Resources, Conservation & Recycling 130 (2018) 127–139

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Environmental impacts of phosphorus recovery from municipal wastewater

A. Amann[a,b,*], O. Zoboli[a,b], J. Krampe[a], H. Rechberger[a,b], M. Zessner[a,b], L. Egle[a,b]

[a] Institute for Water Quality, Resource and Waste Management, TU Wien, Karlsplatz 13/226, 1040 Vienna, Austria
[b] The Centre for Water Resource Systems (CWRS) at TU Wien, Karlsplatz 13/222, 1040 Vienna, Austria

ARTICLE INFO

Keywords:
Phosphorus recovery
Wastewater
Life cycle assessment
Environmental impacts
Material flow analysis
Energy analysis

ABSTRACT

Phosphorus mining from phosphate rock is associated with economic as well as environmental concerns. Through phosphorus recovery from municipal wastewater, countries could decrease their dependency on the global phosphate rock market, however, conceivably leading to an increase in environmental impacts from fertilizer production. In this work 18 phosphorus recovery technologies are evaluated in terms of cumulative energy demand, global warming potential and acidification potential with the methodology of life cycle analysis. These indicators are then contrasted with other environmental criteria, i.e. recovery potential, heavy metal and organic micropollutant decontamination potential and fertilizer efficiency, to determine their overall environmental performance. The LCA shows that a broad spectrum of changes in gaseous emissions and energy demand can be expected through the implementation of P recovery from wastewater. Linkage to further environmental performance results exposes certain trade-offs for the different technologies. Recovery from the liquid phase has mostly positive or comparably little impacts on emissions and energy demand but the low recovery potential contradicts the demand for efficient recycling rates. For recovery from sewage sludge, those technologies that already are or are close to being applied full-scale, are associated with comparatively high emissions and energy demand. Recovery from sewage sludge ash shows varying results, partly revealing trade-offs between heavy metal decontamination, emissions and energy demand. Nevertheless, recovery from ash is correlated with the highest potential for an efficient recycling of phosphorus. Further research should include implications of local infrastructures and legal frameworks to determine economically and environmentally optimised P recovery and recycling concepts.

1. Introduction

Phosphorus (P), as an essential nutrient for all life, takes on a substantial and non-replaceable role in our environment. Nevertheless, current P use practices are accompanied by various environmental concerns, as mining of P from raw phosphate rock (PR) leads to emissions to the air and eutrophication of water bodies, land degradation through phosphogypsum stacks near the mining site (phosphoric acid production) and soil contamination through cadmium (Cd) and uranium (U) application with fertilizers (FEI, 2000; Silva and Kulay, 2003, 2005; Spiegel et al., 2003; Smidt et al., 2012; Hakkou et al., 2016; Kratz and Schnug, 2016). While these environmental concerns cannot be neglected, it were economic concerns, i.e. the increasing awareness of the concentrated PR-mining in only a handful of countries worldwide, the overall increasing demand for P and the fact that PR is a non-renewable resource, that led the European Commission to declare PR as a critical raw material in 2014 (EC, 2014).

Simultaneously, research, governments and industry recognised the importance of another, for the major part unexploited P source: municipal wastewater. Municipal wastewater has the potential to substitute a significant portion of the demand for PR (Binder et al., 2009; Egle et al., 2014; Zoboli et al., 2016a,b) and therefore to increase circular economy while simultaneously reducing overall environmental impacts from current P use practices. Intensive research and innovation in recent years has led to the development of a broad spectrum of technologies for phosphorus recovery from wastewater. Their development was accompanied by comparative studies, dealing mainly with the technical and economic assessment of these technologies, in order to identify those that are technically applicable and can be considered market-feasible alternatives to PR-mining and conventional fertilizer production (Cornel and Schaum, 2009; LfU, 2015; Fux et al., 2015; Egle et al., 2015, 2016; Nättorp et al., 2017). However, to provide a more comprehensive picture for legislators dealing with how future P-recycling can be best put into action, knowledge as to how different technologies could impact the environment is an additional prerequisite. Bearing in mind the environmental impacts from

* Corresponding author at: Institute for Water Quality, Resource and Waste Management, TU Wien, Karlsplatz 13/226, 1040 Vienna, Austria.
E-mail address: aamann@iwag.tuwien.ac.at (A. Amann).

https://doi.org/10.1016/j.resconrec.2017.11.002
Received 23 February 2017; Received in revised form 25 October 2017; Accepted 1 November 2017

conventional fertilizer production, such assessments are also indispensable to avoid the replacement of one environmental problem (e.g. land degradation through PR mining) with another (e.g. increased energy demand for P recovery).

Environmental impact assessment related to P recovery from municipal wastewater and sewage sludge treatment and recycling has been covered by some studies in the past. Johansson et al. (2008) studied sewage sludge recycling options, namely use for restoration, composting, hygienisation and agricultural use and also one super-critical oxidation P recovery technology (AcquaReci®). Of special importance for this work is that (i) they found the consideration of environmental savings for PR-derived fertilizer replacement to have large impacts on the results, and (ii) the magnitude of these savings depends on the amount but, more importantly, also on the fertilizer that is assumed to be replaced. Further, the P recovery technology AquaReci® was correlated with environmental savings due to the simultaneous possibility for energy recovery, and due to the stabilisation of the sludge through total destruction of organic material. Major environmental impacts were however derived from the use of magnesium oxide, a first indication that indirect effects through chemical use can be expected to play a major role in this work. Buonocore et al. (2016) also found different circularity patterns of reuse in WWTP (especially co-digestion of sludge with reuse of effluent water for fertirrigation of energy crops) to decrease overall environmental impacts of WWTPs, e.g. effects on climate change, fossil depletion, eutrophication, human toxicity and terrestrial acidification. However, they doubted that the use of eutrophication and human toxicity indicators are appropriate tools to evaluate potential impacts in these categories as local conditions are highly relevant, but cannot be accounted for in the assessment. Lederer and Rechberger (2010) attributed a thermo-chemical treatment process that recovers P from sewage sludge ash (SSA) as more effective in terms of P recycling compared to agricultural sludge application and mono-incineration with soil application of the residual ash. Correlated advantages were organic micropollutant (OM) and heavy metal removal, however, with low additional emissions but higher energy requirements, revealing certain trade-offs between different environmental criteria in the case of P recovery. Compared to a conventional mineral P fertilizer, findings from Linderholm et al. (2012) indicate a higher energy demand and lower greenhouse gas emissions through struvite precipitation of P and higher energy demand and emissions through recovery from SSA with the AshDec® process. They therefore detected large differences in environmental effects from those technologies especially due to varying chemical use and energy requirements.

Nevertheless, none of the presented studies deal with comparing the broad spectrum of currently available P recovery technologies. In this context, the profound study done by Remy and Jossa (2015) inside the EUs P-REX project has played a particularly significant role in the life cycle assessment (LCA) of P recovery technologies and was beneficial for comparison and plausibilisation of the results in this work. Though a similar assessment approach was used by Remy and Jossa as in the here presented work, various modelling choices in their study (e.g. use of sludge from a reference WWTP of 1,000,000 PE, focus on the sludge treatment line with only simplified accounting for altered return loads to the WWTP) do not consider all impacts of material flows changes on the whole wastewater treatment process and do not reflect more medium-scale WWTPs (as mainly present e.g. in Austria) to a satisfying extent. In addition, the here presented work provides the final piece to a comprehensive study on P recovery from wastewater. Previously published work dealt with the quantification of unexploited phosphorus flows (Egle et al., 2014), an overview of the technologies that were assessed (Egle et al., 2015) and an integrated comparative technological, environmental and economic assessment to determine optimal recovery concepts and technologies (Egle et al., 2016). In Egle et al. (2016) a first set of environmental criteria seen as directly relevant to phosphorus recycling and soil conservation (i.e. nutrient, heavy metal and organic micropollutant content, direct heavy metal emissions particularly to soil, recovery rate and solubility/plant availability) was addressed by using material flow analysis (MFA), the damage unit (DU) method, the reference soil method and knowledge taken from a literature review. This work complements these criteria by using LCA to analyse further impacts (i.e. gaseous emissions and energy demand) that are not in direct relation to the agricultural application of products, but provide additional information for legislators and decision makers on global and national relevant aspects. In this context, this work will refrain from using a fully aggregated impact factor through choosing weighting coefficients for the single impact factors, since (i) only some environmental impacts are calculated via LCA and (ii) it is preferred to rather provide a set of results, where trade-offs between different criteria are fully disclosed, than an incomprehensible absolute value. The same approach was taken by Remy and Jossa (2015), therefore applying the same allows for an enhanced comparison between two studies that can be seen as complementary in each other as they look at this topic from two different contexts and scales.

As P recovery technologies are implemented at, or in succession to WWTPs and can have beneficial or unfavourable impacts on their environmental footprint (e.g. reduction energy demand, de/increase of chemical use), this study aims at analysing these impacts in relation to a defined reference WWTP. In addition, putting into place a successful circular economy concept for P will replace a share of the demand for PR-derived fertilizer and therefore reduce the overall environmental impact of PR-derived fertilizer production, which can be accounted for as credits. Finally, to provide the adequate perspective with P being a major, non-substitutable nutrient for all human life, this work will compare the environmental impacts from P-recycling to our overall impacts per capita.

2. Materials and methods

The potential emissions and energy demand brought forth by the different P recovery technologies are analysed through life cycle assessment (LCA; ISO standard 14040, 2006). LCA is a widely used methodology to quantify environmental impacts of a technology, in this case for the recovery of a P material. Through adequate system boundaries, LCA supports the incorporation of all related impacts not only on-site but also preceding and succeeding a technology (e.g. utility production, waste disposal). This enables the comparison of environmental impacts from fairly different technologies and material uses, as is the case in this study. In accordance with ISO 14040, the steps undertaken in this study are defining system boundaries, the functional unit and environmental indicators, setting up a life cycle inventory of related material flows, performing the impact assessment and lastly, interpreting the results.

2.1. System and boundary definition

To analyse additional or reduced environmental impacts of P recovery from wastewater, the status quo is defined first. For this purpose, a typical WWTP with a pollution load of 100,000 population equivalents (PE) (corresponding to a P_{tot} load of 65,700 kg a^{-1}), a mono-incineration plant for sewage sludge and a waste management process for treatment and disposal of occurring wastes are chosen as a reference system (see detailed descriptions of the reference system in previous work by Egle et al. (2015, 2016) and for chosen resource demand in Tables A2–A4). The only adaption made in comparison to previous work was to change the co-incineration to mono-incineration for the reference system, as to avoid alteration of the results due to the impact of a change in energy yield. This impact should of course not be neglected for optimising national sludge disposal and P recovery concepts when co-incineration is part of the current treatment schemes. Final receiving compartments for this reference system are the processes of waste management, soil/agriculture, the atmosphere and the hydrosphere, each with a stock function. The system is structured as a