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Life Cycle Assessment (LCA) of the integrated technology for the phosphorus recovery from sewage sludge ash (SSA) and fertilizers production

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Abstract: The paper presents an application of Life Cycle Assessment (LCA) method for the environmental evaluation of the technologies for the fertilizers production. LCA has been used because it enables the most comprehensive identification, documentation and quantification of the potential impacts on the environment and the evaluation and comparison of all significant environmental aspects. The main objective of the study was to assess and compare two technologies for the production of phosphorus (P) fertilizers coming from primary and secondary sources. In order to calculate the potential environmental impact the IMPACT 2002+ method was used. The first part of the LCA included an inventory of all the materials used and emissions released by the system under investigation. In the following step, the inventory data were analyzed and aggregated in order to calculate one index representing the total environmental burden. In the scenario 1, fertilizers were produced with use of an integrated technology for the phosphorus recovery from sewage sludge ash (SSA) and P fertilizer production. Samples of SSA collected from two Polish mono-incineration plants were evaluated (Scenario 1a and Scenario 1b). In the scenario 2, P-based fertilizer (reference fertilizer – triple superphosphate) was produced from primary sources – phosphate rock.

The results of the LCA showed that both processes contribute to a potential environmental impact. The overall results showed that the production process of P-based fertilizer affects the environment primarily through the use of the P raw materials. The specific results showed that the highest impact on the environment was obtained for the Scenario 2 (1.94899 Pt). Scenario 1a and 1b showed the environmental benefits associated with the avoiding of SSA storage and its emissions, reaching -1.3475 Pt and -3.82062 Pt, respectively. Comparing results of LCA of P-based fertilizer production from different waste streams, it was indicated that the better environmental performance was achieved in the scenario 1b, in which SSA had the higher content of P (52.5%) in the precipitate. In this case the lower amount of the energy and materials, including phosphoric acid, was needed for the production of fertilizer, calculated as 1 Mg P_2O_5. The results of the LCA may play a strategic role for the decision-makers in the aspect of searching and selection of the production and recovery technologies. By the environmental evaluation of different alternatives of P-based fertilizers it is possible to recognize and implement the most sustainable solutions.

Introduction

Phosphorus (P) is one of the most important raw materials (RM) for human nutrition, which cannot be substituted by any other element (Krüger et al. 2014). Feed and fertilizer industry is the main segment of phosphorus usage (Herzel et al. 2016). Around 89% of the total mined P resource is used in the production of phosphate fertilizers for agriculture and feed additives. Phosphorus is used on a small scale in the production of sodium tripolyphosphate (STPP) (Kowalski et al. 2018), including detergents and cleaning products (8%) and in other industrial applications such as in lighting or electronics (3%). Phosphorus reserves only exist in the earth's crust in the form of the phosphate rock, which is mined (Krüger et al. 2014). P resources, among which phosphate rock is the most significant source, are limited and non-renewable (Sholz et al. 2013). Therefore, the sustainable management of this valuable resource should be implemented on the local, regional, and global levels (Smol 2019). In Europe, the production of P is carried out in Finland and Russia, and it could cover only up to 12% of European demand for P resources. Almost all demand for phosphate rock (88%) and all demand for phosphorus (100%) is satisfied by import, mainly from Morocco, Algeria, Russia, Syria, Kazakhstan and China (COM No. 490, 2017).

In order to increase the security of this RM on the European level, in 2013, the European Commission (EC) published the specially dedicated document 'Consultative Communication on the Sustainable Use of Phosphorus' (COM No. 517, 2013). The EC underlined that the current situation, where P resources are wasted and lost at every step of its life cycle, causes concerns about future supplies and soil and water pollution, both in the European Union (EU) and worldwide. Therefore, the EC initiated a debate on the state of play and the actions that should be considered in order to increase the P recovery from waste streams. Next year (2014) the phosphate rock, which is an important source of phosphates, was indicated as a Critical Raw Material (CRM) for the European economy (COM No. 297, 2014) due to the risks of its shortage of supply in the EU and its impact of a shortage on the economy is greater than other RMs (COM No. 490, 2017). In the 2017, the list of CRMs was extended and currently next to phosphate rock, phosphorus is also indicated as the CRM. In the presented Communication, the EC indicated 'End-of-life recycling input rate' which measures the ratio of recycling from old scrap to EU demand of a given RM (the sum of primary and secondary material supply inputs to the EU). This indicator for the phosphate rock is equal to 17%, and for phosphorus to 0% (COM No. 490, 2017). As there is a high potential for recovery of those materials from waste, the values of presented indicators should be higher in the EU. Therefore, further actions should be taken by the Member states in this area. It must be also pointed out that this concept is in the line with the circular economy (CE) (COM No. 398, 2014, COM No. 614, 2015) which is an essential way to deliver the resource efficiency agenda, which has been established under the Europe 2020 Strategy for smart, sustainable and inclusive growth (COM No. 2020, 2010). In 2015, the EC presented the CE Action Plan (Circular Economy Package) (COM No. 614, 2015) which includes measures that should help stimulate Europe's transformation towards the CE model. In the CE Action Plan, the EC provided a concrete and ambitious programme of action, considering the whole cycle: from extraction of primary RMs, their production and consumption to waste management. The CE action plan includes also the issues related to the market for secondary RMs, including the fertilizes resources such as phosphorus, and a revised legislative proposal on waste. The first executive act of the proposed CE Package is the proposal for a regulation of the rules on the making available on the market of CE marked fertilising products, including the fertilizers produced from P-rich waste streams (COM No. 157, 2016). This makes the production of fertilizers from waste extremely important for the EU and it can be expected that technologies in this field will develop in the following years.

Phosphorus could be recovered from serval waste streams (Cieślik and Konieczk 2017). One of the most promising P secondary source is domestic waste – in particular sewage sludge (SS) and sewage sludge ash (SSA) (Kalmykova and Fedje 2013, Smol et al. 2016) containing large amounts of P, which, if recycled in line with the CE model, may potentially cover up to 30% of EU's demand of phosphate fertilizers (COM No. 517, 2013). Currently, there is largely unexploited investment potential remaining in relation to this in the European countries. Anyway, there is a positive trend in this direction. As a consequence of the above EC's recommendations, in the last years the significant increase in research works on technologies for P recovery from waste streams and fertilizers production is observed and more and more of those technologies are available on the market. For now, the full scale P – recovery technologies from digestate and from liquor are in operation in Germany, Belgium, United Kingdom, Denmark, Netherlands, France, Italy and Spain. In Poland, there is one installation under construction for struvite production at the sewage treatment plant in Cielcza, supervised by the Jarocin Waterworks Company (P-REX project, 2018).

All technologies and solutions are focused on use of waste as an alternative source of raw materials (Ciesielczuk et al., 2018) in fertilizer industry should be evaluated from economic (Generowicz et al. 2011, Kowalski et al. 2012, Jóźwiakowski et al. 2015, Makara et al. 2016), environmental (Feng and Reisner 2011, Koneczna and Kulczycka 2011; Moghim and Garna 2019) and social points of view. The impact of the above technologies on the environment can be evaluated using environmental assessment methods (Kowalski et al., 2007, Gaska et al., 2017). One of those methods is the Life Cycle Assessment (LCA), which enables the most comprehensive identification, documentation and quantification of the potential impacts on the environment and the evaluation and comparison of all significant environmental aspects (Heimersson et al. 2016, Kulczycka et al. 2015).

The current paper presents an application of LCA method for the environmental evaluation of the integrated technology for the P recovery from SSA and fertilizers production. The technology has been developed in the framework of the Polish project "PolFerAsh – Polish Fertilizers form Ash" which has been conducted in the Cracow University of Technology and Mineral and Energy Economy Research Institute of the Polish Academy of Sciences in Poland, and has received the founding from the National Centre for Research and Development.

Materials and Methods

Environmental evaluation of the two scenarios of P-based fertilizers production was conducted with use of the Life Cycle Assessment method. It is a widely used technique helpful in the quantification of environmental impacts of products and technologies in the fertilizer sector (Amann et al. 2018, Chojnacka et al. 2019). The conducted LCA is in the line with the ISO 14044 guidelines (ISO, 2006a) and the ISO 14040 principles (ISO, 2006b). The following steps are part of the presented LCA: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation of the results. The impact assessment is implemented using the LCA software SimaPro 8 (8.5). In order to calculate the potential environmental impact the IMPACT 2002+ method was used. The methodology of all steps of research is presented in the following sections.

Goal and scope definition

The aim of the LCA was to assess and compare the processes of P-based fertilizers production from primary and secondary sources. The specific potential environmental impacts were evaluated for the following scenarios:

- Scenario 1: P-based fertilizer from secondary sources – waste-based fertilizer production scenario,
- Scenario 2: P-based fertilizer from primary sources – baseline fertilizer production scenario.

The global objective of the research was to assess whether and under what conditions waste-based fertilizer production scenarios are actually associated with better overall environmental performance than baseline scenario. In order to pursue this objective, the comparison of the impacts of waste-based fertilizer production scenarios with baseline fertilizer production scenario was made.

A functional unit of the system was defined as 1 Mg P_2O_5 contained in the fertilizer – precipitate in the scenarios 1a and 1b, and superphosphate in the scenario 2. In the scenarios 1a and 1b, the final product of the evaluated technology was P-based fertilizer produced from P – precipitate (extract) obtained during leaching process. For the products obtained, the nutritional value of the phosphorus content in the form of P_2O_5 was determined. Depending on the presented variants, P_2O_5 phosphate content in the obtained precipitates was 40.8% for scenario 1a, and 52.5% for scenario 1b. The final product in the scenario 2 was the commercial product – triple superphosphate, with the P content – 48% expressed as P_2O_5.

The system boundaries of presented LCA include all processes that are related to the production of fertilizers from secondary and primary sources (from cradle to gate). The use phase is not taken into account as it is a comparative study of different scenarios with the same functional unit. The block diagram of material flow of technology for the phosphorus extraction from SSA and fertilizer production is shown in Figure 1. In all scenarios the assessment includes all unit processes related to the upstream chain and does not include the processes related to the distribution and end use of the product received – downstream. The evaluation covers the transport of SSA to the disposal site up 100 km from place of origin. For such a specific product system, only the material and fuel-energy flows are analyzed, as the designed technology is waste-free and emission-free (only steam emission to air occurs).

Life cycle inventory (LCI)

In the present research, two scenarios of P-based fertilizer production were evaluated:

Scenario 1: production of P-based fertilizer form secondary sources (SSA) – the PolFerAsh technology for the production of ammonium phosphate. In this case, SSA collected from two Polish monoincineration plants was indicated as Scenario 1a, and Scenario 1b.

Scenario 2: production of P-based fertilizer form primary sources – the technology for the production of reference fertilizer – triple superphosphate.

Scenario 1 – the PolFerAsh technology

Under the PolFerAsh project, an installation allowing for the production of commercial products in the form of ammonium phosphate or calcium and ammonium nitrate, originating from renewable sources was developed. The developed PolFerAsh technology is a waste-free technology for the production of fertilizers based on the SSA (alternative sources of P raw materials). According to the legal restrictions (EPA, 2002), the SSA is classified as 'fly ash other than those mentioned in 19 01 13, waste code 19 01 14'. In the investigated technology, phosphoric acid was proposed as a leaching agent because of a high P recovery rate (up to 99%). The specific description of the evaluated technology is provided in the previous work of the authors (Gorazda et al. 2017, Smol et al. 2015). In the present study, two different samples of SSA from monoincineration plants obtained through combustion of municipal sewage sludge in fluidized bed were used for the production of fertilizers. The extracts obtained through phosphoric acid leaching (wet chemical treatment and neutralization processes) of SSA were used for the production

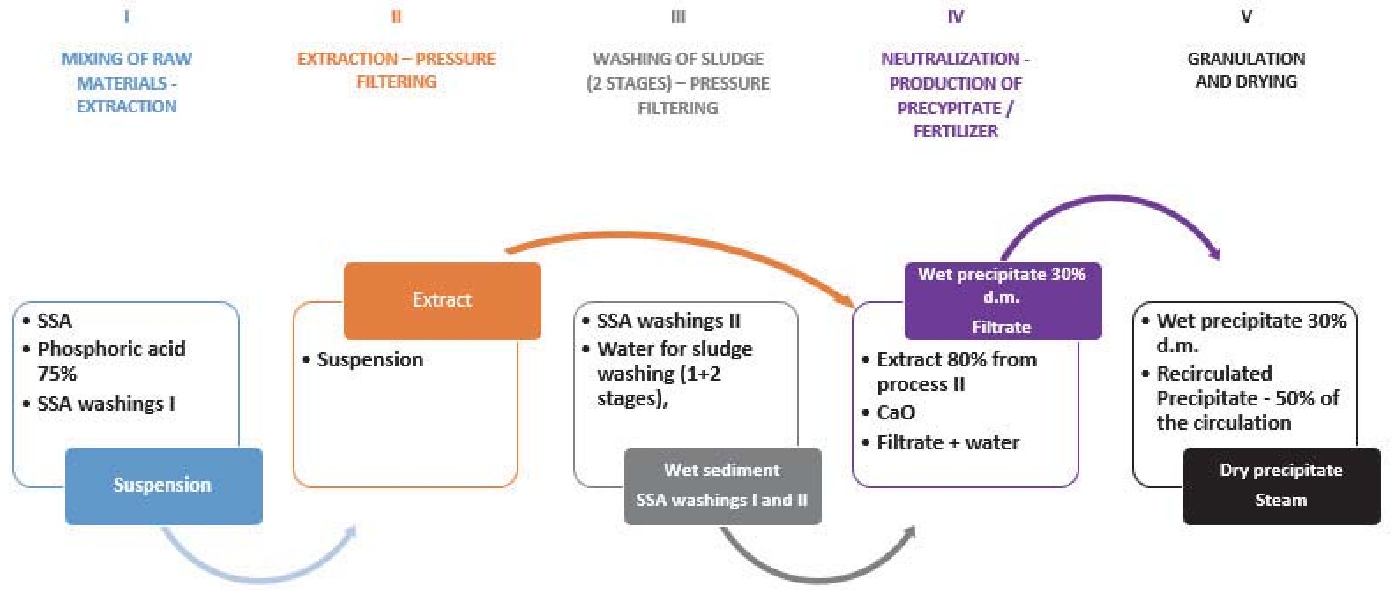

Fig. 1. Block diagram of material flows of the PolFerAsh technology

of P fertilizers. The waste after the leaching of P was directed to the construction materials.

Scenario 2 – reference fertilizer

The reference fertilizer was chosen based on the similar phosphorus content – 48% expressed as P_2O_5 in triple superphosphate (TSP). It is a phosphate fertilizer containing calcium dihydrogen phosphate, obtained mainly from phosphates and apatites by treating them with mineral acids. In the case of triple superphosphate, the used acids are, as in the case of the designed technology, phosphoric acids. In addition, the fertilizer may be in a granular form, such as a precipitate obtained in the PolFerAsh technology. Considering the above properties of superphosphate, it seems to be representative both in terms of technology and physicochemical product, suitable for comparative analysis. The profile of the usage of resource and emission generation for triple superphosphate was obtained from the international Ecoinvent database (v.3.2 2014). According to the data included in the inventory table, 1 kg P_2O_5, refers to 2.08 kg triple superphosphate with a P_2O_5 content of 48.0%. Production process included activities regarding production of fertilizes from phosphoric acid and phosphate rock. Transports of raw materials and intermediate products to the fertilizer plant as well as the transport of the fertilizer product from the factory to the regional department are also included. Production and waste treatment of catalysts, coating and packaging of the final fertilizer products were not included.

The data used for the analysis were derived from the multi-laboratory and micro-technical studies. In this case, data quality for P-based fertilizers production was assumed to be high and representative for the evaluated PolFerAsh technology. The individual components of the profiles used in the analysis of fuels, materials, and energy were collected from the international Ecoinvent database (v.3.2 2014). The reference system was indicated by the project team based on existing data of SSA and fertilizer quality and long-term experience of project experts in performing environmental assessments. The reference process was modelled with datasets from Ecoinvent database (v.3.2 2014), representing conditions for EU/global average. Ecoinvent datasets for mineral fertilizer production rely on primary sources of the 1990s, however, they represent the latest available datasets for mineral P and N fertilizer production according to information provided by the European Fertilizer Association (EFA with Frank Brentrup – Yara, as LCA representative) (Remy and Jossa 2015). The inventory data used for the two analyzed scenarios are presented in Table 1.

Life cycle impact assessment (LCIA)

The ILCD 2011 Midpoint+ V1.10 method was applied. It combines midpoint and endpoint approach, which is presented for 16 following impact categories: Climate change [GWP100], Ozone layer depletion [OLD], Human toxicity: non-cancer effects [HT NCE] and cancer effects [HT CE], Particulate matter [PM], Ionizing radiation: human health [IR HH] and E (interim) [IR E], Photochemical ozone formation [POF], Acidification [AC], Terrestrial eutrophication [TEU], Freshwater eutrophication [FWEU], Marine eutrophication [MEU], Freshwater eco-toxicity [FEW], Land use [LU], Water resource depletion [WRD] and Mineral, fossil, and renewable resource depletion [AD]. All the above categories represent the environmental areas, which can be affected by the product or process (technology) being analysed (Bartolozzi et al. 2018).

In the current study, in the first place the impact assessment results (characterization) were obtained. Then, the normalization and weighting have been done in order to select the most relevant impact categories. These categories were further discussed. Based on the characterization level result and then normalized ones, the selected environmental impact categories were considered among others as the most meaningful for the present study, and calculated according

Table 1. Inventory data used for LCA analysis

Products/materials	**Unit**	**Amounts (per functional unit – 1 Mg P_2O_5 contained in the fertilizer) for Scenario**		
		1a	**1b**	**2**
Inputs				
Input material	–	Ash	Ash	Phosphate rock
P recovery*	%	89.3	46.1	
Phosphate rock, as P_2O_5	Mg			0,3
H_3PO_4 phosphoric acid (75%)	Mg	1,01	1,2	
H_3PO_4 phosphoric acid (70%)	Mg			0,966
Chemical factory, organics	p			8,33E-10
Tap water (stage II)	Mg	5,11	3,36	
CaO quicklime	Mg	0,3	0,25	
Tap water (stage IV)	Mg	7,18	5,99	
Electricity	kWh	0,31	0,31	1,4965
Avoided waste				
Storage of averaged residues after municipal waste incineration	Mg	-0,73	-1,27	

* related to total P load in raw sludge (= 100%)

to the ILCD 2011 Midpoint+ V1.10 method (European Commission 2010, 2012, Goedkoop et al. 2009), with the SimaPro LCA software (Pré 2016).

It should be also underlined that in the current research the LCA approach, where the disposed waste does not have its technological history, was adopted, because waste is produced in the final stage of the life cycle of another production system. Only the process of waste collection and transport as well as the process of its management in a given place and with use of a given technology are assessed. In the case of superphosphate, as for other products, the technological history of the process of obtaining materials for its production has been taken into account, constituting environmental damage throughout the entire life cycle of the product.

In order to determine the environmental benefits associated with the analyzed technology, system expansion with '*avoided approach*' was used. This approach assumed that the amount of secondary source (material or product) obtained from recovery processes allows for the avoidance of the primary production of the same or of a lower amount of that source, according to the difference between the quality of the secondary and the primary goods (Nessi et al. 2012). Therefore the SSA disposal process was included in the analyzed system. Due to the fact that currently the main method of the SSA disposal is storage, its use for the production of other goods (as fertilizers) causes an avoidance of its landfilling. It helps to avoid leaching of emissions from dumps, air emissions in the form of dusts, and the energy needed for the disposal of SSA. In the present analysis, a profile for the storage of averaged residues after municipal waste incineration was used (based on Ecoinvent database, v.3.2 2014) since the environmental information on storage of the analyzed SSA was inaccessible. Despite the significant differences in the physical and chemical characteristics between municipal waste and municipal sewage sludge, the comparative analysis of the ash composition after combustion showed that they are characterized by similar structure. It was therefore considered that, for the LCA analysis, this profile would be representative of the method of the analyzed ash storage.

Results

The results of LCA are presented and discussed below. In the first stage of the analysis, the comparison of two fertilizer production scenarios from waste (scenario 1a and 1b) has been presented and then in the second stage of the research they were compared with the production scenario of fertilizers from primary deposits (scenario 2).

Characteristic of precipitates

The characteristic of the obtained precipitates is presented in Table 2. The final results of the P recovery from SSA was the solid fertilizer ($CaHPO_4*2H_2O$) in the form of granules. The obtained precipitates have different content of total phosphates. In the SSA collected from mono-incineration plant in scenario 1b, the total phosphates content was equal to 52.53%, while in the scenario 1a it was lower – 40.8%. The analyzed SSA have a good fertilizer properties, especially in terms of the content of phosphorus and calcium. The commercial fertilizer has similar total phosphates (as P_2O_5) by weight which is equal to 48%.

Overall LCA results

The results of the LCA analysis of the technologies for the fertilizers production from primary and secondary sources showed that the processes contribute to a potential environmental impact. The results after the characterization step of the LCA for all scenarios are shown in Table 3. The presented results indicate that the highest impact is reported in the following categories: climate change, land use and freshwater eco-toxicity. This impact is caused by:

- emission of SO_2, and nitrogen oxides affecting respiratory disorders, which are associated with the production of phosphoric acid and the sulfuric acid used in the PolFerAsh technology,
- emission of CO_2 from the production of phosphoric acid and quicklime, which are important materials used in the fertilizer production,
- using primary fuels in the mentioned processes,

Table 2. Characteristic of the precipitates after the neutralization stage

Component	Scenerio 1a	Scenerio 1b
	Percentage share [%]	
Ca	13.6	32.21
Fe	0.33	1.71
Zn	not detected	0.09
Mg	0.49	0.02
Cu	0.027	1.88
Cd	$0.48*10^{-3}$	$0.87*10^{-3}$
Pb	not detected	not detected
Soluble phosphates,% P_2O_5/Citric acid 2%	42.55	33.21
Soluble phosphates,% P_2O_5/Ammonium citrate	42.84	40.35
Soluble phosphates,% P_2O_5/Water	1.29	1.04
Total phosphates,% P_2O_5/HCl: HNO_3	44.30	52.53

- avoided emissions of arsenic and antimony to water resulting from the elimination of the SSA storage.

The difference in all analyzed scenarios in each impact category could be expressed in the percentage. In the current research this is illustrated in Figure 2. In the ILCD 2011 Midpoint+ V1.10 method, the highest impact in the analyzed category is 100%. As can be seen, the scenario 1a generated the highest environmental impact in the following 11 out the 16 impact categories: climate change, ozone layer depletion, particulate matter, ionizing radiation (human health), photochemical ozone formation, acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, water resource depletion, and mineral, fossil, and renewable resource depletion. Scenario 2 generated the highest environmental impact in the following 3 out the 16 impact categories: human toxicity (non-cancer effects), ionizing radiation E (interim) and land use.

Weighting histogram for the dominant impact categories for all evaluated processes is presented in Figure 4. Based on the overall results, it was indicated that the highest impact on the environment was obtained for the Scenario 2 (1.94899 Pt). Scenario 1a and 1b showed the environmental benefits associated with the avoiding of SSA storage and its emissions, reaching -1.3475 Pt and -3.82062 Pt, respectively.

Table 3. Midpoint results of the LCIA characterization

Category	**Unit**	**Scenario**		
		1a	**1b**	**2**
Climate change (GWP100)	kg CO$_2$ eq	2287.2080	1096.2729	1617.0793
Ozone layer depletion (OLD)	kg CFC-11eq	0.0003	0.0002	0.0002
Human toxicity, non-cancer effects (HT NCE)	CTUh	0.0001	-0.0005	0.0009
Human toxicity, cancer effects (HT CE)	CTUh	-0.0025	-0.0034	**0.0001**
Particulate matter (PM)	kg PM2.5 eq	3.1836	2.8084	2.8339
Ionizing radiation, human health (IR HH)	kg U235 eq	201.0960	163.5149	158.5983
Ionizing radiation E (interim) (IR E)	CTUe	0.0007	0.0005	0.0009
Photochemical ozone formation (POF)	kg NMVOC eq	10,7783	8.4101	7.2413
Acidification (AC)	mol Hþ eq	42.9567	37.5433	24.2873
Terrestrial eutrophication (TEU)	mol N eq	32.0058	23.4709	24.0952
Freshwater eutrophication (FWEU)	kg P eq	30.4803	28.0714	2.8413
Marine eutrophication (MEU)	kg N eq	2.9067	2.1668	2.1588
Freshwater eco-toxicity (FWE)	CTUe	**-145944.4500**	**-198384.1400**	5915.2452
Land use (LU)	kg C deficit	**4591.3004**	**3237.7200**	**10917.3510**
Water resource depletion (WRD)	m^3 water eq	336.6163	308.1001	22.2200
Mineral, fossil, & renewable resource depletion (AD)	kg Sb eq	3.7279	3.4192	1.8503

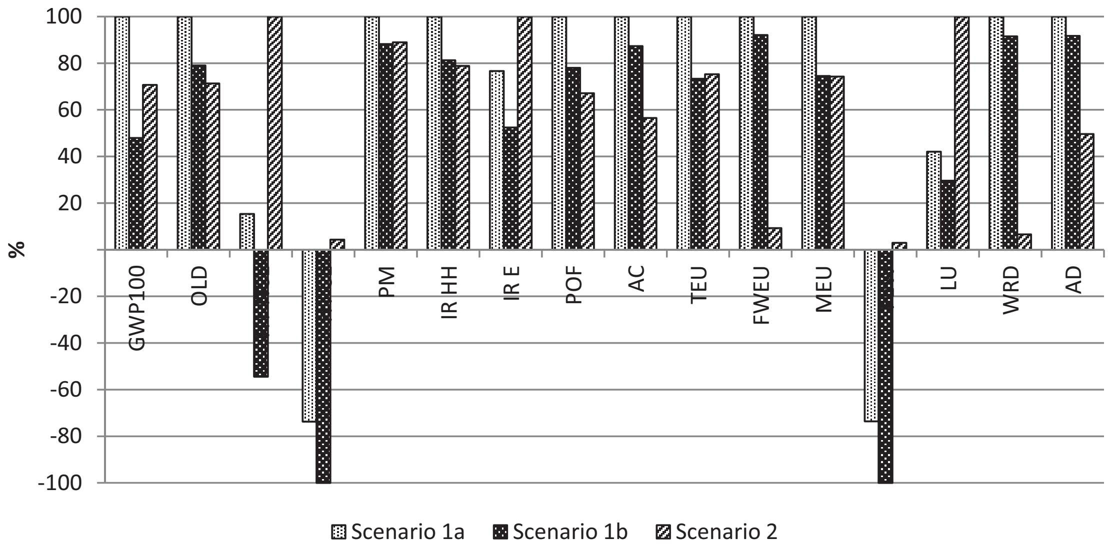

Fig. 2. Characterization histogram of the analyzed scenarios

Comparing the results of tested PolFerAsh technology for different waste streams, it was shown that scenario 1a causes higher environmental impact than scenario 1b (Tables 3 and 4, Figures 3 and 4). Due to the lower P content (40.8% in scenario 1a, 52.5% in scenario 1b) in the precipitate, the higher amount of the energy and materials, including phosphoric acid, is needed for the production of fertilizer, calculated as 1 Mg P_2O_5. Another important aspect influencing the overall indicator is the aspect of avoiding SSA storage. In the scenario 1a, higher amount of waste is used for the fertilizer production, so the environmental benefits of avoiding disposal are higher, balancing the same amount of environmental damage.

Discussion

The LCA is the technique of environmental management that has been used by many authors for the evaluation of the possible alternatives for the substitution of P raw materials coming from primary sources in fertilizes by P recovered from waste, as municipal wastewater (Bradford-Hartke et al.

Table 4. Midpoint results of the LCIA normalization

Category	Unit	Scenario		
		1a	1b	2
Climate change (GWP100)	kg CO_2 eq	0.0165	0.0079	0.0117
Ozone layer depletion (OLD)	kg CFC-11eq	0.0009	0.0007	**0.0006**
Human toxicity, non-cancer effects (HT NCE)	CTUh	0.0180	-0.0638	0.1172
Human toxicity, cancer effects (HT CE)	CTUh	**-4.5530**	**-6.1759**	0.2709
Particulate matter (PM)	kg PM2.5 eq	0.0559	0.0493	0.0497
Ionizing radiation, human health (IR HH)	kg U235 eq	0.0119	0.0096	0.0094
Ionizing radiation E (interim) (IR E)	CTUe	0.0000	0.0000	0.0000
Photochemical ozone formation (POF)	kg NMVOC eq	0.0227	0.0177	0.0152
Acidification (AC)	mol Hþ eq	0.0605	0.0529	0.0342
Terrestrial eutrophication (TEU)	mol N eq	0.0121	0.0089	0.0091
Freshwater eutrophication (FWEU)	kg P eq	1.3731	1.2645	0.1280
Marine eutrophication (MEU)	kg N eq	0.0115	0.0085	0.0085
Freshwater eco-toxicity (FWE)	CTUe	-1.1133	-1.5133	0.0451
Land use (LU)	kg C deficit	0.0041	0.0029	0.0097
Water resource depletion (WRD)	m^3 water eq	0.2757	0.2523	0.0182
Mineral, fossil, & renewable resource depletion (AD)	kg Sb eq	**2.4608**	**2.2570**	**1.2214**

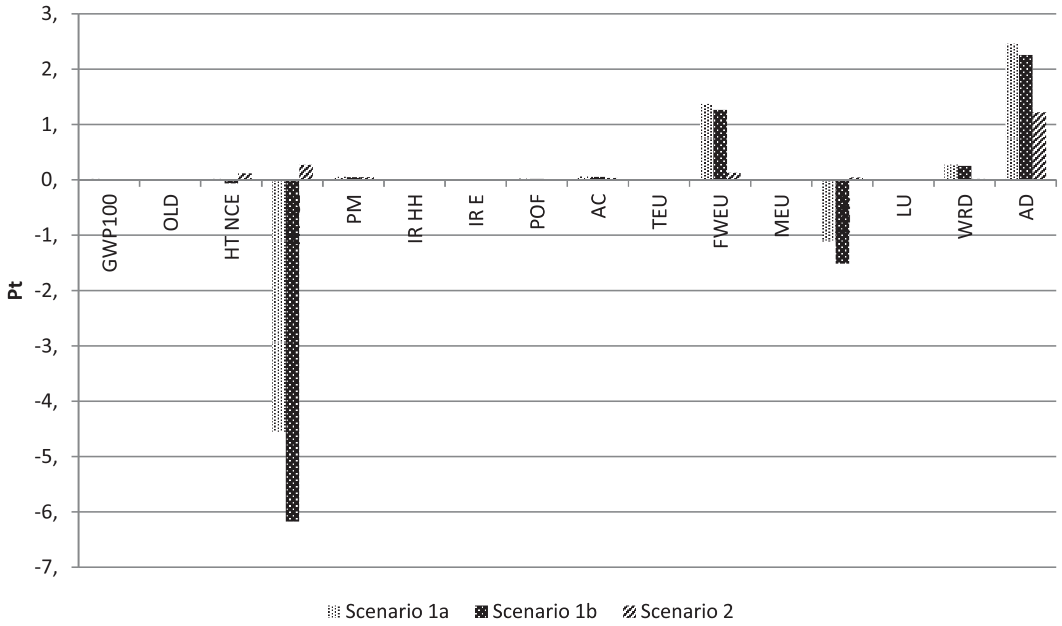

Fig. 3. Normalization histogram of the analyzed scenarios

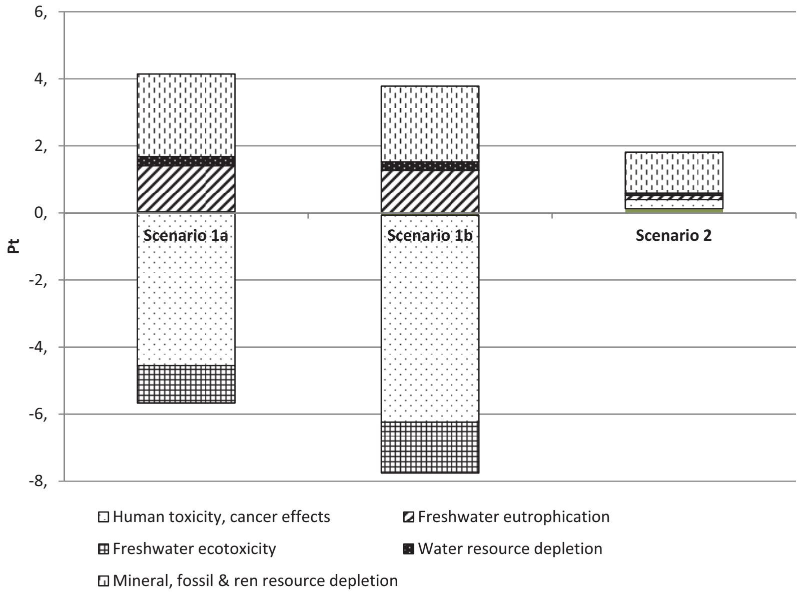

Fig. 4. Weighting histogram for the dominant impact categories

2015), sewage sludge and sewage sludge ash (Łukawska 2014; Ciesielczuk et al. 2016), sludge and food waste (Nakakubo at al. 2012), and sediments of the reservoirs (Kostecki et al. 2017). In other studies, different system boundaries have been adopted, which makes it impossible to directly compare the results of the current paper. Fehrenbach et al. (2011) evaluated the environmental impacts of the 5 selected processes for P recovery (Remy, Jossa, 2015). The results showed that for defined weighting of indicators, the variations in product quality (cadmium and lead content) have the largest impact on the environmental profile. Linderholm et al. (2012) analyzed different pathways of P recycling to agricultural land, including an application of sewage sludge directly to the land, struvite from PEARL® process, and recovery of P from SSA in the ASH DEC process (Linderholm et al. 2012). The direct application of sludge on farmland showed the lowest environmental impact, especially for energy input and greenhouse gas emissions. In 2014, the evaluation of 20 different P recovery technologies, based on a selection from a list of 46 technologies identified in the literature was published by Egle et al. (2014a). This assessment included environmental criteria based on LCA, but also technical and economic aspects have been studied. The LCA showed many differences of the investigated methods and technologies of P recovery. The summary of the research was that ash-based recovery processes are recommended due to their high P recovery potential, high product quality, and relatively moderate efforts in energy and chemical input (Remy, Jossa, 2015). Egle et al. published further results of LCA evaluation of the P recovery technologies from waste generated in the wastewater treatment plants (WWTPs) in the following years (2014b, 2015, 2016). Subsequently, Amann et al. (2018) published the results of the LCA of P recovery technologies to complement the integrated and comparative assessment done by Egle et al. (2014a, 2014b, 2015, 2016) in the previous years. The LCA results showed that the recovery of P from SSA have partly revealing trade-offs between heavy metal decontamination, emissions and energy demand. In the comparation to the technologies for the P recovery from sewage sludge and wastewater, recovery from SSA is the most promising as it provides a high P recycling rate, and heavy metal decontamination is possible. Moreover, there are no organic micropollutants in the final product and some positive effects in terms of energy demand and reduction of gaseous emissions could be achieved (Amann et al., 2018).

The comparison of the currently available P recovery processes has been also conducted under the EUs P-REX project (Sustainable sewage sludge management fostering phosphorus recovery and energy efficiency) which focused on the holistic large scale evaluation of innovative and available P recovery technologies from municipal sewage sludge or SSA. The results of the environmental evaluation of P recovery technologies were published by Remy and Jossa (2015). In this study, the selected processes for P recovery technologies from sewage sludge, liquor, or sewage sludge ash SSA in their potential environmental impacts, with use of the LCA methodology, have been studied. Results of the P-REX project showed that the quality of products from liquor and sludge is good with low content of heavy metals, therefore this solution leads to a limited potential toxicity for both humans and ecosystems. In the project, the recovery of P from SSA was evaluated for a few methods, as:

- Mephrec® – a melting process in a shaft furnace at high temperatures, yielding a metal phase and an inorganic slag where P can be recovered, developed by the company Ingitec (Scheidig et al., 2013),
- Leachphos – acidic leaching of mono-incineration ash at low pH by the addition of diluted H_2SO_4, developed by the company BSH Umweltservice GmbH,
- Ecophos® – the digestion of SSA into a large excess of H_3PO_4, originally developed by the representatives of the phosphate industry to process low-grade P input material into a high-quality P product (Remy, Jossa, 2015),
- Ash Dec – thermo-chemical treatment of mono-incineration SSA in a rotary kiln to increase plant availability and decrease heavy metal content of the

SSA, developed by the company Outotec and BAM Federal Institute for Materials Research and Testing (Adam et al., 2009).

All above processes have been evaluated and the results of the LCA are presented in Table 5. The findings showed that the use of chemical leaching (sulphuric acid) yields 70% of P recovery from SSA (with moderate chemical demand). There is still problem of the leached SSA and co-precipitated materials which have to be disposed, and the final product could contain some heavy metals. Other evaluated solution was the complete digestion of SSA in phosphoric acid and multi-stage cleaning with ion exchangers. In this method the recovery of P amounted 97%, and a high-quality product (H_3PO_4) and several coproducts (with an overall low environmental impact) have been obtained. In the thermo-chemical treatment of SSA, approx. 98% of P was recovered with moderate energy demand in the case of integration into an existing mono-incineration facility. Anyway, in this case the final product contains high amounts of selected heavy metals (zinc and copper). In the metallurgic treatment of dried sludge or SSA, up to 81% of P was obtained, but the information on the product quality, energy input, and energy recovery options are missing. The above results of the environmental impacts of P recovery from SSA have been evaluated in relation to a reference model of sludge treatment and disposal in mono-incineration (Remy, Jossa, 2015).

As mentioned, it is impossible to direct the comparison of the LCA results of the PolFerAsh technology with the provided in the P-REX project results since in the project (P-REX) "system change" perspective has been used in the evaluation. It means that all additional impacts of P recovery scenarios (i.e. changes between reference system and P recovery scenario) were allocated to the process of P recovery, assuming an annual time horizon, and the assumed functional unit was "per annual operation of a sludge line for 1 Mio pe WWTP", and in the current study it was defined as 1 Mg P_2O_5 contained in the fertilizer. Moreover, in the P-REX project different methodology has been adopted (ReCiPe). Anyway, the results of the P-REX project have played a particularly significant role in the LCA of P recovery technologies (Amann et al. 2018). It should be underlined that the results of the LCA could play a strategic role for the decision-makers and regulators in the aspect of searching and selection of the P recovery technologies. By the environmental evaluation of different alternatives in the P management it is possible to recognize and implement the most sustainable solutions, which are recommended by the EC as a way towards the circular economy. Moreover, the target group of LCA results should be industry representatives (technology developers and providers of P recovery processes), and operators of WWTPs (Remy, Jossa, 2015), who are able to implement P recovery technologies and thus reduce their dependence on imports in Europe. The implementation of P recovery solutions that have the lowest impact on the environment is currently supported by the EC, as one of the ways to achieve both – sustainable development goals (SDGs) and the assumptions of the CE (Smol 2019). Therefore, further development and implementation of technologies for the recovery of P from SSA (which show the highest P recovery potential and heavy metals elimination) should receive financial support in the new EU financial perspective 2021–2027.

Conclusions

The results of the LCA of the technologies for the fertilizers production from primary and secondary sources showed that both processes contribute to a potential environmental impact. The overall results showed that the production process of P-based fertilizer affects the environment primarily through the use of the phosphorous raw materials. The highest impact on the environment was obtained for the Scenario 2 (1.94899 Pt) in which P-based fertilizer (triple superphosphate) was produced form primary sources. Scenario 1a and 1b showed the environmental benefits associated with the avoiding of SSA storage and its emissions, reaching -1.3475 Pt and -3.82062 Pt, respectively. Comparing the results of LCA of P-based fertilizer production from different waste streams, it was indicated that better environmental performance was achieved

Table 5. Environmental impacts of P recovery from SSA in relation to a reference model of sludge treatment and disposal in mono-incineration for a 1 Mio pe WWTP (Remy, Jossa, 2015)

Technology/Scale	Pathways	P yield[1]	Fossil energy demand	Global warming	Eutrophication freshwater	Ecotoxicity	Human toxicity
Mephrec® Model	Ash metallurgic	ChemP[1]	81%	-14.5	1.1	38.9	51.8
Leachphos Large pilot	Ash leaching 1	ChemP[2]	70%	2.7	0.5	147.0	167.1
Ecophos Full-scale planning	Ash leaching 2	EBPR[2]	97%	-6.1	-2.1	-9.6	-8.5
Ash Dec Pilot/model	Ash thermo-chemical	EBPR[2]	98%	-8.1	-1.0	421.6	549.0
Ash Dec Pilot/model	Ash thermo-chemical (integr. in mono-inc)	EBPR[2]	98%	-12.6	-1.6	421.6	549.0

[1] related to total P load in raw mixed sludge = 100%,
[2] both EBPR and ChemP sludge or SSA possible,
ChemP – chemical phosphorus removal
EBPR – enhanced biological phosphorus removal

in the scenario 1b, in which SSA had the higher content of P (52.5%) in the precipitate. In this case the lower amount of the energy and materials, including phosphoric acid, was needed for the production of fertilizer, calculated as 1 Mg P_2O_5.

The presented results of the LCA could play a strategic role for the decision-makers during the selection of the most sustainable method of P-based fertilizer production from primary or secondary sources.

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References

Adam, C., Peplinski, B., Michaelis, M., Kley, G. & Simon, F. G. (2009). Thermochemical treatment of sewage sludge ashes for phosphorus recovery, *Waste Management*, 29(3), pp. 1122–1128.

Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M. & Egle, L. (2018). Environmental impacts of phosphorus recovery from municipal wastewater, *Resources, Conservation and Recycling*, *130*, pp. 127–139.

Bartolozzi, I., Baldereschi, E., Daddi, T. & Iraldo, F. (2018). The application of life cycle assessment (LCA) in municipal solid waste management: A comparative study on street sweeping services, *Journal of Cleaner Production,* 182, pp. 55–465.

Bradford-Hartke, Z., Lane, J., Lant, P. & Leslie, G. (2015). Environmental benefits and burdens of phosphorus recovery from municipal wastewater, *Environmental science & technology*, *49*(14), pp. 8611–8622.

Ciesielczuk, T., Rosik-Dulewska, C. & Kusza, G. (2016). Ekstrakcja fosforu z osadów ściekowych i popiołów ze spalania osadów – analiza problemu, *Polish Journal for Sustainable Development*, 20, 21–28.

Ciesielczuk, T., Rosik-Dulewska, C., Poluszyńska, J., Ślęzak, E. & Łuczak, K. (2018). Ashes from Sewage Sludge and Bottom Sediments as a Source of Bioavailable Phosphorus, *Journal of Ecological Engineering*, 19(4), pp. 88–94.

Chojnacka, K., Kowalski, Z., Kulczycka, J., Dmytryk, A., Górecki, H., Ligas, B. & Gramza, M. (2019). Carbon footprint of fertilizer technologies, *Journal of Environmental Management,* 231, pp. 962–967.

Cieślik, B. & Konieczka, P. (2017). A review of phosphorus recovery methods at various steps of wastewater treatment and sewage sludge management. The concept of "no solid waste generation" and analytical methods, *Journal of Cleaner Production*, 142, pp. 1728–1740.

Commission of European Communities. Communication. A strategy for smart, sustainable and inclusive growth Europe 2020 (COM No. 2020, 2010).

Commission of European Communities. Communication on the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative. (COM No. 297, 2014).

Commission of European Communities. Communication. Towards a circular economy: A zero waste programme for Europe (COM No. 398, 2014).

Commission of European Communities. Communication No. 614, 2015. Closing the loop – An EU action plan for the Circular Economy. (COM No. 2015, 614).

Commission of European Communities. Communication on the 2017 list of Critical Raw Materials for the EU (COM No. 490, 2017).

Commission of European Communities. Consultative Communication on the Sustainable Use of Phosphorus (COM no. 517, 2013).

Commission of European Communities. Communication on the Circular Economy Package. Proposal for a Regulation of the European Parliament and of the Council laying down rules on the making available on the market of CE marked fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 (COM no. 157, 2016).

Egle, L., Rechberger, H., Krampe, J. & Zessner, M. (2016). Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies, *Science of the Total Environment*, 571, 522–542.

Egle, L., Rechberger, H. & Zessner, M. (2014a): Phosphorrückgewinnung aus dem Abwasser (Phosphorus recovery from wastewater). Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Sektion VII Wasser, Vienna, Austria.

Egle, L., Rechberger, H. & Zessner, M. (2015). Overview and description of technologies for recovering phosphorus from municipal wastewater, *Resources, Conservation and Recycling*, 105, pp. 325–346.

Egle, L., Zoboli, O., Thaler, S., Rechberger, H. & Zessner, M. (2014b). The Austrian P budget as a basis for resource optimization, *Resources, Conservation and Recycling*, 83, pp. 152–162.

Environmental Protection Agency. (2002). *European waste catalogue and hazardous waste list,* Environmental Protection Agency (EPA 2002).

European Commission – Joint Research Centre, Institute for Environment and Sustainability, (2010). *Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment*, Background document, (ILCD) Handbook – International Reference Life Cycle Data System. First edition, Italy. Publications Office of the European Union (European Commission 2010).

European Commission, Joint Research Centre, Institute for Environment and Sustainability (2012). *Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods. Database and Supporting Information*. First edition. February 2012. EUR 25167. Luxembourg. Publications Office of the European Union (European Commission 2012).

Goedkoop, M.J., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. & Van Zelm, R. (2009). ReCiPe 2008, *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*. First edition, Report 1 Characterisation. Ministerie van VROM, Den Haag. Netherlands.

Feng, W. & Reisner, A. (2011). Factors influencing private and public environmental protection behaviors: Results from a survey of residents in Shaanxi, China, *Journal of environmental management*, 92(3), pp. 429–436.

Fehrenbach, H. & Reinhardt, J. (2011): *Ökobilanzielle Bewertung der in der Förderinitiative entwickelten Verfahren (LCA of investigated processes)*. In: Phosphorrecycling – Ökologische und wirtschaftliche Bewertung verschiedener Verfahren und Entwicklung eines strategischen Verwertungskonzepts für Deutschland (PhoBe) (Recycling of Phosphorus – Ecological and Economic Evaluation of Different Processes and Development of a Strategical Recycling Concept for Germany (PhoBe)), Aachen, Germany. (in German)

Gaska, K., Generowicz, A., Zimoch, I., Ciuła, J. & Iwanicka, Z. (2017). A high-performance computing (HPC) based integrated multithreaded model predictive control (MPC) for water supply networks, *Architecture Civil Engineering Environment*, 10(4), pp. 141–151.

Generowicz, A., Kulczycka, J., Kowalski, Z. & Banach, M. (2011). Assessment of waste management technology using BATNEEC options, technology quality method and multi-criteria analysis, *Journal of Environmental Management*, 92(4), pp. 1314–1320.

Gorazda, K., Tarko, B., Wzorek, Z., Kominko, H., Nowak, A. K., Kulczycka, J., Henclik, A & Smol, M. (2017). Fertilisers production from ashes after sewage sludge combustion–A strategy towards sustainable development, *Environmental research*, 154, pp. 171–180.

Heimersson, S., Svanström, M., Laera, G. & Peters, G. (2016). Life cycle inventory practices for major nitrogen, phosphorus and carbon flows in wastewater and sludge management systems, *The International Journal of Life Cycle Assessment,* 21(8), pp. 1197–1212.

Herzel, H., Krüger, O., Hermann, L. & Adam, C. (2016). Sewage sludge ash—a promising secondary phosphorus source for fertilizer production, *Science of the Total Environment*, 542, pp. 1136–1143.

ISO (International Organization for Standardization), 2006a. *ISO 14044: Environmental Management e Life Cycle Assessment – Requirements and Guidelines*.

ISO (International Organization for Standardization), 2006b. *ISO 14040: Environmental Management e Life Cycle Assessment – Principles and Framework*.

Jóźwiakowski, K., Mucha, Z., Generowicz, A., Baran, S., Bielińska, J. & Wójcik, W. (2015). Zastosowanie analizy wielokryterialnej do wyboru rozwiązania technologicznego przydomowej oczyszczzalni ścieków zgodnego z ideą zrównoważonego rozwoju, *Archives of Environmental Protection*, 41(3), pp. 76–82. (in Polish)

Kalmykova, Y. & Fedje, K.K. (2013). Phosphorus recovery from municipal solid waste incineration fly ash, *Waste Management*, 33(6), pp. 1403–1410.

Koneczna, R. & Kulczycka, J. (2011). Export Competitiveness of Polish Environmental Products in Select Manufacturing Sectors, *Polish Journal of Environmental Studies*, 20(6), pp. 1531–1539.

Kostecki, M., Janta-Koszuta, K., Stahl, K. & Łozowski, B. (2017). Speciation forms of phosphorus in bottom sediments of three selected anthropogenic reservoirs with different trophy degree, *Archives of Environmental Protection*, 43(2), pp. 44–50.

Kowalski, Z., Generowicz, A. & Makara, A. 2012. Ocena technologii składowania odpadów komunalnych metoda BATNEEC, *Przemysł Chemiczny*, 91(5), pp. 811–815. (in Polish)

Kowalski, Z., Kulczycka, J., Skowron, G. & Sobczak, A. (2007). Comparative evaluation of calcium feed phosphate production methods using Life Cycle Assessment, *Archives of Environmental Protection*, 33(1), pp. 83–94.

Kowalski, Z., Smol, M. & Kulczycka, J. (2018). Kompaktowany ("ciężki") tripolifosforan sodu, *Przemysł Chemiczny*, 97(4), pp. 575–578. (in Polish)

Krüger, O., Grabner, A. & Adam, C., (2014). Complete survey of German sewage sludge ash, *Environmental Science & Technology,* 48(20), pp. 11811–11818.

Kulczycka, J., Lelek, L., Lewandowska, A. & Zarebska, J. (2015). Life Cycle Assessment of Municipal Solid Waste Management – Comparison of Results Using Different LCA Models, *Polish Journal of Environmental Studies*, 24(1), pp. 125–140.

Łukawska, M. (2014). Analiza specjacyjna fosforu w osadach ściekowych po termicznym spaleniu, *Inżynieria i Ochrona Środowiska*, 17 (3), pp. 433–439. (in Polish)

Makara, A., Smol, M., Kulczycka, J. & Kowalski, Z. (2016). Technological, environmental and economic assessment of sodium tripolyphosphate production – a case study, *Journal of Cleaner Production,* 133, pp. 243–251.

Moghim, S. & Garna, R. K. (2019). Countries' classification by environmental resilience, *Journal of Environmental Management,* 230, pp. 345–354.

Nakakubo, T., Tokai, A. & Ohno, K. (2012). Comparative assessment of technological systems for recycling sludge and food waste aimed at greenhouse gas emissions reduction and phosphorus recovery, *Journal of Cleaner Production*, 32, pp. 157–172.

Nessi, S., Rigamonti, L. & Grosso, M. (2012). LCA of waste prevention activities: a case study for drinking water in Italy, *Journal of Environmental Management*, 108, pp. 73–83.

Pré Consultants B.V. *SimaPro 8.0.4.3 User Manual*. 2016.

Remy, C. & Jossa, P. (2015). Sustainable Sewage Sludge Management Fostering Phosphorus Recovery and Energy Efficiency. Life Cycle Assessment of Selected Processes for P Recovery from Sewage Sludge, Sludge Liquor or Ash. EU P-REX Project. Report Deliverable D 9.2.

Scheidig, K., Mallon, J., Schaaf, M. & Riedl, R. (2013).. P-recycling fertilizer from the melt gasification of sewage sludge and sewage sludge ash, *KA–Korrespondenz Abwasser, Abfall*, *10*, 845–850. (in German)

Smol, M. (2019). The importance of sustainable phosphorus management in the circular economy (CE) model: the Polish case study, *Journal of Material Cycles and Waste Management*, 21(2), 227–238.

Smol, M., Kulczycka, J., Henclik, A., Gorazda, K. & Wzorek, Z. (2015). The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy, *Journal of Cleaner Production*, *95*, 45–54.

Smol, M., Kulczycka, J. & Kowalski, Z. (2016). Sewage sludge ash (SSA) from large and small incineration plants as a potential source of phosphorus–Polish case study, *Journal of environmental management,* 184, 617–628.

U.S. Geological Survey (2018). *Mineral commodity summaries 2018*, U.S. Geological Survey, doi.org/10.3133/70194932.