



Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies

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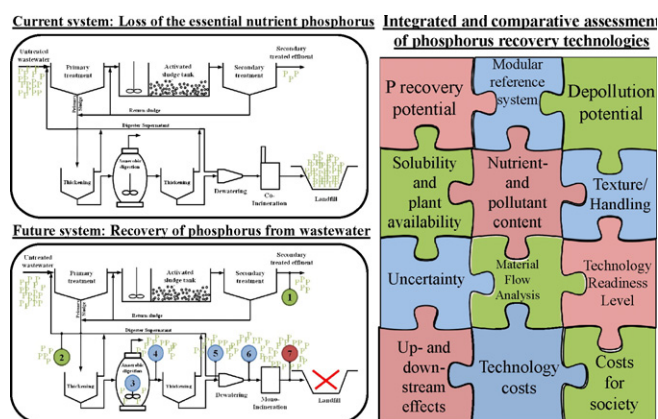
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HIGHLIGHTS

- Wastewater P can be recovered, but an integrated technology assessment is missing.
- Various methods and parameters are chosen to deliver an holistic picture.
- This assessment comprises technological, environmental and economic criteria.
- Sludge ash combines most promising P source and promising recovery technologies.
- Technologies show significant tradeoff between recovery rate, depollution and cost.

GRAPHICAL ABSTRACT



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ABSTRACT

Phosphorus (P) is an essential and limited resource. Municipal wastewater is a promising source of P via reuse and could be used to replace P derived from phosphate rocks. The agricultural use of sewage sludge is restricted by legislation or is not practiced in several European countries due to environmental risks posed by organic micropollutants and pathogens. Several technologies have been developed in recent years to recover wastewater P. However, these technologies target different P-containing flows in wastewater treatment plants (effluent, digester supernatant, sewage sludge, and sewage sludge ash), use diverse engineering approaches and differ greatly with respect to P recycling rate, potential of removing or destroying pollutants, product quality, environmental impact and cost. This work compares 19 relevant P recovery technologies by considering their relationships with existing wastewater and sludge treatment systems. A combination of different methods, such as material flow analysis, damage units, reference soil method, annuity method, integrated cost calculation and a literature study on solubility, fertilizing effects and handling of recovered materials, is used to evaluate the different technologies with respect to technical, ecological and economic aspects. With regard to the manifold origins of data an uncertainty concept considering validity of data sources is applied. This analysis revealed that recovery from flows with dissolved P produces clean and plant-available materials. These techniques may even be beneficial from economic and technical perspectives under specific circumstances. However, the recovery rates (a maximum of 25%) relative to the wastewater treatment plant influent are relatively low. The approaches that recover

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P from sewage sludge apply complex technologies and generally achieve effective removal of heavy metals at moderate recovery rates (~40–50% relative to the WWTP input) and comparatively high costs. Sewage sludge ash is the most promising P source, with recovery rates of 60–90% relative to the wastewater P. The costs highly depend on the purity requirements of the recycled products but can be kept comparatively low, especially if synergies with existing industrial processes are exploited.

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1. Introduction

Phosphorus (P) is an essential nutrient in the agricultural sector (fertilizer and feed). Phosphate rock (PR) is the raw material for mineral P fertilizer production and feed production and is classified as a critical raw material by the European Commission (EC, 2014). Due to population growth and changes in diet as a result of rising living standards in emerging and developing countries, the agricultural demand for P and consequently its criticality will increase (Reijnders, 2014; Van Vuuren et al., 2010). Furthermore, countries lacking P deposits are entirely dependent on imports and are therefore vulnerable to market fluctuations in fertilizer and mineral P prices (World Bank, 2016). These challenges have been discussed intensely on scientific and various political levels during the last years. One of many measures for reducing dependency is the recovery of P from obviously available but currently often unexploited national P sources, e.g., municipal and industrial wastewater, meat and bone meal (MBM) and other organic wastes (Scholz et al., 2014). This work focuses on technologies designed to recover P from municipal wastewater, sewage sludge (SS), and sewage sludge ash (SSA). The national P budgets in Central Europe show that municipal wastewater contains a P load that could theoretically replace 40 to 50% of the annually applied mineral P fertilizer in agriculture (Zoboli et al., 2015; Egle et al., 2014a; Gethke-Albinus, 2012; Binder et al., 2009). Due to potential environmental and health risks (heavy metals (HMs), organic micropollutants (OMs) and pathogens), acceptance of direct sludge applications and thus direct P recovery is low or decreasing in several European countries (Ott and Rechberger, 2012). With the current alternative sludge treatment methods, such as co-incineration in the cement industry, caloric power plants and waste incinerators, P is irretrievably lost.

Consequently, numerous new technological approaches have been developed and in some cases implemented at full scale in recent years to recover wastewater P at different access points in wastewater treatment plants (Fig. 1). Additionally, the existing P industries have shown interest and the ability to integrate SSA or recovered P materials, such as magnesium-ammonium-phosphate (MAP), into their processes to replace raw phosphate ore and produce marketable products, such as

mineral fertilizers, animal feed, phosphoric acid, and even P in its pure form (P_4). In this work, the term “recovered material” is used for P-containing outputs from the recovery processes, as most of these outputs are not yet classified and marketable products.

Considering more than 50 known P recovery approaches is already difficult for (political) decision makers, but comparing them regarding nutrient recovery potential, removal and destruction of potential hazardous substances and assessing the quality of the recovered P-rich materials is even harder. Possible positive or negative effects on the treatment of wastewater are often neglected. Effects on the environment, such as resource demand, wastes that require additional treatment and gaseous emissions, are displayed insufficiently. Furthermore, the realistic and comprehensible costs of the technologies for a society can only be calculated with a reliable and robust database and an appropriate reference system.

The aim of this work is first to develop an appropriate methodological approach for a comparative and integrated technical, environmental and economic assessment of technologies to recover P from different wastewater-related streams. The European Programme P-Rex aimed to achieve similar objectives (P-Rex, 2015). A significant novelty of this study compared to others is the assessment of the technologies within a defined reference system. This allows a comparative assessment along the entire process chain, including the entering wastewater, the treatment plant, thermal sludge treatment, final disposal of resulting waste streams, and the application of the recovered P-rich materials in agriculture or industrial processes. The core of this work is a detailed material flow analysis of P and selected heavy metals to track the paths of P and pollutants from the wastewater treatment plant (WWTP) influent to their final destination (e.g., recovered P material, waste, atmosphere or water bodies). A prerequisite for any meaningful assessment is knowledge of the technical principles and a good resource demand database and a complete substance flow analysis. Fundamental data on the technological background, detailed material flow models, input and output data on resource- and energy demand, recovered material and occurring wastes are provided in Egle et al. (2014b, c), Egle et al. (2015) and P-Rex (2015) and are summarized in Table A 7, A 8, A 9.

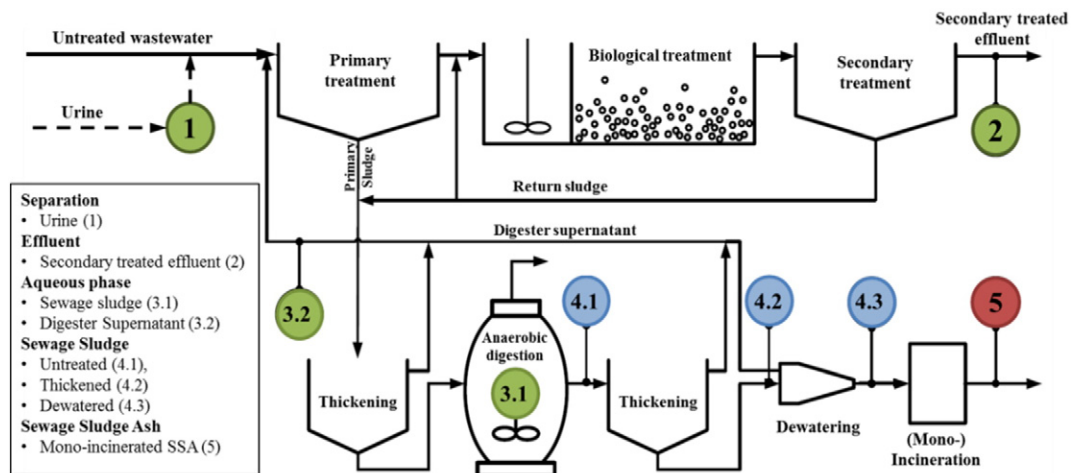


Fig. 1. Various possible access points for P recovery approaches during wastewater and sewage sludge treatment or before/after incineration (Montag, 2008; modified sketch)

Nineteen different approaches, covering the broad field of P recovery technologies, have been selected to apply the developed method (Table 1). The selection criteria for the technologies were access to information and data and the readiness level (full- and pilot-scale implementations were preferable, but unique recovery processes with low technology readiness levels were included to cover a wide range of available technologies). As the P recovery sector is a quite young and dynamic market, some promising technologies could be missing in this selection due to insufficient data to perform this assessment, e.g., the recovery of P as MAP from digester supernatant (**STRUVIA®** (Mêlé et al., 2014), **REPHOS®** (Lebek and Lohmar, 2013), and **PHOSPAQ®** (Abma et al., 2010)), the recovery of phosphoric acid from SSA (**TetraPhos®**; Remondis, 2015), or SS leaching with CO₂ instead of mineral acids (**Budenheim** carbonic acid process; Stössel, 2013). However, the selected technologies within this work cover most of the technical principles of those that are not considered. The methodology in this work can be applied to these technologies and to newly developed technologies as soon as reliable data are available. Due to the complexity, the methodology and results of a more detailed environmental assessment, including gaseous emissions and cumulative energy demand, is an integral part of a subsequent paper in progress.

2. Materials and methods

Technical principles of P recovery technologies have been frequently published; however, the required information and data to perform an integrated technology assessment is often missing. This work builds upon the work of Pinnekamp et al. (2011), Egle et al. (2015) and P-Rex® (2015), in which the fundamental technological background, detailed material flow models and resource- as well as energy demand were brought together. To achieve a meaningful and robust technology

assessment, an extensive review of the literature was performed, technology developers were contacted, recovery plants were visited and laboratory trials were performed to validate the data. The required information and data for this work are subdivided into the following sections: (1) resource demand (e.g., chemicals and energy demand), (2) substance flow data on P, (3) substance flow data on HM, (4) nutrient content, (5) heavy metal pollutant contents in the recovered materials, (6) organic micropollutant contents in the recovered materials, (7) solubility and plant availability, (8) investment cost (capital costs), (9) operating costs, and (10) revenues and savings. Table A 5 and 6 show the origin and quality of the data for different sectors of the investigated technologies.

The information and data gathered originates from several sources, and some assessment criteria data are incomprehensible or not available. Depending on the source of the data, different uncertainties need to be considered. Therefore, a qualitative uncertainty concept (Section 2.5) is applied.

2.1. Modular reference system

For a robust comparison of the technologies, the data on the processes of the P recovery technologies have to be transferred to a defined reference WWTP for an integrated comparison within a defined reference system. The development of a “modular system” with defined reference processes, including detailed sub-processes, forms the basis for this comparative assessment (Fig. 2). The introduction of sub-processes is essential, as recovery technologies address different P sources of a WWTP (e.g., digester supernatant, untreated/treated SS). A reference WWTP with a pollution load of 100,000 population equivalents (PE) (equivalent to a P load of 65,700 kg yr⁻¹), P removal by iron dosing (alternatively, biological P (Bio-P) removal for P recovery from the aqueous phase), and sludge treatment processes, such as thickening

Table 1
Considered P recovery technologies from the aqueous phase (green: digester supernatant, dissolved P in anaerobically digested sludge and effluent), sewage sludge (blue) and sewage sludge ash (red). This color code for the different P recovery access points is applied throughout this paper.

aqueous phase	sewage sludge [SS]	sewage sludge ash [SSA]
REM-NUT®¹ [2; ion exchange, precipitation]	Gifhorn process⁷ [4.1; wet-chemical leaching]	AshDec® depollution¹² [5; thermo-chemical, ash depollution, Cl-source: e.g., MgCl ₂]
AirPrex®² [3.1; precipitation/crystallization]	Stuttgart process⁸ [4.1; wet-chemical leaching]	AshDec® Rhenania¹³ [5; thermo-chemical, Rhenaniaphosphat, Na ₂ SO ₄]
Ostara Pearl Reactor®³ [3.2; crystallization]	PHOXNAN⁹ [4.2; wet-oxidation]	PASCH¹⁴ [5; acidic wet-chemical, leaching]
DHV Crystalactor®⁴ [3.2; crystallization]	Aqua Reci®¹⁰ [4.2; super critical water oxidation]	LEACHPHOS®¹⁵ [5; acidic wet-chemical, leaching]
P-RoC®⁵ [3.2; crystallization]	MEPHREC®¹¹ [4.3; metallurgic melt-gassing]	EcoPhos®^{16*} [5; acidic wet-chemical, leaching, P-acid production]
PRISA⁶ [3.2; precipitation/crystallization]		RecoPhos®¹⁷ [5; acidic wet-chemical, extraction]
		Fertilizer Industry^{18*} [5; acidic wet-chemical, extraction]
		Thermphos (P₄)^{19*,**} [5; thermo-electrical]

¹Liberi et al. (2001), ²Heinzmann (2009), ³Adnan (2002), ⁴Britton et al. (2008), ⁵Berg et al. (2007), ⁶Montag (2008), ⁷Esemen (2013), ⁸Weideler et al. (2005), ⁹Blöcher et al. (2012), ¹⁰Stenmark (2003), ¹¹Scheidig et al. (2013), ¹²Nowak et al. (2011a), ¹³Hermann (2014), ¹⁴Montag et al. (2011), ¹⁵Morf (2012), ¹⁶DeRuiter (2014), ¹⁷Weigand et al. (2013), ¹⁸Ten Wolde (2013), ¹⁹Schipper et al. (2004); *integration of SSA as secondary raw materials to substitute raw phosphate rock, **Thermphos, the only P₄-producer in Europe went bankruptcy in 2012 and is therefore actually no relevant solution for Europe.

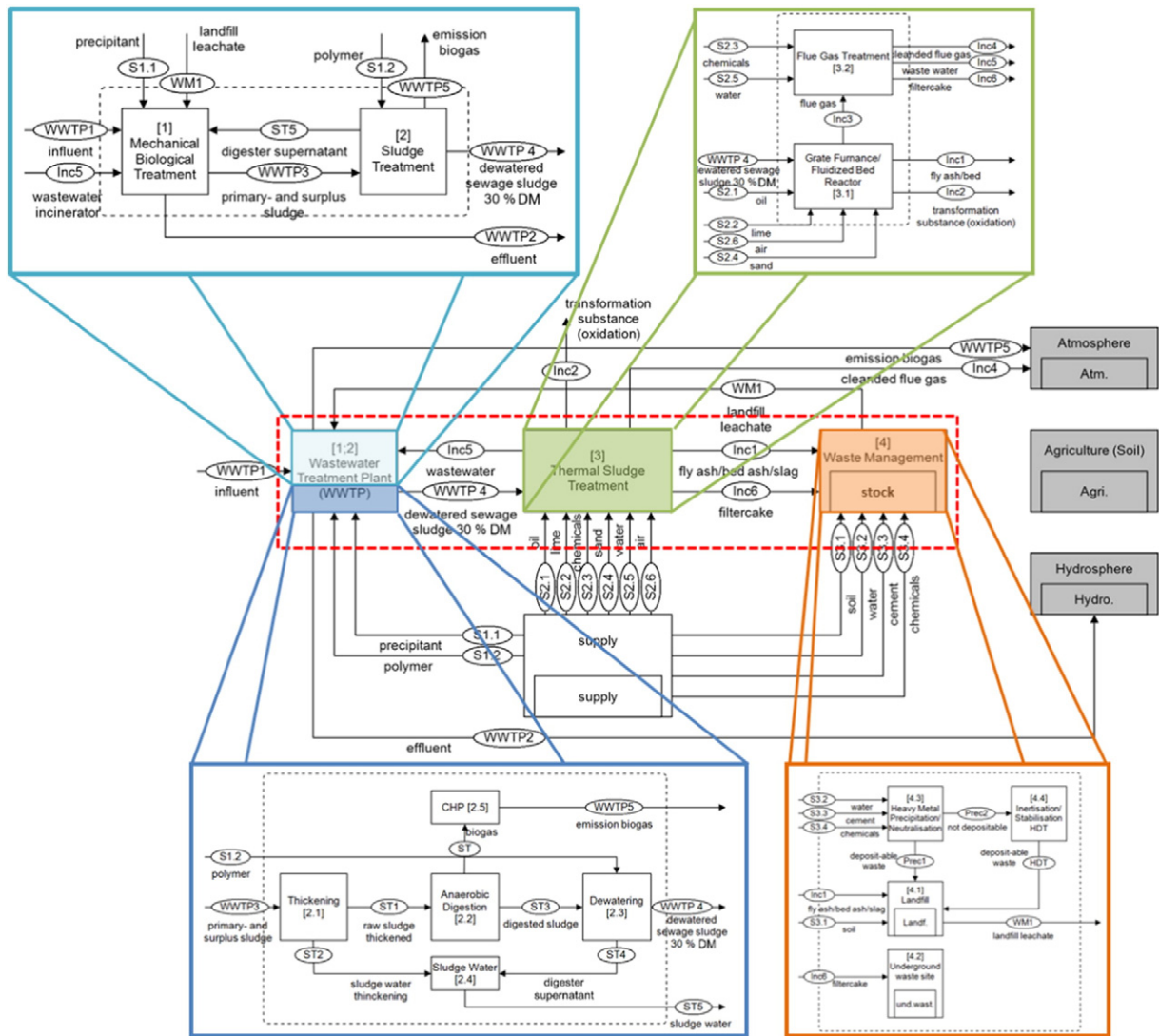


Fig. 2. Process scheme for the reference substance flow model (STAN-model) with sub-processes for WWTP (blue), thermal sludge treatment (green), waste management (orange), a supply process (red line: system boundaries), and the final processes atmospheres, agriculture (soil) and hydrosphere.

(5% DM), anaerobic digestion, dewatering with polymers (30% DM) and co-incineration of sewage sludge (e.g., waste incineration plant or cement industry) have been chosen. These WWTP conditions were chosen because P recovery from combined collected and untreated wastewater is not possible due to its complex composition. Due to the transfer of P from wastewater to sewage sludge (up-concentration) by biological or chemical P removal, which is a typical cleaning step of WWTPs in Central European landlocked countries with sensitive receiving water bodies, P recovery is possible. Detailed WWTP characteristics (e.g., wastewater composition, mass flows, transfer coefficients for P and the selected pollutants) are given in Table A 1 and 2. All assumptions are made in order to have a reference system typical for the Central European situation. Additionally, sensitivity analyses have been performed to estimate how the size of the WWTP impacts the overall results, especially with respect to cost.

As acceptance of direct agricultural SS application is decreasing, especially in Central European countries, thermal sludge treatment, and in particular co-incineration of SS, was chosen as the reference sludge treatment process. The selected reference thermal sludge treatment process is a grate furnace (output: slag), and the resulting flue gas is

treated. The resulting outputs are wastewater, filter cake, and treated flue gas. In case of future P recovery from the residues of the thermal processes, mixing with combustibles that are low in P, rich in ash, and rich in heavy metals needs to be avoided (e.g., mono-incineration or co-incineration with selected secondary fuels). The selected reference incineration system for mono-incineration is a fluidized bed reactor creating fine and powdery ash (fly ash). For simplification, it is assumed that the resource demand, flue gas treatment, and transfer of P and heavy metals are equal for mono- and co-incineration systems (Table A 3; Table A 4).

For the waste management system, an immobilization/stabilization process is integrated for non-directly disposable waste occurring from P recovery processes. Disposable waste is either landfilled or transported to an underground waste site (e.g., filter cake from flue gas treatment).

2.2. P recovery potential and pollutant removal

The methodology of material flow analysis (MFA; Brunner and Rechberger, 2004) is applied to track the path of P and the selected

heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn) from the source (WWTP input) to the final recovered material, wastes or other emissions (output). In the MFA, input and output flows, possible stocks and changes in stocks are balanced in the defined system for a defined period of one year. The goal is the identification of transfer coefficients for the selected processes (Table A 2). MFA is the appropriate method, especially with respect to P recovery and depollution potential. Additionally, direct emissions to the atmosphere, agricultural soil, and water bodies can be illustrated (Fig. 3). Due to substance transformations, this method cannot be applied to organic micropollutants (OMs) and pathogens. Therefore, the path of OMs and pathogens is assessed by the comparison of the load in the reference sewage sludge and the load in the recovered material, if data are available. The considered OMs are adsorbable organically bound halogens (AOX), polycyclic aromatic hydrocarbons (PAH) and dioxins and furans (PCDD/F). For P and HMs, the outcome is a percentage distribution from the WWTP influent to the terminal receivers, including soil (agriculture), waste management, atmosphere and hydrosphere.

Fig. 4 shows the methodology used to assess P recovery and depollution potential for a given technology (Steps 1 and 2) and within the whole process chain (Steps 1–4). Step 1 and 2 is the creation of the MFA for a recovery technology (example in Fig. 4: wet-chemical leaching approach from sewage sludge ash - PASCH). For this example the elements P (Step 1) and Cd (Step 2) are displayed. Step 3 is the integration of the recovery process into the defined reference system (the example of P is displayed). For this recovery technology the process “incineration” has to be changed to “mono-incineration”. Then the “mono-incineration” output flow “sewage sludge ash” is input to the material flow model of PASCH. Resource demand for the process “recovery approach PASCH” and the process “waste management” is provided by the process “supply”. The P-rich PASCH output “calcium phosphate” is an input to the process “agriculture soil”. Occurring solid waste flows of the recovery process need proper treatment and are input into the process “waste management”. The flow “neutralised process water” from this technology is a backflow to the process “WWTP”. Result (step 4 in Fig. 4) is a percentage share distribution of P and selected heavy metals from the influent of the reference WWTP to the atmosphere, hydrosphere, agriculture (soil) or the waste management sector (e.g., landfill or underground deposit).

2.3. Characterization of the recovered materials/products

The characteristics of recovered materials or products, in particular with regard to nutrient and pollutant content, plant availability and handling, is essential because agriculture and industry demand products with certain specifications. However, the recovered materials and products vary significantly in terms of these criteria.

2.3.1. Nutrient content, solubility and plant availability

To assess the recovered material with regard to nutrient content, solubility and plant availability, an extensive literature research was conducted. The literature sources are presented in the Appendix (Table A 5 and 6). As the recovered materials may be suitable for agricultural use, their macro-nutrient contents (P, N, Ca, and Mg) are presented in Fig. 9. In addition to the nutrient content, the plant availability of P is crucial. State of the art extraction tests (e.g., water, citric acid, neural/alkaline ammonium citrate, mineral acids) for mineral fertilizers are critically discussed with respect to their suitability for predicting the availability of newly recovered P materials for plants (Weinfurter, 2011). Therefore, results from pot or field trials are more meaningful. If data are available, the plant uptake or fertilizing efficiency of a recovered material was assessed in relation to the efficiency of a commercial Single Superphosphate fertilizer (relative fertilizer efficiency, RFE). If there was a lack of data on certain materials, data from a similar type of material was used. For recovered products with direct industrial applications, such as phosphoric acid or P_4 , a qualitative assessment with regard to their suitability for industrial use was performed.

2.3.2. Pollutant content

To apply a recovered product, the most important criteria with regard to pollutant content are the limit values of the applicable national fertilizer ordinances (HM, OM, and microbiological-hygienic parameters). This is the prerequisite for direct use of recovered products as fertilizers. Thus, as a first step, the recovered material is compared to Austrian limit values for mineral P fertilizers. However, even in cases where the limit values are met, different recovered materials exhibit distinct differences in their pollutant contents. To assess the purity and ensure the comparability of these recovered materials with regard to heavy metals, two methods – damage unit (DU) (Brans, 2008) and

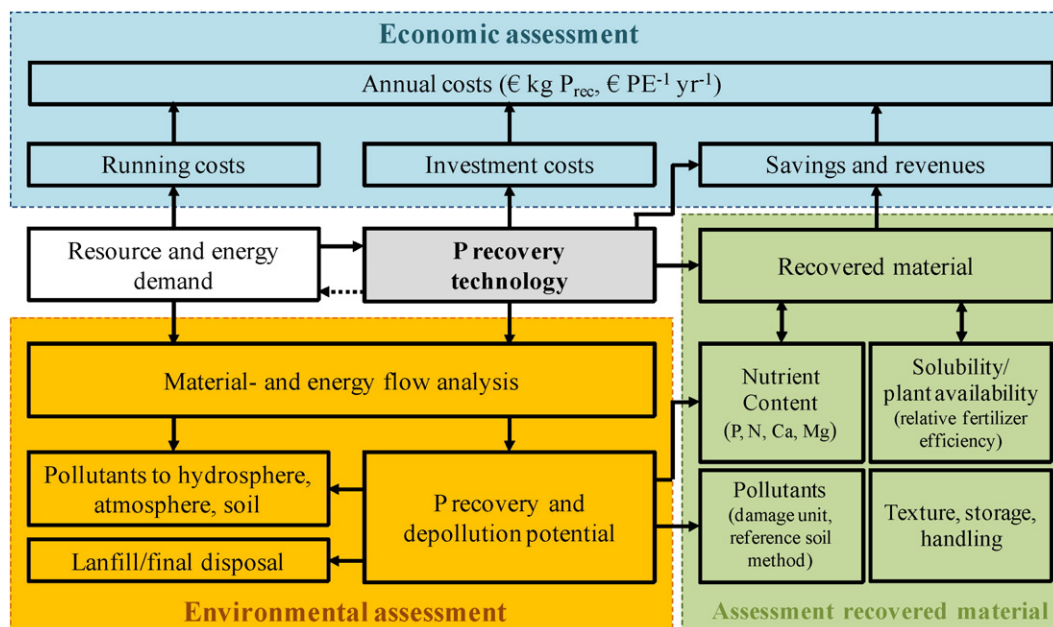


Fig. 3. Applied methods to assess the selected P recovery technologies with regard to environmental and economic aspects and to assess the quality of the recovered materials.

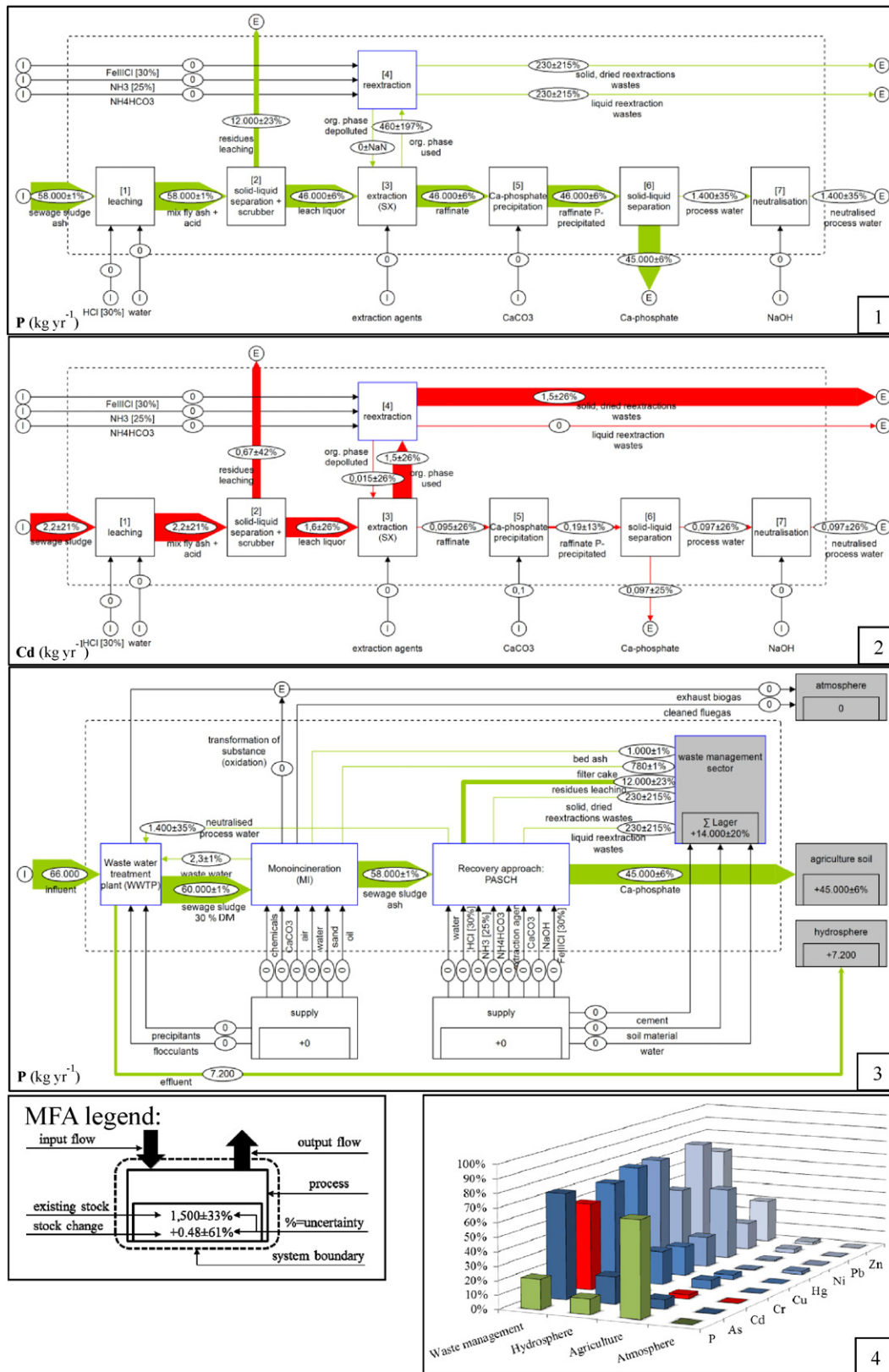


Fig. 4. MFA methodology applied to a leaching technology to recover P from SSA for P (1) and Cd (2), integration of the recovery process P into the reference model (3) and final percentage distribution of P and heavy metals to the receiving processes waste management, hydrosphere, agriculture and atmosphere (4).

reference soil method (RSM) – are applied to compare the recovery products with respect to their heavy metal contents. The heavy metals As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn are considered here.

The principle of the DU method is to express the pollution load as a harmfulness coefficient. A DU value is calculated by taking into account a certain limit value for heavy metals (e.g., compost class A+, Compost

Regulation Austrian, 2000) and calculating the quotient by dividing each heavy metal content of a final product by the defined limit value. The quotients are summed up and are related to the P content of the product (Formula 1; example see Table 2). The result is a dimensionless value (DU_p). Low DU_p values correspond to low pollutant contents.

$$C_{DUP} = \frac{\sum_{i=1}^n \frac{C_i}{C_i^{\text{reference}}}}{P \text{ concentration}} \quad (1)$$

C_{DUP} : Concentration of the damage unit related to the P content; C_i = Concentration of a heavy metal in the recovered material; $C_i^{\text{reference}}$: Concentration of a heavy metal in the reference material (e.g., compost class A +)

Formula 1. Calculation of the damage unit.

The reference soil method calculates the maximum number of years of application of a recovered material to a defined reference soil (1 ha, closed system, 20 cm soil depth, with defined heavy metal content; Smidt, 2010, Klik, 2001) until a tolerable or critical heavy metal concentration is reached. The reference soil is considered a closed system (e.g., no output via leaching). The annual applied P load is 40 kg P ha⁻¹. This method considers two factors: 1) the relevance of a possible harmful effect (lower tolerable load means higher priority) and 2) the heavy metal content related to the relevant nutrient (1 kg of P; DU_p). A commercial mineral fertilizer (SSP with 88 g P kg DM⁻¹), a reference sewage sludge and a reference SSA with defined heavy metal contents are given as references. For organic micropollutants and pathogens in the output material of the recovery processes, the dataset is not as complete as for HM, and data are missing for some materials (Table A 5). If data are available, a qualitative assessment regarding the removal of OM and pathogens is carried out (very good depollution (+), moderate depollution (o), no depollution (-).

2.3.3. Texture and handling

For agriculture applications, the quality criteria for the recovered material are high. Important aspects include storage properties (e.g., no dust, no humidity, and no reactivity), a certain grain size (2–5 mm) and strong enough grains for use in modern application equipment (spreaders). For categorization, the recovered materials are classified as “directly applicable” if they already possess a certain grain size (2–5 mm) or are coarse grained. Otherwise, the recovered materials are classified as “not directly applicable” if their texture is crystalline/powdery and therefore need further treatment steps, such as classification or granulation. If P is recovered by industrial processes in the form of a subsequently marketable product, the classification is “marketable”.

2.4. Cost calculation

Economic calculations are based on the settings of the reference WWTP (100,000 population equivalents (PE)) for recovery from supernatant and sewage sludge, as these technologies have to be implemented directly at the WWTP where the sewage sludge is produced. Recovery technologies can also be applied at larger than 100,000 PE WWTPs, and investment costs do not increase linearly with the plant

Table 2
Calculation method of the damage unit related to the P content (DU_p) for a commercial Single Superphosphate (SSP) heavy metal content based on Kratz et al. (2016).

	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Compost Class A + (mg kg DM ⁻¹)	0.7	70	70	0.4	25	45	200
SSP (mg kg DM ⁻¹)	31	89	20	0.03	24	64	161
Quotient DU	14.9	1.3	0.3	0.06	1.0	1.4	0.8
\sum DU kg DM ⁻¹	19.7						
P (g kg DM ⁻¹)	88						
DU g P ⁻¹ (DU_p)	0.22						

size (economy of scale). Therefore, cost calculations are also performed for a WWTP with 500,000 PE to evaluate the sensitivity of the cost calculations to the plant size. To recover P from SSA, transport to and treatment at centralized plants are feasible. As centralized plants with a high throughput are required (otherwise these plants are not economic), the economic calculations for the recovery of P from SSA are based on a capacity of 15,000 Mg of SSA per year, which corresponds to ~1.75 million PE⁻¹ yr⁻¹. Transport of sewage sludge from a WWTP to a centralized incineration and recovery plant is considered.

2.4.1. Annual costs for recovery technologies

Annual costs consist of capital and operating costs. Capital costs are calculated with the annuity method, whereby the investment costs are multiplied by an annuity factor (AF; Formula 2). The data on investment costs originate from the literature, feasibility studies or direct contact with operators of pilot- or commercial-scale plants (Table A 11). The calculation of the annuity factor includes the rate of interest (5% if no information is given by the plant operators) and the expected typical depreciation times of the plant components. The expected useful life is, unless otherwise known, 15 years for construction engineering.

$$AF = \frac{i * (1 + i)^n}{(1 + i)^n - 1} \quad (2)$$

i = rate of interest, n = expected useful life

Formula 2: Calculation of the annuity factor.

Detailed Material and Energy Flow Analysis is used to calculate the operating costs by multiplying the resource demand (Table A 7, 8, 9) by its market price (Table A 10). The details on the origin of the data (and therefore their uncertainty) are considered (Section 2.5.1). The operating costs include maintenance costs (unless otherwise known, 1% of the investment costs), personnel costs (50,000 € per man-year) and the costs of the disposal of the resulting wastes.

2.4.2. Savings and revenues

The considered savings include, for example, reduced disposal costs due to improved dewatering (2–5 percentage points; Ewert, 2009) of the sludge (€ per Mg of sludge reduced) or reduced nutrient back-flow of P and NH₄ in the digester supernatant. Reduced P back-flow corresponds to a lower demand of iron precipitants, and a reduced NH₄ back-flow results in a lower energy demand for aeration (Table A 7).

To take revenues for recovered materials into account, large uncertainties have to be considered. Currently, many different P-rich materials are produced, but there is no existing market. Therefore, the value of a recovered material is calculated by multiplying the nutrient components (P, N, Mg, and Ca) by their common market value (P: 1.7 € kg⁻¹, N: 1.1 € kg⁻¹, Mg: 0.3 € kg⁻¹, and Ca: 0.1 € kg⁻¹) (World Bank, 2016). This is a weak point of this method, as it assumes that the bioavailability of the total P content is the same for all recovered materials. However, this is not the case (Section 3.3.1). To consider the bioavailability from an economic perspective is not possible as the recovered materials are so varied. Unlike a water-soluble mineral fertilizer, some of the materials are not immediately availability to plants, but their yield is similar. Additionally, plants have the ability to take up even minimally soluble nutrients if there is a deficiency of easily available nutrients. Therefore, the total recovered P load is considered in the revenue calculations. The uncertainties related to these assumptions are considered in a sensitivity analysis (see Section 2.5.2). In addition to the revenues for nutrients, the revenues for producing energy (heat and electricity) during the recovery process are credited in case that they are significant (Table A 8).

2.4.3. Integrated cost calculation

In addition to the cost calculation for the operation of a recovery technology, the costs for the whole process chain are calculated, including costs related to the required changes in the reference system

(e.g., type of incineration, changes in the treatment schema, and changes in the amounts and routes of waste disposal). The objective is to capture all costs as well as savings, e.g., reduction of flocking agents, reduced energy demand due to NH_4 removal, improved dewatering of the sludge or revenues from selling the recovered material or produced energy, in connection with the implementation of a P recovery technology from a macroeconomic perspective. These calculations are based on the following reference processes: WWTP processes (Haslinger et al., 2015), thermal sludge treatment (co-incineration/mono-incineration; DWA, 2010), disposal of resulting wastes, and P recovery and transportation.

2.5. Uncertainty concept

2.5.1. Uncertainty in the data on technologies

As the data from the literature review originate from many different sources, the data quality differs strongly. Therefore, the uncertainty in the data is assessed qualitatively depending on the source. In this work, the uncertainty is categorized as low (+), moderate (o), high (-) and very high (-) (Table 3). If no data are available for certain technologies, missing data can be generated based on knowledge of the basic chemical principles (e.g., magnesium demand for precipitation of dissolved P) or knowledge of other similar technologies. The uncertainty concept is also applied to these alternatively gathered data (for examples, see Table 3). In addition to the uncertainty in the data, one particular challenge is the evaluation of possible future savings and revenues. This is a crucial point in the integrated technology assessment and will be discussed in the following section (Section 2.5.2.).

2.5.2. Sensitivity of the cost calculations

In a sensitivity analysis of the cost calculations, the impacts of the considered WWTP size as well as the impacts of the expected savings and revenues on the costs of implementing a P recovery technology into a given waste water and sludge disposal system are analyzed. This task is challenging because, for example, no market for secondary raw materials exists at present, and revenues from product sales can therefore vary significantly. Furthermore, P recovery technologies may

Table 3

Assessment of the uncertainty in the data with respect to their origin and the uncertainty associated with missing data for selected examples.

Data source and examples	Uncertainty
Doctoral and diploma theses and peer-reviewed papers.	Low (+)
Verifiable data from plant operators (e.g., data from feasibility studies).	
Personal information and plant visits.	
Chemical fundamentals (e.g., stoichiometric ratio Mg:P for P precipitation, dissolution rate of P and heavy metals at different pH).	
Reports in conference transcripts and conference presentations.	Moderate (o)
Unverifiable data from plant operators (e.g., data from feasibility studies).	
No data on organic micropollutants or pathogens in recovered materials from SSA (assuming that organic micropollutants and pathogens are almost or totally destroyed during SS incineration).	
Calculation of the operating cost based on resource demand from laboratory or pilot scale trials.	
Non-scientific reports.	High (-)
Data from non-conference presentations.	
Contradictory data for a technology (e.g., different results for bio-availability of the recovered material).	
No data, only fundamental principles of the technology and consequently rough estimates based on data on other technologies.	
Determining the resource demand based on knowledge of the operational costs.	
No data and no estimates possible based on other technologies, as the technology, resource demand, or output material is unique.	Very high (--)
Estimating the investment costs and capital cost calculation for technologies at, for example, the laboratory stage.	

have beneficial effects on a WWTP, and energy may be recoverable with the simultaneous stabilization of the sludge. However, at the current state of development, it is difficult to predict whether these revenues and savings can be credited to the full extent. The following list details the key assumptions for the sensitivity cost calculation:

- Cost calculations are performed with no or maximum achievable revenues for the recovered material. Maximum revenues are calculated by the total recovered load of nutrients and their market price (Section 2.4.2).
- For technologies that recover the dissolved P from digester supernatant or digested sludge, the nutrient back-flow of P and N to the WWTP can be reduced. This results in a lower demand for iron precipitants and a lower aeration demand. No or maximum savings of precipitants and energy are considered. Savings due to the avoidance of unwanted struvite encrustations in pipes and pumps are not considered, as maintenance cost cannot be assessed for this reference WWTP.
- Additional benefits result from the treatment of sewage sludge. Certain treatment processes, such as aeration and leaching of the sludge with acids, will lead to a better dewaterability and therefore reduced sludge disposal costs. No or a maximum improvement of the dewaterability by two percentage points is considered.
- The reference WWTP is defined with a pollution load of 100,000 PE. Larger units can operate more economically by reduced investment costs due to the economy of scale. Therefore, cost calculations for the technologies recovering P from the aqueous phase or sewage sludge are performed for a WWTP with 100,000 PE and 500,000 PE. The exception is the **MEPHREC®** technology, as this process is designed for larger sludge quantities. Therefore, the best-case scenario cost calculation is carried out for a 1–1.8 million PE WWTP.
- Certain technologies are capable of recovering P from sewage sludge and recovering energy during simultaneous stabilization of the sludge. However, these technologies have only been implemented at the pilot scale and/or no further development has been observed. Therefore, a high degree of uncertainty is associated with the efficiency of the energy recovery and the form of the recovered energy (e.g., electricity, heat or combustible gas). A wide range of values is therefore expected for technologies with an oxidation or metallurgical process step. The cost calculations are performed by taking no revenues and the maximum revenues from the energy recovery into consideration.

Consequently, this sensitivity cost calculation yields a wide range of values between the absolute worst-case scenario (no revenues for the recovered material, no up-scaling, no consideration of other benefits) to the absolute best-case scenario (maximum revenues for the recovered material, up-scaling, full consideration of other benefits) (Section 3.4.2.2.). The variability is a good indicator with regard to the uncertainty of the data. A low fluctuation margin indicates robust data, and a forecast for the expected future economic costs for P recovery can be predicted with low uncertainties.

2.6. Technical maturity

In addition to all the above criteria, the practicability of a technology in its environment is also important. To estimate the technological maturity, the method of technology readiness levels (TRL) is applied (DIN, 2013). TRL is a method used to assess the stage of development of new technologies based on a systematic analysis. The scale ranges from 1 (basic principles observed) to 9 (actual system proven in operational environment) (Table A 12). In addition to the actual state of development, an outlook for the future potential of a technology is given. The outlook is a result of the different assessment parameters given in this work (educated guesses) and discussions with experts in this field of

research. As an example, a technology tested at the laboratory scale but with an outlook for a pilot plant is classified as TRL 4/5–6 (recent stage of development: 4, technology validated in lab; stage of development to be expected: 5, technology validated in relevant environment; 6, technology demonstrated in relevant environment). A technology that has been tested at the pilot scale but without visible development prospects is classified as TRL 5–6/- (-, no further development expected).

2.7. Functional unit

For a comparative assessment, all results are related to 1 kg P recovered ($\text{kg P}_{\text{rec}}^{-1}$). The costs and revenues are expressed in € per kg P recovered ($\text{€ kg P}_{\text{rec}}^{-1}$) or € per population equivalent and year ($\text{€ PE}^{-1} \text{ yr}^{-1}$). PE is a reference value for the pollution load in wastewater (1 PE = 120 g COD d^{-1} in the influent load to the WWTP; in Austria, approximately 2 PE of raw wastewater is produced per inhabitant, with 1 PE stemming directly from the population and 1 PE stemming from industrial sources). To consider the recovery potential of a technology and to compare these values with conventionally produced mineral fertilizers, the use of the functional unit $\text{kg P}_{\text{rec}}^{-1}$ is advantageous. The reference costs for P gained from raw phosphate rock (30% P_2O_5) and for a commercial Triple Superphosphate (46% P_2O_5) are $0.9 \pm 0.3 \text{ € kg P}^{-1}$ and $1.7 \pm 0.5 \text{ € kg P}^{-1}$, respectively (Time range: 2011–2015; World Bank, 2016). Nonetheless, for technologies that can generate a profit, the functional unit $\text{kg P}_{\text{rec}}^{-1}$ is not an appropriate indicator, as a higher recovery potential lowers the profit for 1 kg of P, which can distort the results. In this case, it is helpful to consider the results from both functional units.

3. Results

3.1. Reference sewage sludge and sewage sludge ash

With simultaneous P removal from wastewater, approximately 90% of P is transferred into the sewage sludge. Therefore, the recycling rate with a direct agricultural sewage sludge application is 90% with regard to WWTP influent. The HM transfer from wastewater to the sludge was considered at different rates depending on the considered HM (50–80%, Table A 2). Without a depollution step, all HM and OM are released to the environment when applying sewage sludge directly to agricultural fields (Fig. 6a).

Due to slight losses during incineration, the retrieval rate of P in SSA is 87% with respect to the wastewater input (Fig. 8). The retrieval rate of HM in the ash is 80–98%, except for Hg, which features a retrieval rate of approximately 5% (Table A 4). OMs are mostly destroyed at temperatures $> 850 \text{ °C}$. The formation of dioxins is not expected with a mono-incineration of the sewage sludge (Zeggel et al., 2015). However, if secondary chlorine-containing materials are co-incinerated to improve the calorific value, the formation and transfer of dioxins to the SSA has to be considered. The concentrations of P, HM and OM in the reference sewage sludge and SSA, which are the basis for the ongoing technology assessment, are presented in the following table (Table 4).

3.2. Recovery potential and heavy metal removal

Depending on the applied technology, i.e., slow crystallization (DHV Crystalactor®, Ostara®, P-RoC®) or instant precipitation (PRISA), up to 85–95% of the formerly dissolved P can be recovered from digester supernatant. The recovery rate related to the WWTP influent strongly depends on the type of P removal during wastewater treatment. The more P that is removed biologically (enhanced biological phosphorus removal, EBPR), the higher the redissolution rates during anaerobic sludge treatment, resulting in increased recovery rates. Therefore, WWTPs with mainly biological P removal processes are necessary, as the recovery rate has a direct impact on the economic efficiency. However, with 10–30% P recovery related to WWTP influent, the recovery

Table 4

P, heavy metal and organic micropollutant content of the reference sewage sludge and reference sewage sludge ash.

Element	Reference sewage sludge	Reference sewage sludge ash	Unit
P	39	84	g kg DM^{-1}
As	5.3	11.8	mg kg DM^{-1}
Cd	1.5	3.2	mg kg DM^{-1}
Cr	53.4	97.5	mg kg DM^{-1}
Cu	306	566	mg kg DM^{-1}
Hg	0.9	0.1	mg kg DM^{-1}
Ni	41	74.7	mg kg DM^{-1}
Pb	67	123.6	mg kg DM^{-1}
Zn	1,117	1,944	mg kg DM^{-1}
AOX	150	≤ 1	mg kg DM^{-1}
\sum PAH	7	≤ 1	mg kg DM^{-1}
\sum PCDD/F	3,300	≤ 1	mg kg DM^{-1}

potential is generally low. Heavy metals are present in only minor concentrations in digester supernatant; thus, the use of the resulting material as fertilizer would lead to low transfers of HM loads to agricultural soils (Fig. 5). Considering the secondary treated effluent, a recovery of up to 50% is possible, if no specific P removal is applied at the WWTP (Fig. 5).

To recover a greater extent of wastewater P (theoretically up to 90% of the WWTP influent) and to reduce the pollutant transfer to agricultural soils, technologies need to be implemented to process sewage sludge and SSA. In contrast to the aqueous phase, substantial concentrations of heavy metals are present in these two P-rich flows (see reference SS and SSA, Table 4). If depollution technologies are applied, the available technologies show clear differences with regard to P recovery and depollution potential. Wet-chemical leaching (Stuttgart, Gifhorn and Budenheim process), wet-oxidative (LOPROX) and SCWO approaches (Aqua Reci®) show very good depollution potential (up to 98% for all considered heavy metals) for sewage sludge. Therefore, the transfer of heavy metals to the recovered product and ultimately agriculture is low (Fig. 6b, c). The recovery potential of these technologies is 45–65% of the P in the sludge and 40–60% of the P in the WWTP influent. The P that is not recovered remains in the treated (acidified) sludge or other inorganic residuals, which have to be disposed of. The P content in these residuals is therefore irretrievably lost. For the metallurgic MEPHREC® approach, an inconsistent behavior of heavy metals and high uncertainties of the effectiveness of depollution can be observed during the recovery process. The P transfer from SS is up to 70%, relative to the content in SS, or 65%, relative to the WWTP influent (Fig. 6d).

The MFA results for P recovery from SSA differ significantly between the different technologies. Good depollution rates for some HMs and simultaneous high recovery rates of ~98% can be achieved with both AshDec® processes. Some heavy metals, such as Cd, Cu, Pb and Zn, can be reduced by up to 90%, whereas others remain in the SSA at high percentages (As, Cr and Ni) (Fig. 7a). However, the plant availability is critically discussed (Section 3.3.1). To improve the bioavailability, the chloride source can be replaced with sodium sulfate (AshDec® Rhenania). However, this substitution reduces the heavy metal removal (Fig. 7b). From the input SSA, 95% of the P can be recovered as phosphoric acid with the EcoPhos® process. Interfering ions are stepwise removed with selective ion exchangers (~99%) (Fig. 7c). Other wet-chemical leaching approaches show recovery rates of 70–80% relative to the ash input and 60–70% relative to the WWTP influent (PASCH and LEACHPHOS®). Due to the different dissolution properties of P and heavy metals at low pH values, the leaching step alone results in significant depollution with respect to Cr, Fe and Ni (70–90%), but little or no depollution is achieved with respect to Cd and Pb. With a specific depollution step (PASCH), recovery rates similar to LEACHPHOS® can be achieved but with significantly improved depollution with respect to Cd, Cu, Pb and Zn (Fig. 7d, e). The aim of the wet-chemical extraction approaches is the transformation of non-water-soluble P to water-

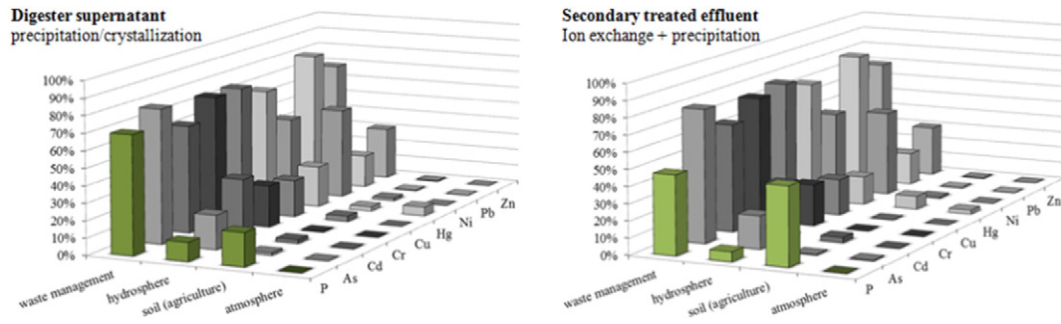


Fig. 5. Distribution (% of total) of P and heavy metals from WWTP influents to environmental compartments for technologies that recover P from the aqueous phase (dissolved P in the digested sludge, digester supernatant, and secondary treated effluent).

soluble compounds. Thus, 100% of the P in SSA is “recovered” with **RecoPhos®** and within the **Fertilizer Industry**. However, 100% of the heavy metal load in the SSA is incorporated into the final product (Fig. 7f). The industrial **Thermphos®** approach shows a similar recovery potential of ~95% (85% related to WWTP influent) by producing a pure P₄ applicable for multiple industrial purposes.

In Fig. 8, the P recovery potentials related to the WWTP influent are summarized. In terms of WWTP effluent without specific P removal during wastewater treatment, up to 50% of influent P can be recovered. For technologies recovering P from the digester supernatant, considerable recovery rates of 10 to a maximum of 25%, with the exception of the **DHV Crystalactor®** with recovery rates of up to 40%, are only achievable in WWTPs with enhanced biological phosphorus removal. However, the number of WWTPs with pure EBPR is limited in many European countries. Regarding the extensive use of wastewater P (~90% of WWTP influent), sewage sludge and consequently SSA need to be addressed. Although possessing great theoretical potential, the realistic recovery rates of technologies that recover P directly from sewage sludge are considerably lower. To achieve the highest recover rates, SSA shows the best preconditions. For leaching technologies (**PASCH**, **LEACHPHOS®**), the recovery potential related to the WWTP input is limited to ~65–70%. Distinctly better recovery rates are achievable with the **EcoPhos®** process (>80% relative to the WWTP input). In processes where SSA becomes a part of the final product (**AshDec®** technologies, **RecoPhos®**, **Fertilizer Industry**), the P recovery rate is in

the range of 85% relative to the WWTP input. The advantages of an SSA strategy are the independent location of an incinerator and an inert P-rich ash that allows the implementation of centralized and greater P recovery units (economy of scale, see Section 3.4.1).

3.3. Characteristics of the recovered materials

3.3.1. Nutrient content and plant availability

The recovered materials from **REM-NUT®**, **Ostara®**, **PRISA**, **Gifhorn** and **Stuttgart approaches**, and **LOPROX** are MAP ($MgNH_4PO_4 \cdot 6H_2O$) crystals. The P content of MAP is in the range of 10–12% (Fig. 9), and it shows almost the same plant uptake efficiency as commercial fertilizers (RFE: 100%) in acidic soils and partially in alkaline soils, although it is not soluble in water (Kratz and Schnug, 2009, Pérez, 2010, Kratz et al., 2010, Wilken et al., 2015). With regard to plant uptake within one or more growing periods, MAP also shows the same performance as commercial fertilizer (Römer, 2013). Calcium phosphate is produced by **DHV Crystalactor®**, **P-RoC®**, **Aqua Reci®**, **LEACHPHOS®**, and **PASCH**, and the P content is approximately 13–17% (Fig. 9). Compared to MAP, the plant availability of the recovered calcium phosphate from the different technologies is not consistent. The bioavailability of the recovered calcium phosphate materials is significantly lower in neutral and alkaline soils, although the calcium phosphate material is soluble in citric acid, similar to MAP (Richards and Johnston, 2001). Compared to commercial mineral fertilizer (SSP or TSP), the effectiveness is only

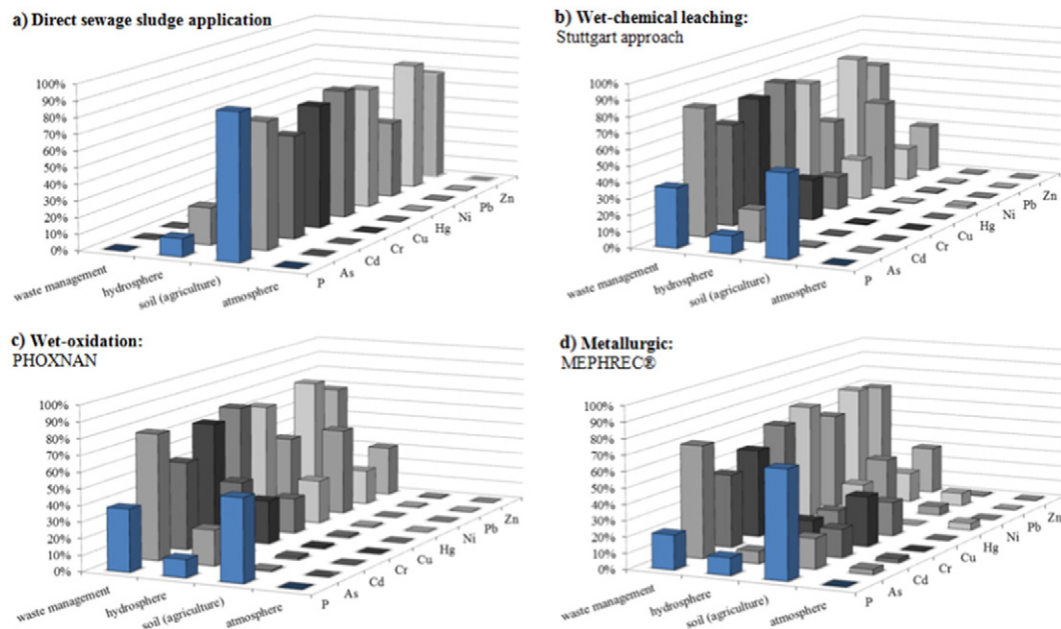


Fig. 6. Distribution (% of total) of P and heavy metals from WWTP influents to environmental compartments for technologies that recover P from sewage sludge.

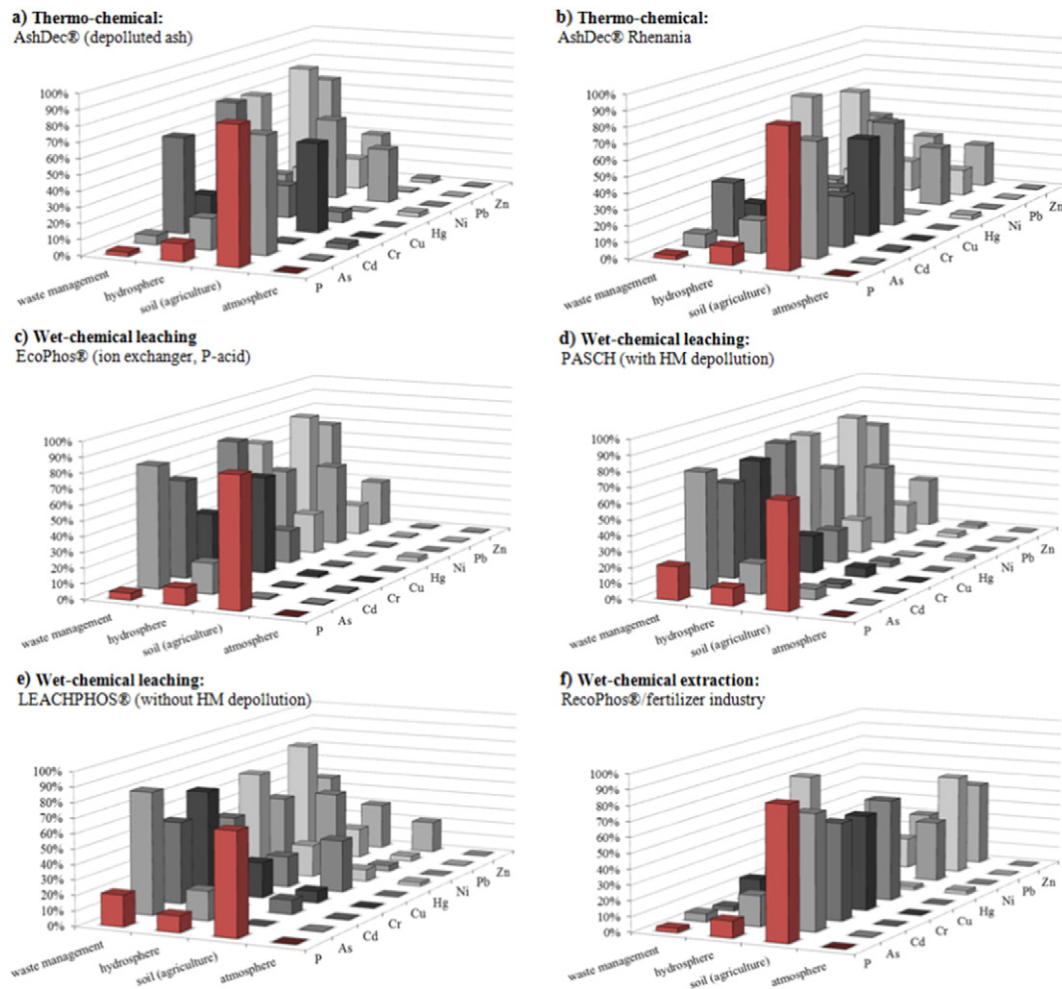


Fig. 7. Distribution (% of total) of P and heavy metals from WWTP influents to environmental compartments for technologies to recover P from sewage sludge ash.

moderate in acidic soils and generally poor in alkaline soils (**DHV Crystalactor®**, **P-RoC®**, **Aqua Recic®**, **PASCH**; [Weinfurter, 2011](#)). The calcium phosphate material recovered from the wet-chemical leaching process **LEACHPHOS®** shows good results in terms of solubility and good plant availability in both acidic and neutral soils (RFE: ~90%) ([Morf, 2013a](#)). The RFE of products from the metallurgic **MEPHREC®**

approach is 50–100% in neutral soils but low (0–25%) in an acidic soil ([Cabeza et al., 2011](#); [Wilken et al., 2015](#)).

In both raw phosphate rock (PR) and untreated SSA, P is not water-soluble and requires further acid treatment ([Krüger and Adam, 2014](#); [Wilken et al., 2015](#)). Untreated SSA exhibits differing fertilizer effects. [Wilken et al. \(2015\)](#) show fertilizing effects for untreated SSA; however,

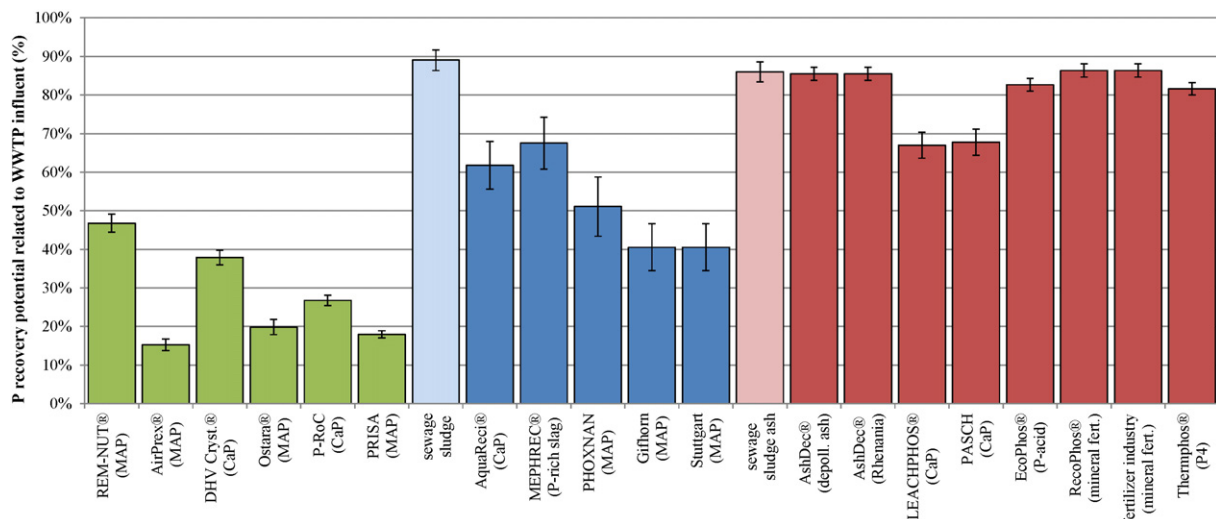


Fig. 8. Summary of P recovery potential (%) of recovery technologies relative to the WWTP influent.

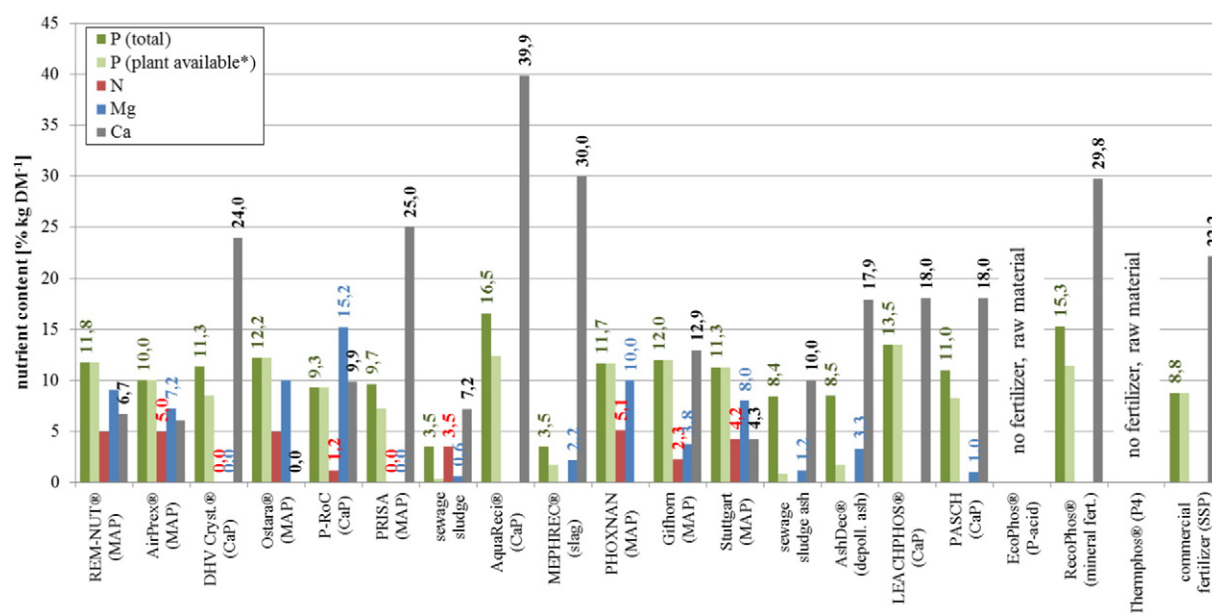


Fig. 9. Macronutrient contents (P, N, Mg, and Ca) of the recovered materials and a commercial fertilizer and the plant availability of the P in acidic and alkaline soils.

the RFE is <20% in neutral soils (pH: 7.1) and <50% in acidic soils (pH: 5.0).

In the materials recovered from SSA, e.g., the depolluted ash from **AshDec®**, a new mineral phase can be observed, possibly implying higher bioavailability of P (Mattenberger et al., 2008; Severin et al., 2013). Nanzer et al. (2014) report RFEs of 70–90% in acidic and neutral soils but only 4% on an alkaline soil. Nonetheless, Römer (2013) reports that the depolluted ash exhibits little improvement over the untreated SSA with regard to plant availability. Wilken et al. (2015) verify these findings in neutral soils but report improved availability in acidic soils (RFE: ~90%). By replacing the chlorine source (e.g., $MgCl_2$) with Na_2SO_4 , this thermo-chemical approach provides a partly depolluted ash (Section 3.3.2) with significantly improved solubility and plant availability in neutral soils (RFE: 75%) and consistently good plant availability in acidic soils (RFE: 75–90%; Hermann, 2014; Herzl et al., 2015).

The **RecoPhos®** process produces an approved fertilizer with 16.6% P (adding P acid to SSA), and results similar to those of commercial fertilizer have been reported. For this approach, however, it is unclear if the available P originates from the ash or from the added phosphoric acid, which is water-soluble. To use SSA as a secondary raw material in the **Fertilizer Industry**, non-water-soluble P of SSA is partially transformed into water-soluble compounds using sulfuric acid. The iron and aluminum contents, resulting from chemical P removal during wastewater treatment, and the ash/ H_2SO_4 ratio affect the conversion of non-water soluble P to water soluble P (water solubility: untreated ash: 0–1%; Fe-ash treated with acid: 40–55%; Al-ash treated with acid: 50–90%; Petzet and Cornel, 2011). Phosphoric acid (**EcoPhos®**) is fully plant available. As P acid, pure P_4 from the **Thermphos®** process is a universally applicable raw material in the fertilizer, food, feed, and chemical industries. Fig. 9 gives an overview of the macronutrient contents (P, N, Ca, and Mg) of the recovered materials with the ratio of actually plant available P in relation to the total P content (RFE).

3.3.2. Pollutant contents

3.3.2.1. Heavy metals. All the recovered materials exhibit significantly lower damage unit values relative to untreated sewage sludge, ash (SS: $DU_p = 0.5$, SSA: $DU_p = 0.35$) and even commercial fertilizer (Single Superphosphate, $DU_p = 0.23$) (Fig. 10). Due to the low evaporation temperature of mercury leading to the transfer of mercury to the flue

gas (>95%), SSA shows lower concentrations and consequently lower damage unit values compared to SS. Heavy metals are present in only minor concentrations in digester supernatants; thus, the recovered materials show very low DU_p (<0.02). A comparatively higher DU_p for the **PRISA** process results from the high Zn concentration in the recovered MAP material (Montag, 2008). Products from the oxidation and wet-chemical leaching technologies applied to digester supernatant (<0.03), even though sewage sludge contains greater pollutant contents. This is a result of the good pollutant elimination rate and the greater P recovery rate, as the damage unit is also based on the amount of recovered P. A DU_p in the range of 0.05 or less for materials derived from ashes is possible with thermo-chemical or the acidic wet-chemical leaching technologies with a specific HM removal step (**PASCH**, **EcoPhos®**). For the metallurgic **MEPHREC®** approach and technologies that recover P from SSA little or no depollution, the damage unit values are still less than those of a SSP. For the **RecoPhos®** approach, a low damage unit is the result of mixing SSA with phosphoric acid and the consequent enrichment of P. The DU_p for SSA integrated into the **Fertilizer Industry** without a HM removal step and extraction with sulfuric acid is the same as for SSA (DU_p : 0.35).

Due to the good depollution rates, the recovered materials can be applied more often than a SSP (except **MEPHREC®**) and SS/SSA until a limiting heavy metal concentration in the soil is reached (Fig. 11). For the SSP, Cd, a heavy metal with great damage potential, limits the application to 1,450 a. For SS and SSA, the limiting heavy metals are Cu and Zn, respectively, but Cd is present in both at only micronutrient levels. The DU_p values indicate that most materials based on P recovered from SSA exhibit higher pollution potentials than those derived from most other P sources, and the RSM shows similar results. For most of the recovered products derived from SS, Cu and Zn are the limiting elements, contrary to SSA products, where Ni is the limiting element for two technologies (**DHV Crystalactor®** and **AshDec® depollution**). Fig. 11 presents the application factor for the recovered material compared to SSP, for which Cd is the limiting element. This factor shows how many times more the recovered material can be applied compared to a SSP until the defined critical Cd concentration is exceeded.

From the existing literature, no material produced by the investigated recovery technologies (except raw SS and SSA) has ever reached the heavy metal limit values in the fertilizer regulations (EC, 2003).

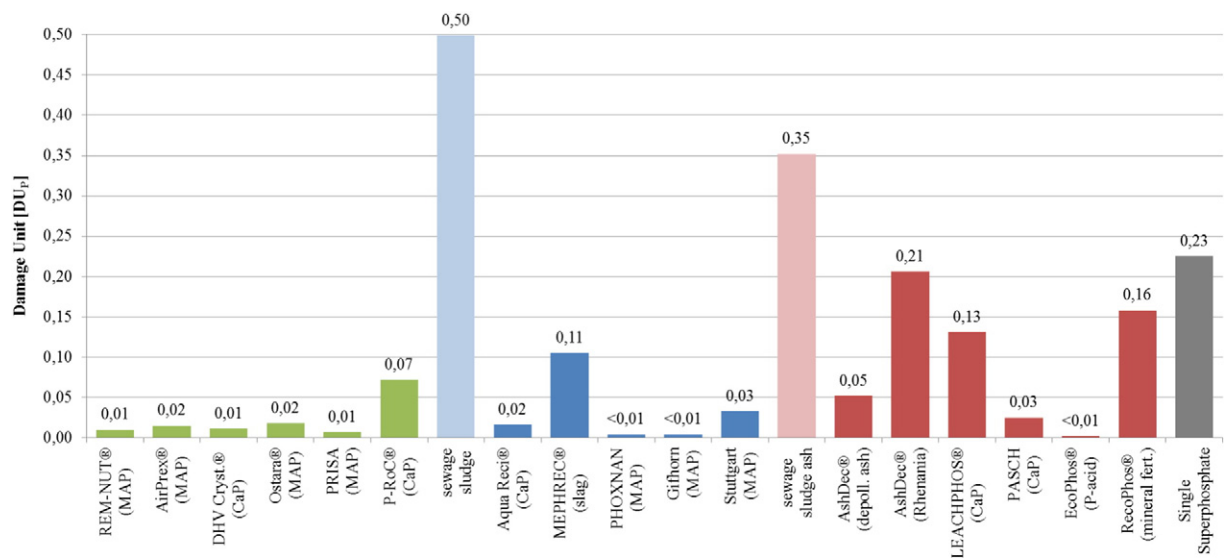


Fig. 10. Damage unit (DU_p) values for recovered materials, reference sewage sludge/ash and commercial fertilizer (SSP).

3.3.2.2. *Organic micropollutants and pathogens.* Little or no OMs or pathogens have been detected in recovered material from digester supernatant (Montag, 2008; Pinnekamp, 2011), secondary treated effluent (Ueno and Fujii, 2003) and anaerobically digested sludge (Heinzmann, 2013). This is, in part, a result of the already low concentration of OMs in these P-rich flows. Additionally, during precipitation or crystallization of dissolved P, these pollutants are minimally incorporated into the crystal structure of the precipitants, e.g., struvite (Rontelap et al., 2007; Uysal et al., 2010; Antkalyi et al., 2011).

For the wet-chemical **Gifhorn** and **Stuttgart processes** from sewage sludge, organic micropollutants can be detected but at significantly lower concentrations than in the raw SS (Weideler, 2010; Günther, 2011; Pinnekamp, 2011). With wet-oxidative or metallurgic technologies, pathogenic microorganisms and OMs are destroyed completely or to a great extent. The pathogens and OMs are destroyed when SS is incinerated properly without mixing with other wastes. The formation of dioxins and furans is possible, but generally these compounds are not detectable or detectable only in small quantities in ashes derived from mono-incineration of sewage sludge (<1 ng kg ash⁻¹; Krüger and Adam, 2014) (Table 5).

3.3.3. Texture and handling

As all the materials produced by the different recovery technologies are inorganic, storage is possible. Nevertheless, the criteria for direct application with modern spreaders are currently only fulfilled by certain technologies (e.g., **Ostara**®, **DHV Crystalactor**®, **RecoPhos**®, **AshDec**® output after granulation, and the **Fertilizer Industry**). For most other technologies, the recovered material is coarse grained or powdery and dusty. Therefore, further treatment processes, e.g., granulation, are needed (Table 6). The output of the **EcoPhos**® process is a concentrated, marketable, liquid phosphoric acid.

The results from Section 3.1 to 3.3 are summarized in Table A 15.

3.4. Economic assessment

3.4.1. Annual costs of the recovery technologies

With more than 28 € kg P_{rec}⁻¹ the **REM-NUT**® approach to recover P from the effluent of a WWTP is the most expensive technology. These extremely high costs result from the great need of resins and chemicals. The annual costs, without savings and revenues, of recovering P from digester supernatant, where P is already present in its dissolved form, are

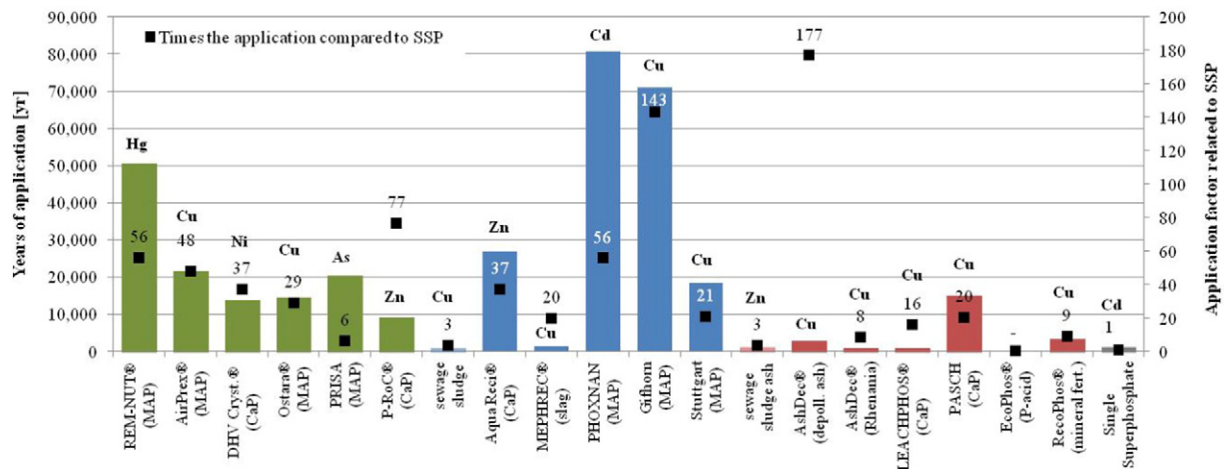


Fig. 11. Years of application of the recovered materials, reference sewage sludge/ash and commercial fertilizer until a defined critical concentration is reached, including the limiting heavy metal and the number of times the material can be applied relative to SSP if only Cd is the limiting element (black square + number).

Table 5

Concentration of organic micropollutants in sewage sludge, SSA, recovered materials from P recovery processes and mineral fertilizers (for missing technologies, no OM data are available).

	AOX	B(a)P	LAS	NPE	PCB	Phthalates	Σ PAH 16	PCDD/F
	[mg kg DM ⁻¹]							[ng kg DM ⁻¹]
SS ^{1,2}	180	–	2,000	30	0.05–0.1	–	6–16	3,000
SSA ³	<10	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<1
REM-NUT® ⁴	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
PRISA ⁵	84	–	<0.1	0.5	–	–	<410	–
P-RoC® ⁶	–	0.001	10	–	–	0.02	–	–
AirPrex® ⁷	55	–	–	–	0.03	–	–	0.00002
PHOXNAN ⁶	–	n.d.	n.d.	–	–	–	–	–
Gifhorn ⁵	197	0.005	40	2	–	1	–	–
Stuttgart ⁸	–	0.005	0.7	2.1	<10	–	60	–
PASCH+	–	–	0.3	–	–	0.05	–	–
Min. fertilizer ¹	–	0.009	138	0.03	0.001	1	–	–

n.d. (not detectable), ¹Kördel and Herrchen (2008), ²Scharf et al., 1997, ³Adam et al. (2007), ⁴Ueno and Fujii (2003), ⁵Montag (2008), ⁶Pinnekamp (2011), ⁷Heinzmann (2009), ⁸Weideler (2010)

approximately 6 to 10 € kg P_{rec}⁻¹ or 0.8 to 2 € PE⁻¹ yr⁻¹ (**Ostara®**, **DHV®**, **PRISA**, **P-RoC®**, Fig. 12). The higher the concentration of dissolved P in the supernatant, the lower the product specific costs. The detailed cost analysis shows that the costs are mainly driven by the investment costs for equipment, such as crystallization reactors. By installing such a reactor in larger treatment plants, the investment costs can be reduced significantly (up to –50% for 200,000 PE) due to the economy of scale. By taking into account possible savings, such as the reduction of P back-flow (reduced demand for flocking agents), avoiding MAP encrustations (and associated maintenance costs) and revenues from the produced fertilizer, these technologies may operate economically. By applying the **AirPrex®** technology immediately after the digester tank, the dewaterability of the digested sludge will be improved due to the aeration of the sludge and the significant reduction of dissolved P (~90%) by the formation of MAP within the sludge. As disposal costs for sewage sludge are one of the main costs for a WWTP in Central Europe, this technology pays for itself from an economic perspective.

Recovering P from sewage sludge is generally more expensive than recovering P from supernatant. For example, the cost of 1 kg P_{rec}⁻¹ produced via the wet-chemical processes is 9–16 € (**Gifhorn** and **Stuttgart processes**). These costs are dominated by the required chemicals, including acids, caustics, and complexation and precipitation agents, and will not be significantly reduced if scaled up. The costs of the wet-oxidation processes, such as **Aqua Reci®** and **PHOXNAN**, are outstandingly high (23–27 € kg P_{rec}⁻¹). However, taking into account revenues, e.g., by using the heat potential of the sludge, converting sludge to an inorganic product and the value of the product, the overall costs will decrease dramatically. Furthermore, in addition to having a recovered material, the output is a disposable inert waste. Thus, further treatment, such as incineration, is not necessary (Fig. 13). Regarding the whole process chain, these technologies could be economical. Similar results have been observed for the **MEPHREC®** process.

The costs of the wet-chemical leaching processes that recover P from SSA are approximately 5–6 € kg P_{rec}⁻¹ or 2.5–3.0 € PE⁻¹ yr⁻¹. These

product-specific costs are also valid for the industrial **EcoPhos®** approach. Depending on the scenario (“hot ash” or “cold ash”), the annual cost of the **AshDec® depollution** and **AshDec® Rhenania** technology is approximately 2 € kg P_{rec}⁻¹. Similar results are observed for the **RecoPhos®** process. The high population-specific costs of >6 € result from the application of expensive phosphoric acid. Due to the enrichment of the ash with P, the product-specific costs are in the range of 2–3 € kg P_{rec}⁻¹. To use the SSA in industrial processes, such as the **Fertilizer Industry** and **Thermphos®**, the assumption is that the ash is used in existing plants; therefore, only the operational costs for the resources were calculated. In this case, the costs of the **Fertilizer Industry** and **Thermphos®** are approximately 1 and 2 € kg P_{rec}⁻¹, respectively.

3.4.2. Integrated cost calculation including sensitivity analyses

3.4.2.1. Reference system. For the integrated economic technology assessment, the costs for the whole reference system were first identified, yielding an annual cost of approximately 11.1 € PE⁻¹ yr⁻¹. Additionally, approximately 1.2 € PE⁻¹ yr⁻¹ (including capital- and operational expenditure) and must be considered for the mono-incineration of sewage sludge compared to co-incineration (12.3 € PE⁻¹ yr⁻¹ total cost with mono-incineration and disposal of fly ash in a landfill). The details of these costs are shown in Table A 13.

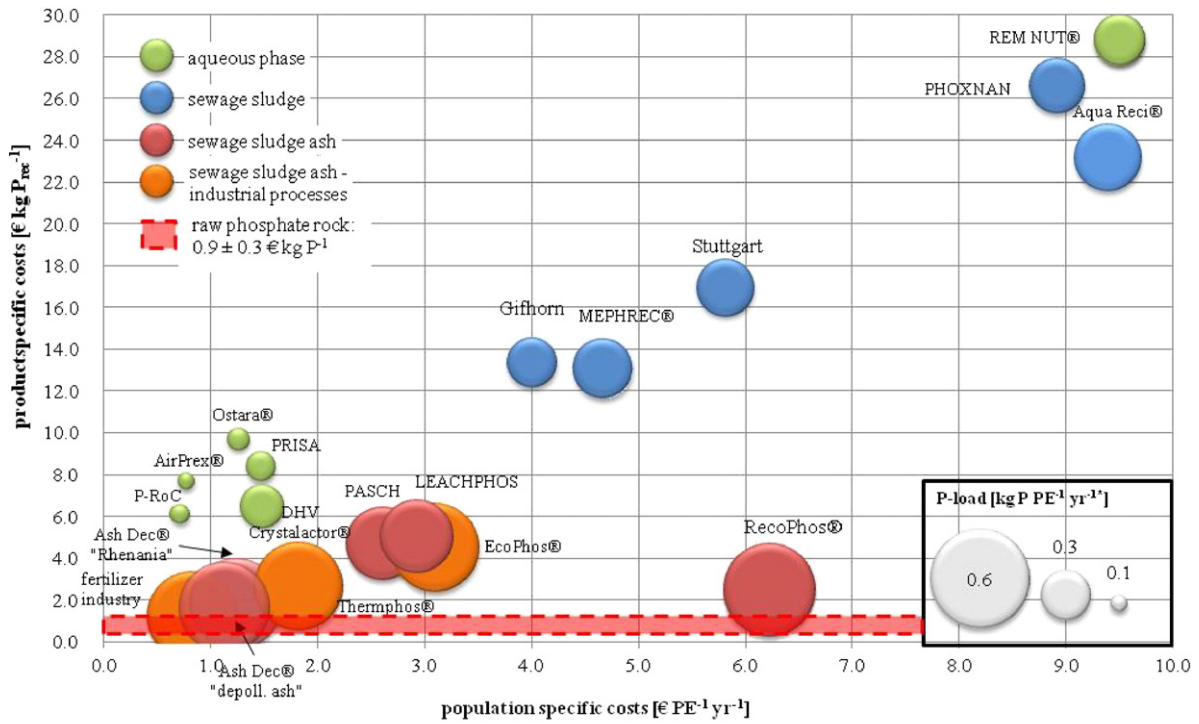
3.4.2.2. Recovery technologies. In contrast to the calculation of the cost of the recovery technology itself, the required costs and the possible savings associated with the integration of the recovery technology into the whole wastewater and sludge disposal system are taken into consideration here. Fig. 13 presents the economic costs associated with the implementation of recovery technologies into the reference system and displays the margin of fluctuation. Additional costs or savings with regard to the reference system (11.1 € PE⁻¹ yr⁻¹) are given as percentage deviations.

The **REM-NUT®** technology is the most expensive technology with regard to 1 kg of recovered P and 1 kg PE⁻¹ yr⁻¹ (Fig. 12). Based on the implementation in the defined reference system, additional costs in the range of 50–65% need to be considered. With annual costs of 0.5–1.5 € PE⁻¹ yr⁻¹, the **AirPrex®**, **DHV Crystalactor®**, **Ostara®**, **PRISA** and **P-RoC®** processes are significantly less expensive (Fig. 12). The implementation of the **AirPrex®** technology to recover dissolved available P directly from digested sludge results in savings due to reduced back-flow of nutrients and improved dewaterability of the sludge. Together with revenues from product sales, this technology is economical, as the revenues and savings exceed the annual costs. For the best-case scenario, the costs can be reduced by 6% compared to the reference system. With the implementation of the recovery technologies **Ostara®**, **PRISA** and **P-RoC®**, the nutrient back-flow via digester supernatant to the WWTP influent can be reduced significantly. Taking into account these savings, the maximum revenues from product sales

Table 6

Grain size and appearance of recovered P materials/products.

Grain size/appearance	Technology
Pellets/Grain size 2–5 (Market ready)	Ostara®, DHV Crystalactor®, AshDec® as granulated PhosKraft® fertilizer, RecoPhos®, Mineral Fertilizer from Fertilizer Industry
Coarse-grained (Market ready)	PRISA, AirPrex®, P-RoC®
Crystalline, powdery (Not market ready)	REM-NUT®, Aqua Reci®, PHOXNAN, Gifhorn, Stuttgart, LEACHPHOS®, PASCH, untreated output from the AshDec® technologies, pure SSA
Liquid (Market ready)	EcoPhos®
Solid (Market ready)	Thermphos®



* Bubble size indicates the recoverable P load in kg P per population equivalent per year. The maximum annual recoverable load of P is 0.66 kg PE⁻¹ yr⁻¹ or 65,700 kg (reference WWTP).

Fig. 12. Product- and population equivalent-specific annual costs for P recovery technologies without savings and revenues from digester supernatant/effluent (green), sewage sludge (blue), sewage sludge ash (red) and recovery of P from SSA in industrial processes (orange).

and the implementation of this technology in a larger WWTP, the revenues and savings exceed the annual costs (Fig. 13). In relation to the cost of the reference system, savings of 1–2% are possible. In comparison, due to the high investment costs and great resource demand, the **DHV Crystalactor®** does not operate economically, even with maximum revenues, maximum savings and an up-scaling of the plant to 500,000 PE. Compared to the reference system, additional costs in the range of 25–30% need to be considered.

High annual costs were shown for the **Aqua Reci®** and the **MEPHREC®** processes as standalone processes (Fig. 12). However, due to the use of the energetic potential of the sludge and the simultaneous mineralization (incineration can be omitted), reduced costs can also be shown for the whole process chain. Therefore, an economical performance is possible under favorable conditions. However, especially for these technologies, the uncertainty in the cost calculation is particularly high, as the data on the energy yield is subject to high degrees of

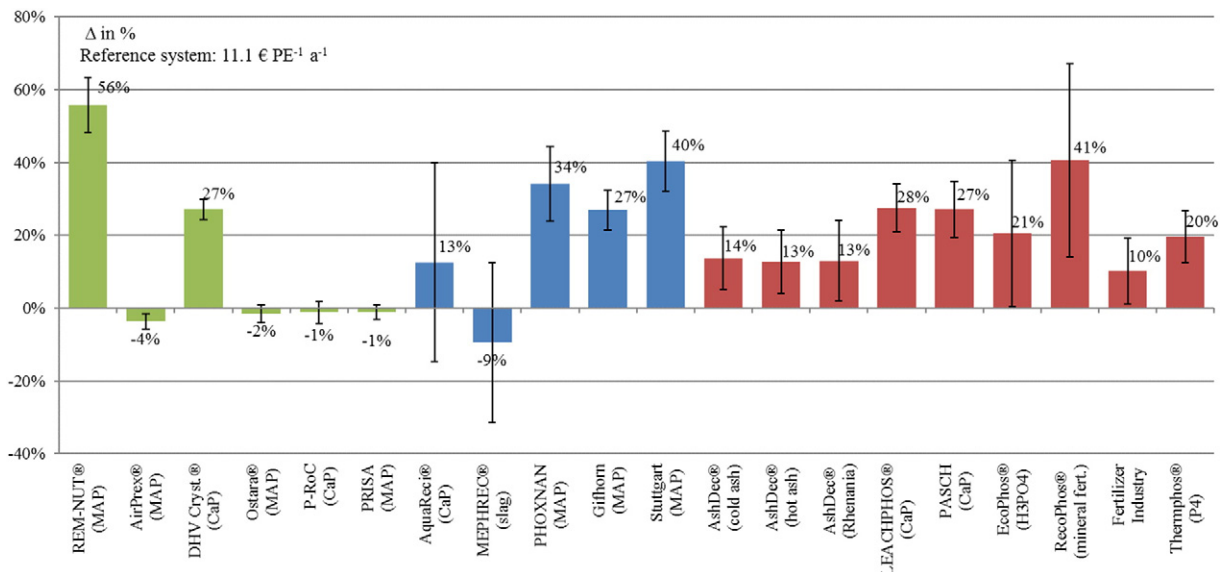


Fig. 13. Range of costs in % of the total costs of the reference system for P recovery technologies taking into account possible savings and revenues.

uncertainty. The wet-chemical sewage sludge leaching technologies (**Gifhorn** and **Stuttgart**) are expensive and increase costs by up to 20–50% compared to the defined reference system. For these leaching technologies, the effect on costs due to possible up-scaling is low, as the costs are dominated by the necessary chemicals. These high costs are particularly noteworthy when compared to the low/moderate recovery rates (40–50% of P with respect to WWTP influent, Section 3.2).

Focusing on recovery technologies from SSA, the possible additional costs associated with the mono-incineration of SS were considered (+1.2 € PE⁻¹ yr⁻¹ or +11% of the total costs of the reference system). The additional costs for both thermo-chemical **AshDec®** (ash depollution and “Rhenania ash”) technologies are in the range of +5–20% compared to the defined reference system. For these technologies, the possible revenues are especially important, as the output is either a depolluted ash with hardly any improved plant availability (revenue: 1 € Mg ash⁻¹) or a “Rhenania ash” with significantly improved plant availability and consequently higher revenues

(≥50 € Mg ash⁻¹). The additional costs compared to the reference system are high (+20%) in association with low revenues, which is the most realistic scenario for the **AshDec®** technology, but lower (+5%) in association with the **AshDec® Rhenania** technology. For recently developed wet-chemical leaching technologies (**PASCH**, **LEACHPHOS®**), the additional costs compared to the reference system are 20 to 35%. Even with the highest possible revenues, the additional costs are +20%. For technologies such as **RecoPhos®** or existing industrial processes where the output is an already marketable product, high revenues are possible. In situations where they can be implemented, these technologies utilized with almost no (**EcoPhos®**, **Fertilizer Industry**) or only small additional overall costs (**Thermphos®**) compared to the reference system. Therefore, by taking the whole process chain, with the necessary and more expensive mono-incineration plants, into account and by assuming maximum revenues for the recovered products of the industrial processes in the best case scenario, no additional costs need to be considered from a macroeconomic perspective. These results are summarized in the overall economic assessment (Table A 16).

3.5. Technical maturity

In recent years, technologies designed to recover the dissolved P from digested sludge and digester supernatant have been successfully implemented in North America, Central Europe and Japan. Three of these full-scale implemented technologies are considered in this work (**AirPrex®**, **DHV Crystalactor®**, **Ostara®**). To recover P from the secondary treated effluent (**REM-NUT®**), no pilot plant or full-scale operation is currently known.

For technologies with an oxidation and a subsequent P recovery unit that have already been tested at a pilot-scale level (**Aqua Reci®** and **PHOXNAN**), no further development is presently recognizable. In comparison, a pilot plant using the metallurgic **MEPHREC®** approach is currently under construction (Nürnberg, Germany). The leaching technology **Gifhorn** has been implemented at the full-scale in a small WWTP in Gifhorn (50,000 PE), while the **Stuttgart process** is currently implemented at the pilot-scale level (Offenburg, Germany).

No further development beyond the known pilot plant installations in Leoben (Austria) is known for the two thermo-chemical **AshDec®** approaches and the leaching approaches **PASCH** and **LEACHPHOS®** (Zurich, Switzerland). In fact, it remains unclear which technology (e.g., precipitation, solvent extraction, ion exchangers) is the most suitable for removing interfering ions, such as metals and heavy metals, that are dissolved with P in the leaching step. With the beginning of the construction of an industrial-scale plant in Dunkerque (France) and the intended integration of SSA to produce phosphoric acid, **EcoPhos®** seems to be a promising industrial technology for P recovery. The chosen method to remove interfering ions is ion exchange. A similar approach with the application of different ion exchangers is applied by

Remondis (**TetraPhos®**; pilot-scale implementation in Hamburg, Germany). Generally, the **fertilizer industry** could be a promising method to integrate SSA into the production process to generate high-quality products, with respect to P and heavy metal contents, (e.g., ICL Fertilizers®, Netherlands). The **RecoPhos®** process, which uses a similar procedural approach as the fertilizer industry (acidic ash extraction with phosphoric acid), has already been implemented at the full scale with a production capacity of 4.000 t per year. However, this plant is no longer in operation for unknown reasons. A detailed overview of the technology readiness levels and an outlook on the development potential of the considered technologies are given in Table A 12.

3.6. Overall uncertainty in the data on the technologies

The uncertainty and reliability of the used data were critically reviewed, as model results can only be as good and/or true as the input data are. The data originates from sources with differing quality and in some cases no data were available. For most of the technologies, reliable data on the resource demand, MFA for P and HM, nutrient and pollutant contents, solubility and plant availability were available, even for technologies at the laboratory or pilot scale. In comparison, the economic technology assessment was challenging for technologies at the laboratory or pilot scale, as investment costs and therefore capital costs were unknown. Although data from feasibility studies are available, especially for technologies that recover P from SSA, moderate or high uncertainties were considered, as there is no practical experience based on full-scale implementation or long-term studies. In Table A 5 and 6, the origins of the information and data, along with their uncertainties (classified according to the qualitative uncertainty concept) are described in greater detail. Table 7 provides a comparative overview of the reliability and robustness of the data for each technology based on the qualitative uncertainty concept. The overall uncertainty is the mean value of the summarized uncertainties according to Table A 5 and 6 (+: 1; 0: 2; -: 3; and -: 4).

As costs are a very important criteria for the implementation of a technology, the uncertainty in the resource and energy demand, the quantity of the recovered material, the yield of energy due to certain procedural approaches and the resulting waste for each technology from the aqueous phase (Table A 7), sewage sludge (Table A 8) and sewage sludge ash (Table A 9) is given in the appendix. Depending on the applied data quality, the robustness and reliability of the assessment results are discussed (Section 4).

4. Discussion

4.1. Paths of P and heavy metals

MFA was successfully applied to a defined reference system. This enables the tracking of P and heavy metal pathways along the whole route from the input wastewater, through sludge treatment processes or P recovery technologies to a recovered material or a waste product. With regard to P, many studies have shown similar recovery rate results for the technologies, as well as relative to a specific WWTP (Hermann, 2009; P-Rex, 2015).

Table 7
Overall uncertainty of the data for the P recovery technologies.

Aqueous phase	Unc. of data	Sewage sludge	Unc. of data	Sewage sludge ash	Unc. of data
REM-NUT®	o/-	Gifhorn	+	AshDec® depollution	+/o
AirPrex®	+	Stuttgart	+/o	AshDec® Rhenania	o
DHV Crystalactor®	o	PHOXNAN	+	PASCH	+
Ostara®	+	Aqua Reci®	o	LEACHPHOS®	+
P-RoC®	+	MEPHREC®	o	EcoPhos®	o
PRISA	+			RecoPhos®	+
				Fertilizer Industry	+/o
				Thermphos®	o/-

The fate of P and heavy metals in the recovery approaches have been investigated to date. The methodology applied in this work is unique as it broadens the perspective to the recovery and depollution potentials for P recovery technologies within the whole wastewater and sludge disposal system. With this approach, the percentages of wastewater heavy metals that end up in the different final sinks are identified (e.g., agricultural soils, landfills, and water bodies). Thus, the different technologies become directly comparable to each other. The results are particularly interesting with respect to the question of the long-term acceptable total load of heavy metals in agricultural soils. This work showed that most of the recovery technologies, with the exception of the wet extraction processes (**Fertilizer Industry**, **RecoPhos®**) achieve a significant reduction in pollutants compared to the raw SS or SSA input material. In the selected approaches, heavy metals are only diluted in the product compared to the SSA. It can be noted that the data used to construct the material flow models and model the path of P and heavy metals is very good, with the exception of particular technologies (e.g., **MEPHREC®**, **Aqua Recic®**), and reliable results with low uncertainty can therefore be generated for most of the investigated technologies.

However, it must be kept in mind that most of the newly developed P recovery technologies were tested under very limited variations of the boundary conditions e.g., on WWTPs with different properties or only on one type of SS/SSA. P recovery rates, HM loads etc. and therefore the data base (input data) used in the MFA are very limited and do not represent a broad spectrum of applications. Furthermore, from certain recovery technologies wastewater occurs, which could affect a WWTP negatively. Exemplary, heavy metal rich wastewater is generated from a process. The question arises, how higher heavy metal inputs affects transfer coefficients within a WWTP. Even if enrichment is possible within the whole process, it cannot be illustrated, due to the fact, that this MFA was not performed as a time series. Consequently, uncertainties need to be considered.

4.2. Quality of the recovered materials and products

As shown with the comparative literature study, compared to commercial mineral P fertilizers, all the recovered materials show poorer or even no solubility in water (similar to untreated raw PR: 1–5%; [Weinfurter, 2011](#)). However, almost all products, even untreated SSA in acidic soils, increase the agricultural yield. Therefore, the results from standard solubility tests (e.g., water, citric acid, and neutral/alkaline ammonium citrate) are often not transferable to the real plant uptake in the field. Field trials demonstrate that struvite and different forms of calcium phosphate, for example, have a relative fertilizer efficiency in neutral soils comparable to a water-soluble commercial SSP, even though the recovered fertilizers show no water solubility ([Wilken et al., 2015](#)). However, studies reveal that the plant availability is not solely influenced by the quality of the recovered product. In fact, natural soil properties, such as pH, P supply and type of vegetation, significantly influence the plant uptake ([Weinfurter, 2011](#)). Therefore, further field trials are required to examine their actual fertilizing effect and especially their long-term behavior.

The applied methods to assess the pollution potential of the recovered materials reveals that, with the exception of **RecoPhos®** and the **Fertilizer Industry**, each recovery technology is able to reduce heavy metals significantly compared to the starting input material sewage sludge or SSA. Furthermore, the pollution potential of each recovered material relative to its P content is lower compared to commercial P fertilizers. These findings are confirmed by the comprehensive toxicity and risk assessment of various recovered products within the European P-Rex study ([Kraus et al., 2015](#)).

Even in simple lab trials or pilot plants, most of the technologies generated a recovered material with properties similar to those expected for a full-scale implementation. This is due to the fact that the chemical principles do not change due to up-scaling for most of the technologies.

The recovered materials from the considered technologies have been tested in many cases and even multiple times by independent laboratories to evaluate the solubility, plant availability, and nutrient and pollutant contents. Therefore, the results from the assessment of the recovered materials feature low uncertainties. These findings are supported by the DU_p and application factor results.

For several recovered materials, data on organic micropollutants and pathogens are incomplete or absent. For some sludge integration methods, such as wet chemical oxidation and super-critical water oxidation, data on the removal and destruction of OMs and pathogens are available in the general literature but not specifically for the recovery technologies. Therefore, greater uncertainties are involved, and further investigations are necessary in this field of research to complete the analysis of the recovered materials. In comparison, the incineration of sewage sludge at >800 °C almost entirely destroys OMs and pathogens. In the case, although no data are available for the recovered materials from SSA, and it can be assumed with a high degree of certainty that the OM and pathogen contents are very low or even below the detection limit.

4.3. Economic assessment

The question of economic P recovery is discussed intensively. This work reveals that recovery of P can be cost-neutral under certain boundary conditions if dissolved P is recovered as struvite or calcium phosphate from the aqueous phase (digester supernatant or dissolved P fraction within the digested sludge) of a WWTP. The positive effects of reduced nutrient back-flow, prevention of maintenance costs, and improved dewaterability account for the largest share of the economic operation of a P recovery technology. Additionally, an economic operation is possible with processes that utilize the energy content of the sewage sludge, destroy the organic content of the sludge, and simultaneously recover a P-rich material. However, for these technologies, the associated uncertainty is very high, as it is very difficult to foresee the actual revenues from heat, electricity or gas generated by technologies with no full-scale implementations currently in existence.

When discussing the cost-effectiveness, the argument is that the recovery technologies should compete with the price of raw PR (0.9 ± 0.3 € kg P^{-1} ; [World Bank, 2016](#)). However, untreated PR is not water-soluble and therefore not immediately plant available without further treatment. In comparison, recovered materials, such as struvite, have a fertilizing efficiency comparable to a triple superphosphate worth 1.7 ± 0.5 € kg P^{-1} ([World Bank, 2016](#)). Within this price range, SSA can be (partly) depolluted with the output of a “Rhenania phosphate” or ash can be treated with phosphoric acid to produce a commercial fertilizer.

The costs of P recovered from SSA are significantly higher than the costs of direct P recycling by applying SS to agricultural fields or in biological sludge treatments, such as composting ([Wiebke and Pinnekamp, 2011](#)). This option is not applicable everywhere and is restricted in several European countries (Netherlands, Switzerland and likely Germany will set similar regulations). For cities and regions where infrastructure with mono-incinerators (e.g., Austria, Switzerland, Germany, Netherlands) is available and a P-rich ash is already generated, little or no additional costs are necessary to recovery of P from SSA compared to disposal routes if maximum revenues are taken into account.

Operational costs can be calculated rather simply, even for technologies with a low technical readiness level. Therefore, the uncertainty for these costs is low. This low degree of uncertainty is based on the profound knowledge of the material flows and resource demands of the recovery technologies. A weak point of the performed economic assessment is the calculation of the capital costs for technologies with a low TRL, as investment costs are unknown at this stage of development.

Possible savings (e.g., reduced nutrient back-flow and improved dewaterability) and additional costs for the disposal of generated

wastes could be calculated with low uncertainties, as the detailed material and substance flow analysis forms a good basis. Compared to the savings, the revenues from the recovered materials are highly uncertain, as there is no existing market for these P-rich secondary raw materials. Therefore, the presented results of the sensitivity cost calculation are a recent snapshot and present the range of costs for a technology.

The assessment of the technologies in this work is based on a defined reference WWTP. Therefore, variations in the results either in a positive or negative direction are unavoidable. It must be considered that even the characteristics of the wastewater and the quality of SS and SSA can vary significantly with respect to the nutrient and pollutant contents. This variability therefore affects the depollution processes, product quality and costs of the recovery technologies.

5. Conclusions

The question of application of P recovery technologies is especially relevant for countries where agricultural reuse of sewage sludge is not currently accepted and/or is restricted by legislation. A large number of technologies have already progressed to commercially working implementations, and others could be implemented without restrictions from a technical perspective. Still, an ideal recovery technology cannot be presented.

As the field of P recovery from municipal wastewater is a young research topic, the evolution is very dynamic. Therefore, changes due to future developments are expected. Nevertheless, the methodological approach presented in this paper is appropriate and applicable to holistically assess P recovery technologies for themselves, but also within existing systems or structures of wastewater and sludge treatment, as well as the disposal of the resulting wastes. This methodology allows already existing and assessed technologies to be compared.

This assessment could be performed with a robust dataset for most of the considered technologies. For 12 out of the 19 technologies, the uncertainty of the dataset can be classified as low or low/moderate. Only two technologies are associated with moderate to high uncertainties. Coincidentally, no further development is presently identifiable for these technologies. As an essential precondition to performing this integrated assessment, detailed databases are required for the resource demand, the paths of P and heavy metals, and investment costs. Incomplete or absent data exist for the quality of the recovered materials with regard to organic micropollutants, pathogens and in some cases the fertilizer efficiency. With respect to the economic assessment, investment costs for technologies with a low TRL level are difficult to predict at this stage of development, and the considered capital costs need to be critically reviewed. Generally, due to low TRL values and unknown market situation, the savings and revenues are associated with great uncertainties, especially for technologies that recover P and energy from sewage sludge simultaneously.

An ideal technology would feature maximum P recovery rates, good removal and destruction of potentially hazardous substances (heavy metals, organic micropollutants and pathogens) and an applicable material with low environmental risks, good fertilizing effects and economic efficiency. However, the results of this paper demonstrate that choosing a certain recovery technology is a trade-off between these criteria.

This work demonstrates that P recovery can be achieved with low costs. In some cases, even financial gains from P recovery can be achieved if dissolved P is recovered from digester supernatant or digested sewage sludge. Nevertheless, the recovery rates are (too) low in this case (<25% of P in raw wastewater). However, if sewage sludge is incinerated, it is currently possible to recover a high percentage (70–90%) of the P in the wastewater input under specific conditions with little additional costs from a macroeconomic perspective. Nevertheless, there is a tradeoff between the requirements for heavy metal depollution and recovery costs. While recovery with little or no heavy metal depollution effort can already be realized without any significant

additional cost compared to a system with sewage sludge disposal in landfills, additional costs associated with significant depollution are estimated to be in the range of 1–2 € PE⁻¹ yr⁻¹. This emphasizes that costs are only one parameter when discussing resource recovery. The re-establishment of natural nutrient cycles implies independence from raw material imports from geopolitically unstable regions, independence from fluctuating market prices, development of regional value chains, and simultaneously lower environmental effects. How much a society is willing to pay for these aspects is not covered in this paper but could be the task of a socio-economic investigation.

This integrated assessment reveals that one final parameter for valuation is not constructive, as the different technologies utilize various P-rich sources along the wastewater and sludge treatment processes and achieve various criteria at different levels. In fact, using numerous assessment criteria delivers an overall picture for a particular recovery technology, which can be compared to other technologies and to the future requirements and expectations for P recovery.

To complete the picture for these technologies, especially with regard to the environmental impacts, an assessment considering greenhouse gas emissions, the acidification potential and the cumulative energy demand is a part of ongoing work.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.scitotenv.2016.07.019>.

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