t d.m. (EUROSTAT)	- Using the data of the Synthesis Report on the use of sludge in spanish agriculture for 2012 sent to the European Union, prepared by Dirección General de Calidad y Evaluación Ambiental y Medio Rural (MAGRAMA), the amount of P product was set from sewage sludge at 5,199% (51990 mg/kg d.dm.) -Total average of P in sluldge= 34158 mg P/kg d.m. (s = 16569)	7,05			1,20					
F20 Sewage sludge to composting or other disposal	P within sewage sludge	Anuario de Estadistica de 2012. MAGRAMA, 8.9. Producción y destino de lodos, estimate that 60084 t d.m. of sludge was disposed to composting or other disposal.	-Average of P content in sludge is 19237 mg P/kg d.m, from Caracterización de Lodos de Depuradoras de España,2012. -P content in slugde is estimated in 31247 mg P/kg d.m (García-Albacete et al.,2012). - Using the data of the Synthesis Report on the use of sludge in spanish agriculture for 2012 sent to the European Union, prepared by Dirección General de Calidad y Evaluación Ambiental y Medio Rural (MAGRAMA), the amount of P product was set from sewage sludge at 5,199% (51990 mg/kg d.dm.) -Total average of P in sluldge= 34158 mg P/kg d.m. (s = 16569)	2,05	2,05	NA	1,20	1,20	0,41	2,05	0,41	2,05
F21 WwTW final effluent	P within WwTW effluent discharged to water bodies	Total average efficiency (P-renoval) in sewage treatment containing primary, secondary and tertiary are 10 %, 25 % and 90 % respectively (Folke 1996). In Spain, in 2012, 71% of the total load was treated by tertiary treatment, 29 % by secondary treatment and 1% by primary treatment (EEA 2012). It is assumed that the average efficiency (P-removal) in 2012 was 71 %.		-	-	-	-	-	-	-	10,05	31,72
		Estimate for P content in WwtW final effluent by mass balance.						-				
F22 Background losses to water	P within background losses to water bodies	Estimate for P within background losses to water bodies by mass balance in process Back Ground.		-	-	-	-	NA	-	-	0,17	0,68

Table A.1 (Continued)

Flow Number and name		Description	Calculations, assumptions and references	Pi content	Estimated Amount (kt P/yr)	Average amount ^{a} (kt P/yr)	Stándar desviation	Uncertainty interval^b	Average confidence^c	Average confidence interval^d (kt P/yr)	Final value^e (kt P/yr)	Final confidence^f (kt P/yr)	In calculation^g (kt P/yr)
F23	Sewage sludge to agriculture	P within sewage sludge	Anuario de Estadistica de 2012. MAGRAMA, 8.9. Producción y destino de lodos, estimate that 914929 t d.m. of sludge was disposed to agriculture.	-Average of P content in sludge is 19237 mg P/kg d.m, from Caracterización de Lodos de Depuradoras de España,2012.	31,25	32,89	1,42	1,20	1,20	6,58	32,89	6,58	32,89
			Common sludges diposed to agriculture in 2012 was 986895 t d.m. (INE 2012)	-P content in slugde is estimated in 31247 mg P/kg d.m (García-Albacete et al.,2012).	33,71			1,20					
			Common sludges diposed to agriculture in 2012 was 986895 t d.m. (EUROSTAT)	- Using the data of the Synthesis Report on the use of sludge in spanish agriculture for 2012 sent to the European Union, prepared by Dirección General de Calidad y Evaluación Ambiental y Medio Rural (MAGRAMA), the amount of P product was set from sewage sludge at 5,199% (51990 mg/kg d.dm.)	33,71			1,20					
				-Total average of P in sluldge= 34158 mg P/kg d.m. (s = 16569)									
F24	Waste for incineration	P within waste for incineration	Waste statistics for Animal and mixed food waste disposed to incineration in 2012 was 65342 t, with a P content of 5093 mg P/kg gives 0,33 kt P/ yr. (EUROSTAT)	The amount of P for RSU was set at 0.5093%, based on the information provided by Dirección General de Calidad y Evaluación Ambiental y Medio Rural (MAGRAMA) (data of 2012).	2,65	2,12	0,75	1,20	1,20	0,42	2,12	0,42	2,12
			Waste statistics for Household and Similar waste disposed to incineration in 2012 was 1502821 t, with a P content of 760 mg P/kg gives 1,14 kt P/ yr. (EUROSTAT)	- Applying P concentrations of similar food types obtained from USDA (2004), suggests that 1 Mt of household food waste contains 0,76 kt P (760 mg P/kg).									
			Waste statistics for Industrial Effluent sludges disposed to incineration in 2012 was 12809 t, with a P content of 4722 mg P/kg gives 0,06 kt P/ yr. (EUROSTAT)	-P content in slugde is estimated in 4722 mg P/kg d.m (García-Albacete et al.,2012).									
			Waste statistics for Animal and vegetal waste disposed to incineration in 2012 was 100268 t, with a P content of 8221 mg P/kg gives 0,82 kt P/ yr. (EUROSTAT)	-P content in food manufacturing slugde is estimated in 8221 mg P/kg d.m (García-Albacete et al.,2012).									
			Waste statistics for Vegetal waste disposed to incineration in 2012 was 34959 t, with a P content of 8221 mg P/kg gives 0,29 kt P/ yr. (EUROSTAT)										
			Total= 0,33 + 1,14 + 0,06 + 0,82 + 0,29 = 2,65 ktP/yr										
			Statistics for inputs to incineration plants for 2012 were 2087878 t, with a P content of 760 mg P/kg gives 1,59 kt P/ yr. (AE 2012, residuos).		1,59			1,20					
F25	Waste for landfill	P within waste for landfill	Waste statistics for Animal and mixed food waste disposed to landfill in 2012 was 65342 t, with a P content of 5093 mg P/kg gives 0,31 kt P/ yr. (EUROSTAT)	The amount of P for RSU was set at 0.5093%, based on the information provided by Dirección General de Calidad y Evaluación Ambiental y Medio Rural (MAGRAMA) (data of 2012).	9,57	9,85	0,39	1,20	1,20	1,97	9,85	1,97	9,85
			Waste statistics for Household and Similar waste disposed to landfill in 2012 was 8795900 t, with a P content of 760 mg P/kg gives 6,70 kt P/ yr. (EUROSTAT)	- Applying P concentrations of similar food types obtained from USDA (2004), suggests that 1 Mt of household food waste contains 0,76 kt P (760 mg P/kg).									
			Waste statistics for Industrial Effluent sludges disposed to landfill in 2012 was 12809 t, with a P content of 4722 mg P/kg gives 1,77 kt P/ yr. (EUROSTAT)	-P content in slugde is estimated in 4722 mg P/kg d.m (García-Albacete et al.,2012).									
			Waste statistics for Animal and vegetal waste disposed to landfill in 2012 was 79626 t, with a P content of 8221 mg P/kg gives 0,65 kt P/ yr. (EUROSTAT)	-P content in food manufacturing slugde is estimated in 8221 mg P/kg d.m (García-Albacete et al.,2012).									
			Waste statistics for Vegetal waste disposed to landfill in 2012 was 17202 t, with a P content of 8221 mg P/kg gives 0,14 kt P/ yr. (EUROSTAT)										
			Total= 0,31 + 6,70 + 1,77 + 0,65 + 0,14 = 9,57 ktP/yr										
			Statistics for inputs to landfill for 2012 were 13318928 t, with a P content of 760 mg P/kg gives 10,12 kt P/ yr. (AE 2012, residuos).		10,12			1,20					

Table A.1 (Continued)

Flow Number and name	Description	Calculations, assumptions and references	Pi content	Estimated Amount (kt P/yr)	Average amount [a] (kt P/yr)	Stándar desviation	Uncertainty interval[b]	Average confidence[c]	Average confidence interval[d] (kt P/yr)	Final value[e] (kt P/yr)	Final confidence[f] (kt P/yr)	In calculation[g] (kt P/yr)
F26 Waste for composting or other disposal	P within waste for composting or other disposal	Waste statistics for Animal and mixed food waste disposed to composting or other disposal in 2012 was 1359429 t, with a P content of 5093 mg P/kg gives 6,92 kt P/ yr. (EUROSTAT) Waste statistics for Industrial Effluent sludges disposed to composting or other disposal in 2012 was 179328 t, with a P content of 4722 mg P/kg gives 0,85 kt P/ yr. (EUROSTAT) Waste statistics for Animal and vegetal waste disposed to composting or other disposal in 2012 was 2182983 t, with a P content of 8221 mg P/kg gives 17,95 kt P/ yr. (EUROSTAT) Waste statistics for Vegetal waste disposed to composting or other disposal in 2012 was 377242 t, with a P content of 8221 mg P/kg gives 3,10 kt P/ yr. (EUROSTAT) Total= 6,92 + 0,85 + 17,95 + 3,10 = 28,82 ktP/yr	The amount of P for RSU was set at 0.5093%, based on the information provided by Dirección General de Calidad y Evaluación Ambiental y Medio Rural (MAGRAMA) (data of 2012). -P content in slugde is estimated in 4722 mg P/kg d.m (García-Albacete et al.,2012). -P content in food manufacturing slugde is estimated in 8221 mg P/kg d.m (García-Albacete et al.,2012).	28,82	22,86	8,43	1,20	1,20	4,57	22,86	4,57	22,86
		Waste statistics for Urban Waste disposed to composting or other disposal in 2012 was 2998130 t, with a P content of 5093 mg P/kg gives 15,27 kt P/ yr. (AE 2012, residuos). Waste statistics for Sludges disposed to composting or other disposal in 2012 was 160742 t, with a P content of 4722 mg P/kg gives 0,76 kt P/ yr (AE 2012, residuos). Waste statistics for Other Organic Waste disposed to composting or other disposal in 2012 was 104966 t, with a P content of 8221 mg P/kg gives 0,86 kt P/ yr. (AE 2012, residuos). Total= 15,27 + 0,76 + 0,86 = 16,90 ktP/yr		16,90			1,20					
F27 Non-farm manures/Compost	P within non-farm manures	In 2012, 367350 tons of compost took place (AE 2012, Residuos. MAGRAMA)with a content of P of 12,23 kt P/ yr.	-P content in compost is estimated in 14164 mg P/kg d.m (García-Albacete et al.,2012).	12,23	12,23	NA	1,20	1,20	2,45	12,23	2,45	12,23
F28 Agricultural losses to water	P lost to water bodies from agricultural land	*Arable land:* a run-off coefficient of 0,8 kg P/ha/yr has been applied (T. Wind et al., 2007), for the surface of 13745506 ha of arable land (INE,2012), gives 10,99 kt P/yr *Non arable land*: a run-off coefficient of 0,075 kg P/ha/yr has been applied (T. Wind et al., 2007), for the surface of 17355004 ha of non arable land (INE,2012), gives 1,30 kt P/yr Total = 12,29 kt P/yr		12,29	12,29	NA	1,33	1,33	4,06	12,29	4,06	12,29
F29 Crop uptake	P removed from agricultural land in crops and grasses	Balance de P en la agricultura española 2012, MAGRAMA AE 2012. 15.2.5. Medios de producción.MAGRAMA.		297,55	297,55	NA	1,10	1,10	29,76	297,55	29,76	297,55
F30 Animal grazing	P taken up during animal grazing	P taken up during animal grazing in 2012 was 42,34 kt P (Balance de P en la agricultura española 2012, MAGRAMA). P taken up in straw and plants in 2012 was 41,89 kt P (Balance de P en la agricultura española 2012, MAGRAMA). Total= 42,34 + 41,89 = 84,32 ktP/yr		84,23	84,23	NA	1,10	1,20	16,85	84,23	12,07	79,85
F31 Animal manure	P in animal manure applied to agricultural land	Balance de P en la agricultura española 2012, MAGRAMA		130,54	130,54	NA	1,10	1,20	26,11	130,54	20,59	133,60

Table A.1 (Continued)

Flow Number and name		Description	Calculations, assumptions and references	Pi content	Estimated Amount (kt P/yr)	Average amount [a] (kt P/yr)	Stándar desviation	Uncertainty interval[b]	Average confidence[c]	Average confidence interval[d] (kt P/yr)	Final value[e] (kt P/yr)	Final confidence[f] (kt P/yr)	In calculation[g] (kt P/yr)
F32	Crop products	P within crop products	Balance de P en la agricultura española 2012, MAGRAMA		213,31	213,31	NA	1,10	1,10	21,33	213,31	12,07	217,70
F33	Animal products	P within animal products	Slaughtered animals: estimates for dressed carcase weights of spanish animal production from Agriculture in Spain (Anuario de Estadistica de 2012. MAGRAMA. 14.2.1. Efectivos y Producciones Ganaderas). Applying an average of P contents of 0,25 % for all meats, slaughtered animals contain 13,4 kt P/yr. Milk: production of 7308001 m3 (Anuario de Estadistica de 2012. MAGRAMA. 14.3.1.1. Otras Producciones Ganaderas) at P content of 0,93 % (FOODSEL, 2008). Spain milk production contains 6,8 kt P/yr. Eggs: production of 9,12 billion eggs (Anuario de Estadistica de 2012. MAGRAMA. 14.3.2.2. Otras Producciones Ganaderas) at P content of 1.91 mg P/g egg, and assuming each egg weighs 50 g. Spain egg production containing 3,27 kt P/yr.		23,49	23,49	NA	1,33	1,33	7,75	23,49	7,62	23,76
F34	Animal feed	P within animal feed	Assuming no accumulation in Animal process and making the mass balance (F30 + F34 = F31 + F33) a P estimatión containing Animal Feed is obtained.		-	-	-	-	-	-	-	21,22	77,52
F35	Seed and planting material	P within seed and planting material	Balance de P en la agricultura española 2012, MAGRAMA		10,21	10,21	NA	1,10	1,20	2,04	10,21	2,04	10,21
F36	Non-food processing waste	P loss during manufacturing non-food	Waste statistics for non-hazarous Industrial Effluent sludges in 2012 was 567371 t, with a P content of 4722 mg P/kg gives 2,68 kt P/ yr. (EUROSTAT) Waste statistics for hazarous Industrial Effluent sludges in 2012 was 74493 t, with a P content of 4722 mg P/kg gives 0,35 kt P/ yr. (EUROSTAT) Total= 2,68 + 0,35 = 3,03 ktP/yr	-P content in slugde is 4722 mg P/kg d.m (García-Albacete et al.,2012).	3,03	2,11	1,31	1,20	1,33	0,69	2,11	0,69	2,11
			T. Wind (2007) suggest an approximation of 25 g/cap/yr forcountries without reported P-emissions from industry. The total P load from this source can be calculated by considering the population of 47265321 (INE, 2012) and gives 1,18 kt P/yr.		1,18			1,33					

a Average value from different calculations for each flow.

b A uncertainty interval was asigned flowing the method described in Section 4.2 (see Table 6).

c Average confidence value is presented here. This average value was used to calculate the average confidence interval.

d Average confidence interval which represents 95% confidence limits.

e This value was entered into the STAN program before the balancing application was performed.

f This confidence were produced by the STAN program after balancing the flows and validating the model.

g This value were produced by the STAN program after balancing the flows and validating the model.

B. Data provided by WWTP of BMA

Martin Gullón and Elena Lacort of BMA provided information on production and management of sludge from WWTPs in BMA during the period 2011-2015 necessary for this study. In Table B.1 parameters provided for each WWTP are collected.

Data provided by the seven WWTP are monthly averages for each parameter and given the volume of data provided, was performed the calculation of annual averages of each, which are presented in Table B.2 to B.8.

Table B 1 Parameters provided by BMA from WWTPs

		WWTP						
Parameter	**Unit**	**Begues**	**Vallvidrera**	**Sant Feliu**	**El Prat**	**Gavà**	**Montcada**	**Besòs**
Influent volume	m^3	x	x	x	x	x	x	x
Average influent volume	m^3	x	x	x	x	x	x	x
Energy demand	kWh	x	x	x	x	x	x	x
Energy production	kWh			x		x		x
Energy selfconsumption	kWh				x			x
Energy sold	kWh				x			x
P total influent concentration	mg/l	x	x	x	x	x	x	x
P total effluent concentration	mg/l	x	x	x	x	x	x	x
DM primary sludge	%						x	x
DM sludge dewatered	%	x	x	x	x	x		x
DM thermaldry sludge	%				x			x
SV	%	x	x	x	x	x	x	x
Sludge disposals	t	x	x	x	x	x		x
Volume sludge send to Besòs	m^3						x	

Table B 2 Annual averages calculated according to data provided by MBA from WWTP Begues for 2011-2015

Parameter	**Unit**	**2011**	**2012**	**2013**	**2014**	**2015**
Influent volume	m^3	497698	341079	352052	321091	340062
Average influent volume	m^3	16390	11185	11571	10564	11181
Energy demand	kWh	261141	211115	185088	190301	184397
P total influent concentration	mg/l	6,20	10,13	9,28	8,55	8,78
P total effluent concentration	mg/l	2,23	3,01	2,32	2,85	3,03
DM sludge dewatered	%	15,60	15,38			
SV	%	77,98	76,98	75,95	74,94	70,03
Sludge to Gavà	t	0	1804	2627	2402	2767
Sludge dewatered	t	331	1944	2627	2402	2767

Table B 3 Annual averages calculated according to data provided by MBA from WWTP Vallvidrera for 2011-2015

Parameter	**Unit**	**2011**	**2012**	**2013**	**2014**	**2015**
Influent volume	m^3	372.764	289.965	287.635	278.363	258.658
Average influent volume	m^3	1021	794	788	763	709
Energy demand	kWh	28283	25480	24924	24293	24583
P total influent concentration	mg/l	5,19	5,47	5,70	5,90	6,29
P total effluent concentration	mg/l	2,60	2,54	3,17	3,48	3,77
DM sludge dewatered	%	14,67	13,77	12,90	12,88	6,65
SV	%	71,21	75,53	74,61	75,17	77,53
Sludge dewatered	t	27	3	1	3	0
Total sludge	t	477	2.052	1.933	2.038	1.886

Table B 4 Annual averages calculated according to data provided by MBA from WWTP Sant Feliu for 2011-2015

Parameter	**Unit**	**2011**	**2012**	**2013**	**2014**	**2015**
Influent volume	m^3	18495096	16826276	17757871	17501815	17412261
Average influent volume	m^3	50672	45992	48625	47992	47738
Energy demand	kWh	500656	450648	491252	527012	549360
Energy production	kWh	3183872	3588464	3891030	3574032	3380954
P total influent concentration	mg/l	5,68	5,97	5,21	5,66	6,03
P total effluent concentration	mg/l	1,92	1,37	1,36	0,71	0,78
DM sludge dewatered	%	25,03	23,98	24,61	24,86	24,41
SV Sludge dewatered	%	56,56	61,61	58,98	56,87	59,67
Sludge dewatered to agriculture	t	3092	3296	0	0	7074
Sludge dewatered to compost	t	0	3664	6125	10971	3283
Sludge dewatered to thermal drying	t	9672	7510	6190	198	0
Sludge dewatered to landfill	t	597	78	1144	963	2021

Table B 5 Annual averages calculated according to data provided by MBA from WWTP El Prat for 2011-2015

Parameter	**Unit**	**2011**	**2012**	**2013**	**2014**	**2015**
Influent volume	m^3	100.789.407	92.748.401	91.432.198	88.519.768	86.357.714
Average influent volume	m^3	276.204	253.497	250.610	242.595	236.558
Energy demand	kWh	46.573.730	39.704.778	39.517.448	36.318.822	38.989.936
Energy selfconsumption	kWh	2.583.351	2.601.777	2.580.082	1.536.496	1.657.547
Energy sold	kWh	66.136.670	70.114.189	67.055.312	33.297.962	32.885.916
P total influent concentration	mg/l	7,20	9,40	9,10	9,10	10,70
P total effluent concentration	mg/l	2,50	3,40	3,10	3,20	3,60
DM sludge dewatered	%	23,23	22,06	22,46	23,14	23,06
DM thermaldry sludge	%	87,30	87,10	87,60	87,90	87,90
SV thermaldry sludge	%	61,00	65,30	65,90	63,20	67,80
Sludge dewatered to agriculture	t	4.637	6.094	10.407	35.984	26.487
Sludge dewatered to landfill	t	0	17	0	0	0
Dry Sludge to agriculture	t	2.619	2.453	1.237	0	179
Dry Sludge to compost	t	1.587	5.333	6.604	1.769	3.490
Dry Sludge to ciment	t	8.686	4.903	3.245	2.613	3.137

Table B 6 Annual averages calculated according to data provided by MBA from WWTP Montcada for 2011-2015

Parameter	**Unit**	**2011**	**2012**	**2013**	**2014**	**2015**
Influent volume	m^3	19.390.637	17.174.046	17.701.007	17.576.677	17.149.895
Average influent volume	m^3	53.135	46.928	48.494	48.164	47.017
Energy demand	kWh	4.198.064	3.950.151	3.940.311	3.851.731	4.117.274
P total influent concentration	mg/l	7,90	164,76	362,58	292,42	298,25
P total effluent concentration	mg/l	2,74	6,05	11,92	13,33	16,58
DM primary sludge	%	2,52	2,40	2,08	2,01	2,24
DM sludge send to Besòs	%	2,02	1,83	1,68	1,78	2,00
SV	%	79,27	81,93	80,38	75,24	72,06
Sludge send to Besòs	m^3	258.424	270.843	326.235	278.030	256.856

Table B 7 Annual averages calculated according to data provided by MBA from WWTP Gavà for 2011-2015

Parameter	**Unit**	**2011**	**2012**	**2013**	**2014**	**2015**
Influent volume	m^3	15667023	14135845	14926929	13279991	13547225
Average influent volume	m^3	42930	38628	40896	36397	37125
Energy demand	kWh	8557695	7808117	7466180	7039029	7613790
Energy production	kWh	2750730	2412716	2903555	2850743	2680569
P total influent concentration	mg/l	9,27	10,59	9,02	9,24	10,13
P total effluent concentration	mg/l	4,06	5,01	2,43	0,65	0,80
DM sludge dewatered	%	22,69	22,09	20,60	21,09	20,33
SV Sludge dewatered	%	68,86	73,10	71,38	70,51	70,98
Sludge dewatered to agriculture	t	8.580	7.982	11.135	11.159	12.152
Sludge dewatered to thermal drying	t	461	1.676	0	0	0
Sludge dewatered to landfill	t	389	1.001	0	0	53

Table B 8 Annual averages calculated according to data provided by MBA from WWTP Besòs for 2011-2015

Parameter	**Unit**	**2011**	**2012**	**2013**	**2014**	**2015**
Influent volume	m^3	127.793.000	135.074.000	118.080.000	116.457.659	122.303.000
Average influent volume	m^3	368.688	349.229	339.332	323.642	319.019
Energy demand	kWh	41.021.286	43.162.072	40.700.497	42.507.069	39.405.039
Energy production	kWh	197.360.349	135.775.423	193.082.505	0	0
Energy demand for sludge treatment	kWh	30.050.979	22.408.002	31.062.208	7.965.354	8.357.783
Energy sold	kWh	167.309.370	115.815.105	162.020.297	0	0
P total influent concentration	mg/l	7,18	9,18	9,08	8,82	9,68
P total effluent concentration	mg/l	2,23	3,80	3,42	3,71	3,59
DM primary sludge	%	4,80	4,68	4,23	4,40	4,22
DM sludge dewatered	%	30,75	29,35	29,18	30,28	28,94
DM thermaldry sludge	%	92,29	93,69	95,30		
SV thermaldry sludge	%	78,33	82,20	80,34	79,36	80,15
Sludge dewatered to compost	t	16.320	9.230	52.131	112.983	121.839
Sludge dewatered to others	t	0	0	352	9.945	8.756
Dry Sludge to compost	t	3.092	7.836	8.652	0	0
Dry Sludge to ciment	t	34.753	32.443	17.011	0	0

C. P content determination of sludge from BMA WWTP

From data given by the seven WWTPs of BMA for the period 2011-2015 (Annex B), the amount of P entering these plants annually (Influent P [t] from Table Annex) is calculated using Equation (Ec. C.1).

$$Influent\ \left[\frac{m^3}{y}\right] \cdot \frac{10^3\ l}{1\ m^3} \cdot P_{influent\ conc} \left[\frac{mg\ P}{l}\right] \cdot \frac{1\ t}{10^9\ mg} = P_{influent} \left[\frac{t}{y}\right] \qquad \text{(Ec. C.1)}$$

To calculate the P sludge mass balance of P (Ec. B.2) is performed.

$$P_{influent} \left[\frac{t}{y}\right] = P_{efluent} \left[\frac{t}{y}\right] + P_{sludge} \left[\frac{t}{y}\right] \qquad \text{(Ec. C.2)}$$

To apply the mass balance of P, they have made the following assumptions:

1. There is no accumulation of P in water treatment.
2. There are only two outputs of P, by the effluent and sludge

In the absence of effluent flows plants or their annual volumes, you can not calculate the total P content of this flow. To determine the total P of this flow has resorted to the Registro Estatal de Emisiones y Fuentes Contaminantes (PRTR-Spain), which are statements emissions from WWTP of Sant Feliu, El Prat, Gava, Montcada and Besòs in 2011-2015. In this record, all plants declare among others, P emitted to water in kg/yr. It is clear that the public information threshold established by Royal Decree 508/2007 is 5,000 kg P/yr. The values declared by the BMA treatment plants between 2011 and 2015 are shown in Table C1.

The concentration of sludge P is calculated based on tons of annual P containing the sludge and the amount of sludge generated annually in dry matter, applying equation (Ec. C.3).

$$P_{Sludge} \left[\frac{mg\ P}{kg\ dm}\right] = \frac{P_{sludge}\left[\frac{t}{y}\right] \cdot \frac{10^9\ mg}{1t}}{Sludge\left[\frac{t\ dm}{y}\right] \cdot \frac{10^6\ kg\ dm}{1t}} \qquad \text{(Ec. C.3)}$$

WWTPs of Vallvidrera and Begues did not declare their P emissions to water during the period 2011-2015 so can not perform the calculations for determining the P content in their sludge. Nor they were presented P emissions to water WWTP of Montcada for 2014 and 2015, nor WWTP of Besòs for 2015.

The annual tons of P present in the sewage sludge and P concentrations calculated are presented in Table C1.

Table C 1 Annual average of total volume (m^3) and P content (mg/l) in influent provided by MBA from WWTPs. Total P content in influent (t), P emissions P to water declared by MBA WWTPs, and calculated total P content in sludge (t) and P content in sludge (mg/kg dm)

WWTP	**YEAR**	**INFLUENT**			**EFLUENT***	**SLUDGE**		
		Flow	P	P	P	P		P
		[m3]	[mg/l]	[t]	[t]	[t]	[t dm]	[mg/kg dm]
Begues	2011	497698	6,20	3	**	-	-	-
	2012	341079	10,13	3	**	-	-	-
	2013	352052	9,28	3	**	-	-	-
	2014	321091	8,55	3	**	-	-	-
	2015	340062	8,78	3	**	-	-	-
	Average for period 2011-2015			3				
Vallvidrera	2011	372764	5,19	2	**	-	-	-
	2012	289965	5,47	2	**	-	-	-
	2013	287635	5,70	2	**	-	-	-
	2014	278363	5,90	2	**	-	-	-
	2015	258658	6,29	2	**	-	-	-
	Average for period 2011-2015			2				
Sant Feliu	2011	18495096	5,68	105	35	70	3349	20896
	2012	16826276	5,97	100	24	77	3508	21905
	2013	17757871	5,21	92	10	82	3327	24648
	2014	17501815	5,66	99	10	89	3003	29653
	2015	17412261	6,03	105	**	-	3016	-
	Average for period 2011-2015			100	20	79	3241	24276
Prat	2011	100789407	7,15	721	252	469	12311	38069
	2012	92748401	9,38	870	158	713	12343	57736
	2013	91432198	9,14	836	130	706	12024	58715
	2014	88519768	9,06	802	225	577	12185	47352
	2015	86357714	10,65	920	**	-	12127	-
	Average for period 2011-2015			830	191	616	12198	50468
Gavà	2011	15667023	9,27	145	55	90	2137	42268
	2012	15606926	9,23	144	64	80	2377	33863
	2013	15552144	9,18	143	14	129	2288	56494
	2014	15298946	9,25	142	16	126	2353	53369
	2015	15168686	9,08	138	***	-	2475	-
	Average for period 2011-2015			142	37	106	2326	46498
Montcada	2011	19390637	7,90	153	52	101	-	-
	2012	19275518	7,98	154	34	119	-	-
	2013	19218612	8,12	156	64	92	-	-
	2014	18760570	8,59	161	**	-	-	-
	2015	18589867	9,13	170	**	-	-	-
	Average for period 2011-2015			159	50	104		
Besos	2011	127793000	7,18	917	296	621	41697	14890
	2012	135074000	9,18	1239	486	754	39426	19116
	2013	118080000	9,08	1073	426	647	38896	16629
	2014	116457659	8,82	1027	482	545	37204	14649
	2015	122303000	9,68	1184	**	-	37755	-
	Average for period 2011-2015			1088	422	642	38996	16321
TOTAL P for period 2011-2015 in BMA				**2319**	**720**	**1548**		

** P statements emissions (kg/yr) declared by WWTP (PRTR-Spain)*
***P emissions (kg / yr) not declared by WWTP*

Following the methodology described in this Annex, the P containing sludge generated in the BMA in 2012 are calculated. Table C2 collects the data and results.

Table C 2 Data and results of P present in the effluents, influents and sludge from all WWTP of MBA

WWTP	**INFLUENT**			**EFFLUENT***	**SLUDGE**
	Flow m3	P mg/l	P tn	P tn	P tn
Begues	341079	10,13	3		
Vallvidrera	289965	5,47	2		
Sant Feliu	16826276	5,97	100	24	77
Prat	92748401	9,38	870	158	713
Gavà	15606926	9,23	144	64	80
Montcada	19275518	7,98	154	34	119
Besos	135074000	9,18	1239	486	754
Total P in MBA			2508	765	1743

D. Final results energy balances

Table D 1

SCENARIO 1			
Process	**Electricity**	**Thermal**	**Fuel**
Centr.	-1665260		
An. Digest.	2064923	19983125	
	-15295792	-16905876	
Centr.	1665260		
Transport			661767
Transport			78941
Incineration	5930942		
	-6577943	-34299272	
Transport			99133
Ecophos	327233	25016985	
Demand	9988359	45000110	839841
Generation	-23538995	-51205148	0
Subtotal	-13550636	-6205038	839841
Total	**-18915833**	kWh/yr	

Table D 2

SCENARIO 2			
Process	**Electricity**	**Thermal**	**Fuel**
Transport			944976
Transport			78941
Incineration	9097852		
	-12547853	-65428093	
Transport			152067
Ecophos	501964		
		38375155	
Demand	9599816	38375154,8	1175983
Generation	-12547853	-65428093	0
Subtotal	-2948037	-27052938	1175983
Total	**-28824992**	kWh/yr	

Table D 3

SCENARIO 3			
Process	**Electricity**	**Thermal**	**Fuel**
Transport			944976
Transport			78941
Composting	1186680		
Demand	1186680	0	1023916
Generation	0	0	0
Subtotal	1186680	0	1023916
Total	**2210596**	kWh/yr	

Table D 4

SCENARIO 4			
Process	**Electricity**	**Thermal**	**Fuel**
Centr.	-1665260		
An. Digest.	2064923	19983125	
	-15295792	-16905876	
Centr.	1665260		
Transport			661767
Transport			78941
Composting	773601		
Demand	4503784	19983125	740708
Generation	-16961052	-16905876	0
Subtotal	-12457268	3077249	740708
Total	**-8639311**	kWh/ayr	

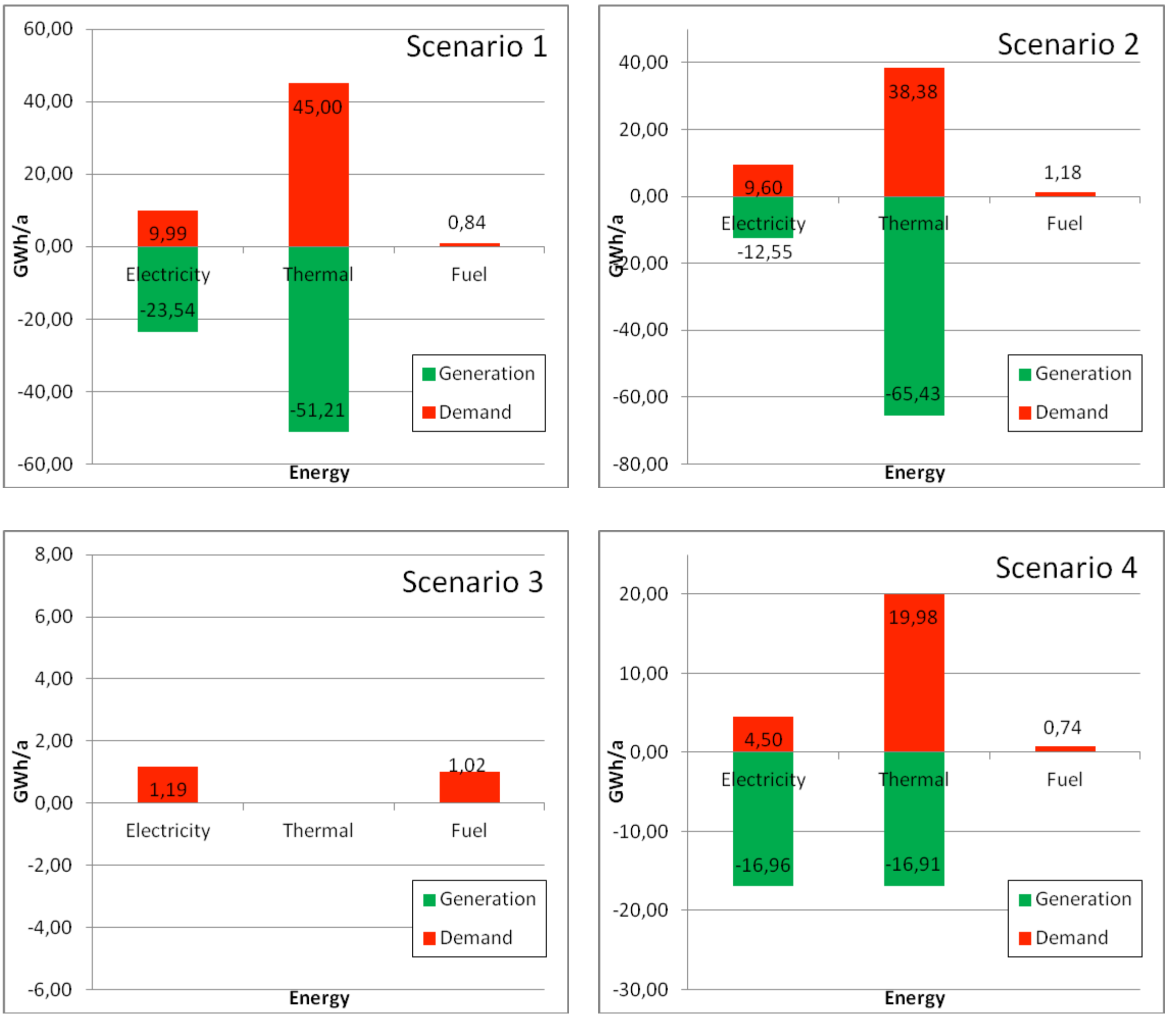

Figure D 1 Demand and genaration of energy by types and Scenario

E. Final results emissions balances

Table E. 1 Final results emissions Scenario 1

SCENARIO 1

Process	Consumption Generation	Units	Factor*	Units	Kg CO2-eq	Concept
Centrifugation	1665260	kWh	-0,08	kgCO2-eq/kWh	-133221	Electricity
	383676	kg	-2,2	kgCO2-eq/kg	-844087	Polymer
An. Digestion	31973	t dm	50	kgCO2-eq/t dm	1598650	Process
	15295792	kWh	-0,08	kgCO2-eq/kWh	-1223663	Electricity
	16905876	kWh	-0,798	kgCO2-eq/kWh	-13490889	Steam
Centrifugation	1665260	kWh	0,08	kgCO2-eq/kWh	133221	Electricity
	218446	kg	2,2	kgCO2-eq/kg	480581	Polymer
Transport	661767	kWh	0,25169	kgCO2-eq/kWh	166560	Fuel
Transport	78941	kWh	0,25169	kgCO2-eq/kWh	19869	Fuel
Incineration	25787	t dm	450,6412	kgCO2-eq/t dm	11620552	Process
	6577943	kWh	-0,08	kgCO2-eq/kWh	-526235	Electricity
	34299272	kWh	-0,798	kgCO2-eq/kWh	-27370819	Steam
Transport	99133	kWh	0,25169	kgCO2-eq/kWh	24951	Fuel
Ecophos	327233	kWh	0,08	kgCO2-eq/kWh	26179	Electricity
	25016985	kWh	0,798	kgCO2-eq/kWh	19963554	Steam
	11623327	kg	1,2	kgCO2-eq/kg	13947992	HCl (37%)
	3163	kg	0,53	kgCO2-eq/kg	1677	Resin
	7308210	kg	-0,89	kgCO2-eq/kg	-6504307	CaCl2 (100%)
	4472188	kg	-0,18	kgCO2-eq/kg	-804994	FeCl3 (40%)
	2013749	kg	-1,45	kgCO2-eq/kg	-2919936	H3PO4 (85%)
			Total generation		**47983785**	
			Total credits		**-53818152**	
			Total CO2-eq		**-5834367**	

Table E. 2 Final results emissions Scenario 2

SCENARIO 2

Process	Consumption Generation	Units	Factor*	Units	Kg CO2-eq	Concept
Transport	944976	kWh	0,25169	kgCO2-eq/kWh	237841	Fuel
Transport	78941	kWh	0,25169	kgCO2-eq/kWh	19869	Fuel
Incineration	39556	t dm	450,6412	kgCO2-eq/t dm	17825508	Process
	12547853	kWh	-0,08	kgCO2-eq/kWh	-1003828	Electricity
	65428093	kWh	-0,798	kgCO2-eq/kWh	-52211618	Steam
Transport	152067	kWh	0,25169	kgCO2-eq/kWh	38274	Fuel
Ecophos	501964	kWh	0,08	kgCO2-eq/kWh	40157	Electricity
	38375155	kWh	0,798	kgCO2-eq/kWh	30623374	Steam
	17829765	kg	1,2	kgCO2-eq/kg	21395717	HCl (37%)
	4852	kg	0,53	kgCO2-eq/kg	2572	Resin
	11210531	kg	-0,89	kgCO2-eq/kg	-9977373	CaCl2 (100%)
	6860176	kg	-0,18	kgCO2-eq/kg	-1234832	FeCl3 (40%)
	2200394	kg	-1,45	kgCO2-eq/kg	-3190571	H3PO4 (85%)
			Total generation		**70183311**	
			Total credits		**-67618221**	
			Total CO2-eq		**2565090**	

Table E. 3 Final results emissions Scenario 3

SCENARIO 3						
Process	**Consumption Generation**	**Units**	**Factor***	**Units**	**Kg CO2-eq**	**Concept**
Transport	944976	kWh	0,25169	kgCO2-eq/kWh	237841	Fuel
Transport	78941	kWh	0,25169	kgCO2-eq/kWh	19869	Fuel
Composting	39556	t dm	153,1	kgCO2-eq/t dm	6056024	Process
	715000	kg	-2,7	kgCO2-eq/kg	-1930500	Phosphorous
			Total generation		**6313733**	
			Total credits		**-1930500**	
			Total CO2-eq		**4383233**	

Table E. 4 Final results emissions Scenario 4

SCENARIO 4						
Process	**Consumption Generation**	**Units**	**Factor***	**Units**	**Kg CO2-eq**	**Concept**
Centrifugation	1665260	kWh	-0,08	kgCO2-eq/kWh	-133221	Electricity
	383676	kg	-2,2	kgCO2-eq/kg	-844087	Polymer
An. Digestion	31973	t dm	50	kgCO2-eq/t dm	1598650	Process
	15295792	kWh	-0,08	kgCO2-eq/kWh	-1223663	Electricity
	16905876	kWh	-0,798	kgCO2-eq/kWh	-13490889	Steam
Centrifugation	1665260	kWh	0,08	kgCO2-eq/kWh	133221	Electricity
	218446	kg	2,2	kgCO2-eq/kg	480581	Polymer
Transport	661767	kWh	0,25169	kgCO2-eq/kWh	166560	Fuel
Transport	78941	kWh	0,25169	kgCO2-eq/kWh	19869	Fuel
Composting	25787	t dm	153,1	kgCO2-eq/t dm	3947945	Process
	654585	kg	-2,7	kgCO2-eq/kg	-1767379	Phosphorous
			Total generation		**6346825**	
			Total credits		**-17459240**	
			Total CO2-eq		**-11112415**	

F. Calculation and final results of cost analysis

Table F. 1 Final results of IC, OMC and Sales and Savings costs of Scenario 1

SCENARIO 1

Process	Consumption Generation	Units	Factor/eq*	Units	IC (Total)	OMC [€/yr]	Sales/Saving/Costs [€/yr]	Concept
Centrifugation	1665260	kWh	-0,06022	€/kWh	- €	- €	- 100.282 €	Electricity
	383676	kg	-3	€/kg	- €	- €	- 1.151.028 €	Polymer
Anaerobic Digestion	31973	t dm	100	€/t dm	- €	3.197.300 €	- €	OMC
	525.000	m3/d	y=x*494*x^(-0,2)/precio$	€	16.571.378 €	- €	- €	IC
	15295792	kWh	-0,06022	€/kWh	- €	- €	- 921.113 €	Electricity
	16905876	kWh	-0,045	€/kWh	- €	- €	- 760.764 €	Steam
Centrifugation	18204	t dm	62,09	€/t dm	1.130.276 €	- €	- €	IC
	18204	t dm	45,67	€/t dm	- €	831.369 €	- €	OMC
Transport Besos	67406	L	1	€/L	- €	67.406 €	- €	Fuel
Transport El Prat	8041	L	1	€/L	- €	8.041 €	- €	Fuel
Incineration	25787	t dm	1500	€/t dm	38.680.058 €	- €	- €	IC
	25787	t dm	300	€/t dm	- €	7.736.012 €	- €	OMC
	6577943	kWh	-0,06022	€/kWh	- €	- €	- 396.124 €	Electricity
	34299272	kWh	-0,045	€/kWh	- €	- €	- 1.543.467 €	Steam
Transport Ash	10097	L	1	€/L	- €	10.097 €	- €	Fuel
Ecophos	383850	kWh	0,06022	€/kWh	- €	23.115 €	- €	Electricity
	29345333	kWh	0,045	€/kWh	- €	1.320.540 €	- €	Steam
	13633760	kg	0,075	€/Kg	- €	1.022.532 €	- €	HCl (37%)
	4452	L	9,8	€/L	- €	43.644 €	- €	Resin
	654584,9607	kg P	0,53	€/kg P	- €	349.945 €	- €	Personnel
	8572000	kg	-1,1	€/Kg	- €	- €	- 9.429.200 €	CaCl2 (100%)
	5246000	kg	-0,81	€/Kg	- €	- €	- 4.249.260 €	FeCl3 (40%)
	3167691	kg	-7,02	€/Kg	- €	- €	- 22.237.191 €	H3PO4 (85%)
	-	-	-	-	874.247 €	- €	- €	IC
			TOTAL		**57.255.959 €**	**14.610.001 €**	**- 40.788.429 €**	

Table F. 2 Final results of IC, OMC and Sales and Savings costs of Scenario 2

SCENARIO 2

Process	Consumption Generation	Units	Factor*	Units	IC (Total)	OMC [€/yr]	Sales/Saving/Costs [€/yr]	Concept
Transport	96253,21	L	1	€/L	- €	96.253 €	- €	Fuel
Transport	8041	L	1	€/L	- €	8.041 €	- €	Fuel
Incineration	39556	t dm	1500	€/t dm	59.333.817 €	- €	- €	IC
	39556	t dm	300	€/t dm	- €	11.866.763 €	- €	OMC
	12547853	kWh	-0,06022	€/kWh	- €	- €	- 755.632 €	Electricity
	65428093	kWh	-0,045	€/kWh	- €	- €	- 2.944.264 €	Steam
Transport	15489	L	1	€/L	- €	15.489 €	- €	Fuel
Ecophos	598170	kWh	0,06022	€/kWh	- €	36.022 €	- €	Electricity
	45730000	kWh	0,045	€/kWh	- €	2.057.850 €	- €	Steam
	21246880	kg	0,075	€/Kg	- €	1.593.516 €	- €	HCl (37%)
	5783	kg	9,80	€/L	- €	56.693 €	- €	Resin
	715255,199	kg P	0,53	€/Kg P	- €	382.379 €	- €	Personnel
	13359130	kg	-1,1	€/Kg	- €	- €	- 14.695.043 €	CaCl2 (100%)
	8175000	kg	-0,81	€/Kg	- €	- €	- 6.621.750 €	FeCl3 (40%)
	3517589	kg	-7,02	€/Kg	- €	- €	- 24.693.475 €	H3PO4 (85%)
	-	-	-	-	955.276 €	- €	- €	IC
			TOTAL		**60.289.093 €**	**16.113.006 €**	**- 49.710.164 €**	

Table F. 3 Final results of IC, OMC and Sales and Savings costs of Scenario 3

SCENARIO 3

Process	Consumption Generation	Units	Factor*	Units	IC (Total)	OMC [€/yr]	Sales/Saving/Costs [€/yr]	Concept
Transport	96253,21	L	1	€/L	- €	96.253 €	- €	Fuel
Transport	8041	L	1	€/L	- €	8.041 €	- €	Fuel
Composting	39556	t dm	500	€/t dm	19.778.000 €	- €	- €	IC
	39556	t dm	140	€/t dm	- €	5.537.840 €	- €	OMC
	45065	t m	-27,918	€/t m	- €	- €	- 1.258.133 €	Sale compost
	112.663	t m	-21	€/t m	- €	- €	- 2.365.928 €	Saving Compost
			TOTAL		**19.778.000 €**	**5.642.134 €**	**- 3.624.061 €**	

Table F. 4 Final results of IC, OMC and Sales and Savings costs of Scenario 4

SCENARIO 4

Process	Consumption Generation	Units	Factor*	Units	IC (Total)	OMC [€/yr]	Sales/Saving/Costs [€/yr]	Concept
Centrifugation	1665260	kWh	-0,06022	€/kWh	- €	- €	- 100.282 €	Electricity
	383676	kg	-3	€/kg	- €	- €	- 1.151.028 €	Polymer
Anaerobic Digestion	31973	t dm	100	€/t dm	- €	3.197.300 €	- €	OMC
	525000	m3/dia	y=x*494*x^(-0,2)/precio$	€	16.571.378 €	- €	- €	IC
	15295792	kWh	-0,06022	€/kWh	- €	- €	- 921.113 €	Electricity
	16905876	kWh	-0,045	€/kWh	- €	- €	- 760.764 €	Steam
Centrifugation	18204	t dm	62,09	€/t dm	1.130.276 €	- €	- €	IC
	18204	t dm	45,67	€/t dm	- €	831.369 €	- €	OMC
Transport	67406	L	1	€/L	- €	- €	67.406 €	Fuel
Transport	8041	L	1	€/L	- €	- €	8.041 €	Fuel
Composting	25.787	t dm	500	€/t dm	12.893.353 €	- €	- €	IC
	25.787	t dm	140	€/t dm	- €	3.610.139 €	- €	OMC
	32.601	t m	-27,918	€/t m	- €	- €	- 910.141 €	Sale Compost
	81.501	t m	-21	€/t m	- €	- €	- 1.711.528 €	Saving Compost
			TOTAL		**30.595.007 €**	**7.638.808 €**	**- 5.479.409 €**	

G. Results of financial assessment

Table G. 1 Financial results of Scenario 1

Scenario 1	**€/yr**		**€/Kg Prec/yr**
IC	2.862.798 €		4,51 €
OMC Annual	14.610.001 €		23,01 €
Sales/Savings Annual	- 40.788.429 €		- 64,24 €
Precovered Annual	634947	Kg	
Lifetime	20	years	
Balance	- 23.315.629 €		- 36,72 €

Table G. 2 Financial results of Scenario 2

Scenario 2	**€/yr**		**€/Kg Prec/yr**
IC	3.014.455 €		4,34 €
OMC Annual	16.113.006 €		23,22 €
Sales/Savings Annual	- 49.710.164 €		- 71,65 €
Precovered Annual	693798	Kg	
Lifetime	20	years	
Balance	- 30.582.703 €		- 44,08 €

Table G. 3 Financial results of Scenario 3

Scenario 3	**€/yr**		**€/Kg Prec/yr**
IC	988.900 €		1,38 €
OMC Annual	5.642.134 €		7,89 €
Sales/Savings Annual	- 3.624.061 €		- 5,07 €
Precovered Annual	715000	Kg	
Lifetime	20	years	
Balance	3.006.973 €		4,21 €

Table G. 4 Financial results of Scenario 4

Scenario 4	**€/yr**		**€/Kg Prec/yr**
IC	1.529.750 €		2,34 €
OMC Annual	7.638.808 €		11,67 €
Sales/Savings Annual	- 5.479.409 €		- 8,37 €
Precovered Annual	654585	Kg	
Lifetime	20	years	
Balance	3.689.149 €		5,64 €