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Phosphorus Recovery from Wastewater – State-of-the-Art and Future Potential

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Abstract

Today, there are already a variety of very different approaches to the recovery of phosphorus from wastewater, sludge and ashes. These approaches differ by the origin of the used matter (wastewater, sludge liquor, fermented or non-fermented sludge ash) and the process (precipitation, wet chemical extraction, and thermal treatment). They are characterized by their process steps, use of chemicals, complexity and effectiveness of the technology, economics, product quality for further use (fertilizer or industrial use), residuals, maturity of the technology, and degree of centralization and are rated positive, negative or neutral. Together these characteristics form the advantages and disadvantages of all the recovery processes. These were phrased as hypotheses that were used in an international expert survey.

The survey showed that P-recovery will become an established process over the next 20 years in industrialized countries for economic reasons. A decisive aspect in this regard will be the quality of the produced fertilizer. Simple technologies such as the recovery from sludge liquor seem to be preferred. If sludge is incinerated, P-recycling from ash then becomes more interesting and has to be considered. P-recovery and source separating sanitation technologies are more appropriate for industrialized countries than for developing countries. As the growing awareness of environmental issues will prevent sludge being used agriculturally in an increasing number of countries in the next decade, the market potential for nutrient recovery technologies will increase in the immediate future.

Keywords

Phosphorus, recovery, wastewater, sludge, sludge ash, economic potential

1 Introduction

According to Cordell et al. (2009) and USGS (2010), the reserves-to-production ratio of phosphate is between 100 and 120 years. However, producing phosphate will become more difficult and expensive much earlier than this because of worsening accessibility and increasing contamination with substances like cadmium and uranium (von Horn and Sartorius 2009). This will raise the price for rock phosphate substantially and the price could increase even more due to temporary shortages in supply and speculation as was the case in 2007/8. While the supply will diminish in the future, demand will continue to rise because ever more biomass will need to be produced to feed an increasing global population and satisfy its growing demand for renewable energy. One way out of this mounting discrepancy is to recover phosphorus (P) from various P-rich wastes like sewage sludge or meat and bone meal.

The interest in nutrient research and especially in P-recovery has increased constantly over the last decade. Phosphate precipitation from wastewater has an even longer history as this has long been used to avoid the emission of P into, and thus the eutrophication of, rivers and lakes. This has also been used for some time to prevent pipes in wastewater treatment plants being clogged with high phosphate loads (industrial processes, enhanced biological treatment plants). As a result, a considerable number of different P-recovery technologies has been researched and developed.

After a short overview of the existing variety of P-recovery technologies (in section 2), we present the methodology (in section 3) and results (in section 4) of a survey of experts in the field of P-recovery concerning (i) the necessity and general potential of P-recovery, (ii) the potentials for P-recovery technologies from wastewater and sludge and (iii) from sludge ash, and (iv) the role of P-recovery in the context of the separation of material flows. The results and conclusions are presented in section 5.

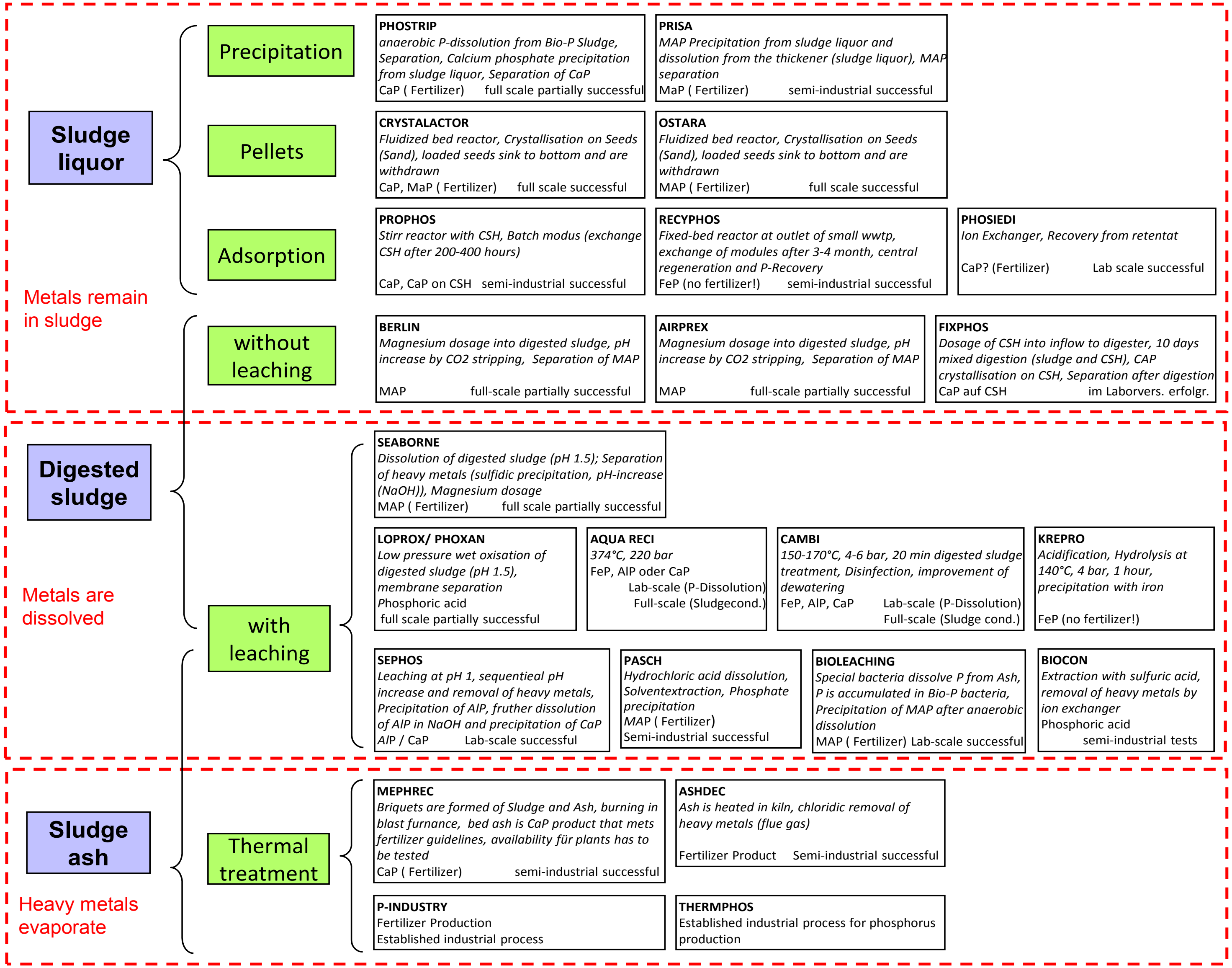
2 BACKGROUND: A COMPARISON OF P-RECOVERY TECHNOLOGIES

2.1 The basic methods of P-recovery

Based on the existing literature, information from the internet and a series of interviews, we were able to distinguish 22 different P- recovery technologies. These were then categorized by the origin of the used matter (wastewater, sludge liquor, fermented or non-fermented sludge, ash) and the three major recovery processes (precipitation, wet-chemical extraction and precipitation, and thermal treatment).

In Figure 1 the basic recovery process (shown in a red dashed box) is the main feature used to structurally distinguish the different technologies and, accordingly, the fate and behavior of the metal ions which are also contained in the wastewater and sludge but which should not contaminate the final product of the P-recovery process. In the precipitation process, phosphate dissolved in the (waste) water or sludge liquor is precipitated or adsorbed, whereas the metal ions remain bound in the sludge and are not (co-)precipitated with the phosphate. If P is to be recovered from the sludge, it first has to be dissolved using a strong acid, heat and/or pressure. Since the metals are also dissolved during this wet-chemical extraction, the metal ions and phosphate then have to be separated before the phosphate product can be precipitated. This requires an intensive use of chemicals and makes the process complex and expensive. If the sludge is incinerated, all the organic substances including the toxic compounds and the most volatile metal compounds are removed. To capture all or at least most of the remaining metal ions, the ash has to undergo a thermal-metallurgical treatment.

Figure 1 Comparison of processes for the recovery of phosphorus from wastewater, sludge, sludge liquor and sludge ash



Within the red boxes, similar processes are placed next to each other. The precipitation processes can be categorized into four different sub-groups: precipitation from liquid (Phostrip, Prisa), pellet formation (Crystalactor, Ostara), adsorption to a carrier (Prophos, Recyphos, Phosiedi) and precipitation in the sludge without prior leaching (Berlin, Airprex, Fixphos). In the Phostrip process (von Horn 2007), phosphate is precipitated from the sludge liquor of the return stream whereas in the Prisa process the precipitation is from the liquor of excess sludge (Montag 2008). The difference between the Crystalactor (Giesen 2009) and the Ostara (Britton 2009) process is the size of the reactor. Furthermore the Crystalactor was developed for the precipitation of multiple ions from industrial wastewater. Prophos (Petzet 2009) is an adsorption reactor working in batch modus and produces calcium phosphate. Recyphos is a concept for small wastewater treatment plants (the produced ironphosphate has to be further processed at a central plant). Phosiedi is an Ion exchanger where phosphate is precipitated from the retentate. Airprex works under a license with the Berlin process. The Berlin process is currently improving the separation of the product from the sludge (Stumpf et al. 2009). In the Fixphos process the phosphate product (Calciumphosphate) is already precipitated in the digester.

For the wet-chemical processes the differences are in the applied extraction chemicals, pressure and temperature as well as in the starting material used (sludge or ash). Seaborne (Bayerle 2009) is a process that dissolves the digested sludge at pH 1.5. In the Loprox/Phoxnan process (Blöcher et al. 2009) membranes are used to separate the phosphate ions (phosphoric acid is produces). Aqua Reci (Stenmark et al. 2005), Cambi (Sievers et al. 2005) and Krepro (Recktenwald 2002) use different high temperatures and pressures for the dissolution of the sludge. In these processes the products need further processing before they can be used in agriculture. Biocon, Sephos (Schaum 2008) and Pasch (Pinnekamp et al. 2007) dissolve ash at pH 1. Pasch works with solvent extraction and Sephos with sequential precipitation to eliminate the metals before the phosphate product is precipitated. Biocon works with an ion exchanger. In the Bioleaching (Zimmermann and Dott 2009) process, special bacteria dissolve phosphate from the ash. Afterwards phosphate is accumulated in bio-P bacteria and can be precipitated after anaerobic dissolution.

For P-recovery by the thermal treatment of sewage sludge (and meat-and-bone meal), the processes can be distinguished according to the thermal process employed or the chemical industry process receiving the ashes.

The Mephrec (Scheidig et al. 2009) process can use a certain amount of sewage sludge and meat-and-bone meal. Contrary to the Ash Dec (Hermann 2009) process the incineration is part of the Mephrec process. Whereas Thermphos produces pure phosphate for industrial use, the fertilizer industry produces multi-component fertilizer products.

2.2 Basic comparison of the methods

PRECIPITATION FROM LIQUID PHASE VERSUS WET-CHEMICAL PROCESS

Compared to the wet-chemical process, precipitation from the liquid phase is a simple process. About 40 % of the phosphate (of WWTP influent) can be recycled in two process steps by adding a magnesium compound as the precipitant. Wet-chemical processes show recovery rates of up to 90 % for sludge and sludge ash, but large amounts of chemicals and many process steps are required, which mean the processes have high investment and operation costs.

Recycling P from the liquid phase can be done on a small or a large scale and at nearly every WWTP whereas the wet-chemical process requires fermentation of the sludge, which is not economical on a small scale. If the sludge is mono-incinerated (i.e. with no other fueling substances present), a wet-chemical P-recovery from the ash is also possible.

Metals remain in the sludge during the precipitation process. The wet-chemical treatment starts with the extraction of P and all metals contained in the sludge. After being dissolved, the phosphate and the metal ions have to be precipitated separately in different steps in order to obtain an uncontaminated phosphate product. This requires large amounts of chemicals and acid-resistant equipment. The process also produces many different residuals (metals, sludge with low pH, leachates) that have to be neutralized and disposed of at high costs. Both technologies can produce fertilizer products for direct use in agriculture.

WET-CHEMICAL PROCESS VERSUS THERMAL-METALLURGICAL TREATMENT

Both processes are complex. The wet-chemical process requires a large number of chemicals whereas the thermal-metallurgical process requires a lot of energy which leads to high operational costs for both processes. The Mephrec process can use energy from sludge incineration which improves the energy balance and makes the process more economical.

Thermal-metallurgical treatment plants can only use mono-incinerated ash. Both the thermal treatment and incineration are large-scale processes. Every ash treatment plant can be combined with several incineration plants, which limits the number of plants. However, the ash can also be easily transported over distances up to 200 kilometers. Basically the amount of recycled phosphate is limited by, and dependent on the rate of mono-incineration. Wet-chemical treatment requires fermentation, which is part of most bigger WWTPs. So most of the phosphate from WWTPs could be recycled using this process.

The wet-chemical process can produce pure fertilizer products for agriculture. The products from thermal-metallurgical treatment meet the requirements for fertilizer products (nickel can be a problem) but are impure fertilizers (bed ash products). The plant availability of the phosphate was a problem to start with, but has been improved recently. The quality of the improved product is still being tested in comparison to other fertilizer products. The wet-chemical process has a more critical rating with regard to residuals as these include high amounts of acid-diluted sludge compounds and leachates.

3 THE EXPERT SURVEY: METHODOLOGICAL ASPECTS

While we were able to identify a wide range of different technical approaches to the recovery of phosphorus from wastewater, these approaches differ substantially with regard to their actual state of development, scale and performance. Moreover, many of the data collected could not be validated and were subject to considerable uncertainty. So we decided to base the comparative evaluation of the available technology approaches not directly on the techno-economic data collected (shown in section 3), but on the opinion of experts in the field of P- recovery. Hypotheses were formed based on the techno-economic results and the experts were asked to judge these hypotheses on a 5-unit scale ranging from full agreement to total disagreement, with indifference located in the middle. In some cases, the question was when rather than whether a technology would reach a certain degree of maturity. Then, alternatively, the judgments had to be given in terms of a time scale from 2015 in the short term through 2030 and 2050 in the medium term to later and never.

Altogether, we formed 23 hypotheses (shown in Annex 1) that were clustered under 4 headings. In the first set of 6 hypotheses we asked the experts how urgent they consider the need for P-recovery and when and under which conditions P-recovery will take place on a large scale in the future. The second set of (6) hypotheses asked for an estimation of the potential of different approaches to P-recovery from wastewater and sewage sludge. In the third set, another 6 hypotheses focused on different determinants of the potential of P-recovery from the ash resulting from sludge incineration. Finally, we used another 5 hypotheses to find out about the potential of a transformed water management system for the recovery of wastewater-borne phosphorus.

We contacted 417 experts in 40 countries for the survey, which was conducted in March and April 2010. The experts were the participants at two conferences, the International Conference on Nutrient Recovery from Wastewater Streams in Vancouver (Canada) in May 2009 and the Baltic 21 in September 2009 in Berlin. Additionally we used the mailing lists of the website “Phosphorous Recovery” (http://www.phosphorus-recovery.tu-darmstadt.de) of the IWAR Institute of the Technische Universität Darmstadt and the Centre Européen d’Études des Polyphosphates (CEEP) as addressees, both of which can be assumed to consist of experts in the field of P-recovery to a large extent. In total, the questionnaire was completed by 197 experts (= 47 %) from30 countries (see Table 1).

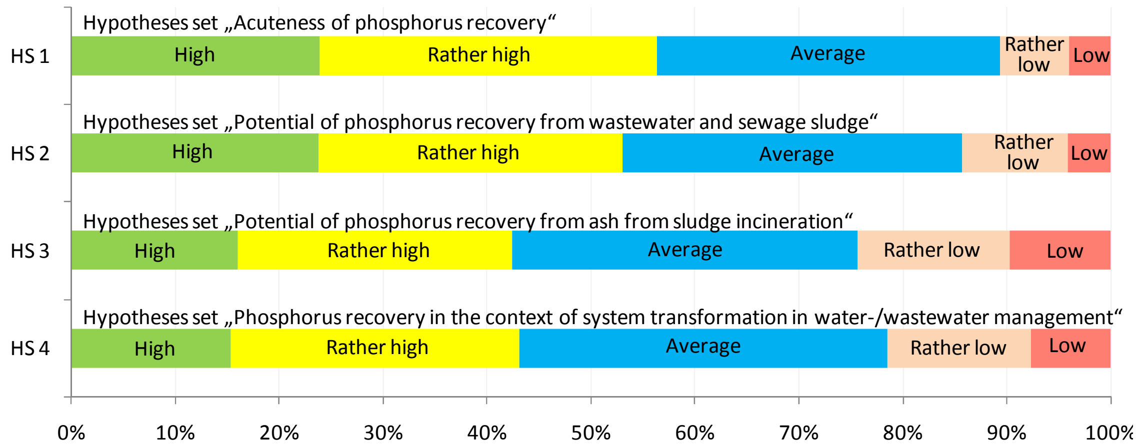
Table 1 Number of survey participants by country of origin

Germany	83	Denmark	5	Poland	3
Canada	21	Japan	5	China	2
USA	17	France	4	Finland	2
Netherlands	9	Switzerland	4	Other countries*	1 each
Sweden	6	Australia	3		
UK	6	Austria	3	Unknown origin	9

Note: Other countries are: Belgium, Brazil, Bulgaria, Chile, Ireland, Israel, Italy, Croatia, Malaysia, New Zealand, Norway, Russia, Singapore, Spain and the Czech Republic

To account for the fact that the survey participants may have different levels of expertise for the different sets of hypotheses, we asked them to indicate their level of (self-assessed) expertise at the end of each set (see Figure 2). This enabled us to specifically assess the responses of high-level experts and yielded more unambiguous results in some cases (see next section).

Figure 2 Shares of survey participants with self-assessed levels of expertise reaching from high to low for the 4 sets of hypotheses

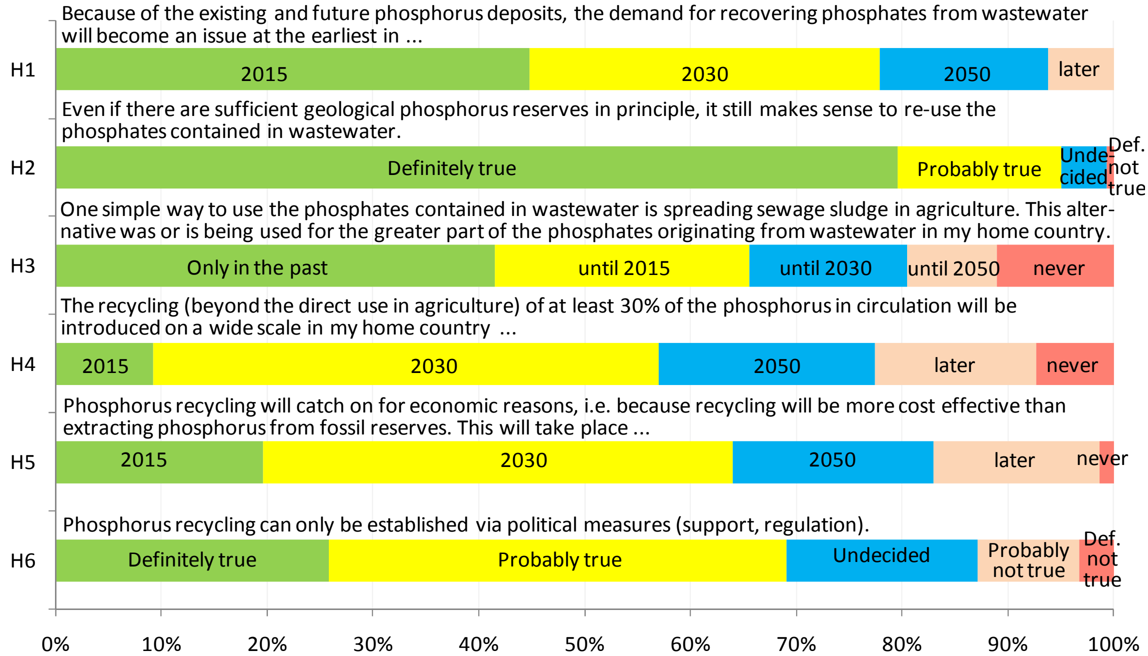


4 RESULTS OF THE EXPERT SURVEY

4.1 Urgency and implementation of P-recovery

The first set of hypotheses focused on the urgency of the need for P-recovery (see Figure 3). In order to frame the problem for the survey participants, it was assumed in the introductory remark that the exploitation of geological phosphorous reserves has a finite perspective, but it nevertheless remains a matter of controversy whether the need for P-recovery is pressing. Hypothesis 1 asked the experts to judge the urgency of P-recovery in view of the finiteness of the existing P reserves. Most of them (44 %) chose 2015 (the earliest possible point in time) and 77 % 2030 or earlier. Only 23 % selected 2050 or later and no one claimed that there will never be such a need. This result is surprising insofar as the static reserves are generally believed to last for 80 years or more. However the result is confirmed by the (strong) agreement of (79 %) 94 % of the respondents with the normative hypothesis 2 that P-recovery should take place even if the geological reserves are far from exhaustion.

Figure 3 Survey results for hypotheses set „Acuteness of P-recovery“



Although the use of sewage sludge in agriculture is well known and widely practised in many countries, less than a quarter of the survey respondents saw this as an approach to P-recovery with future potential (until 2030 or 2050) (hypothesis 3). For 42 % it was an important approach (only) in the past and 24 % consider it an alternative for only a very limited period of time (up to 2015). For the remaining 11 % it neither was nor will be a viable alternative in their home country. Analyzing the country-specific responses reveals that participants from countries with a critical stance to the use of sewage sludge in agriculture (such as Switzerland, the Netherlands and Germany) assign a much lower potential to this approach than participants from countries where it is commonplace (such as Denmark, the US, Japan and Canada). Beyond the direct use of sewage sludge (hypothesis 4), only 9 % of the experts see a potential for significant P-recovery in the short term (by 2015). However, the majority (58 %) believes that 30 % could be recovered by 2030.

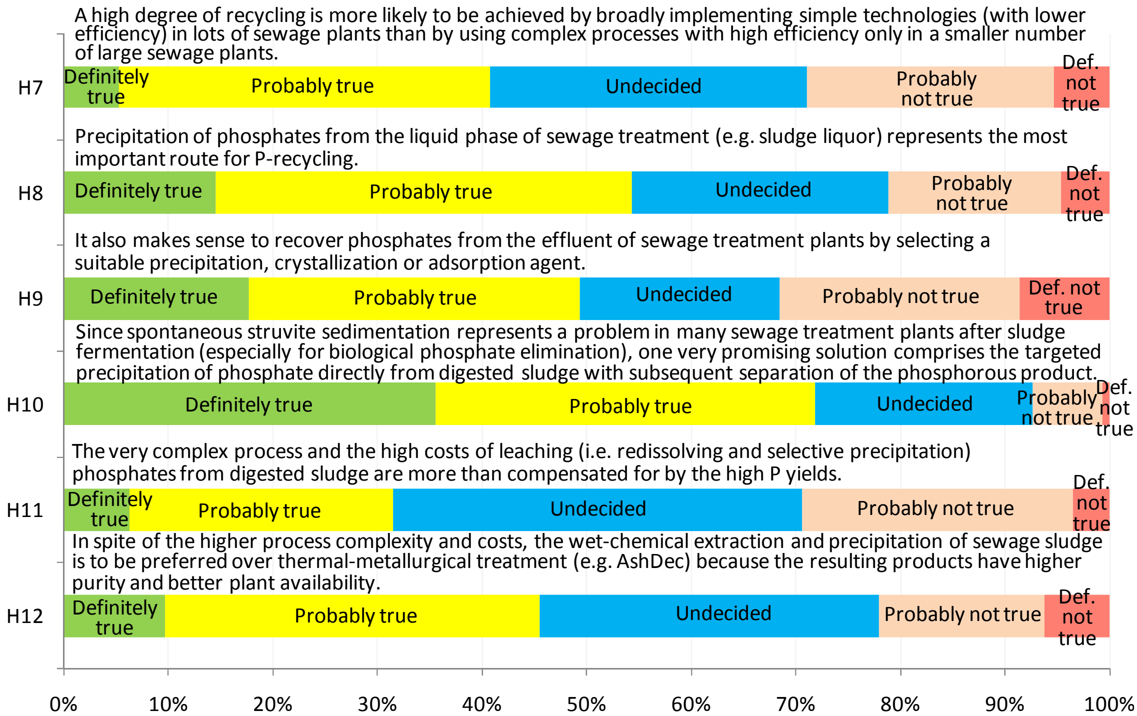
Asked for the driving force behind the recovery of phosphorus (beyond the use of sewage sludge in agriculture), almost 20 % of the respondents believe economic favorability (i.e. recovered P being less expensive than rock phosphate; hypothesis 5) is the major factor until 2015 and this rises to almost two thirds (64 %) until 2030. In this context, 60 % see industrial countries as the primary regions for the diffusion of P-recovery technologies, while only 30 and 10 %, respectively, see emerging economies or developing countries as the primary markets. Interestingly, despite their confidence in the short-to-medium term economic viability of P-recovery, more than two thirds (68 %) of the experts think that additional political measures like regulation or incentives are necessary to establish P-recycling.

The highly positive response to both early economic viability (by 2030) and the need for governmental support of P-recovery raised the question whether the same respondents who believed in early economic viability also saw a need for governmental support, or whether the two groups may have taken opposite stances. A comparison of the actual responses to hypotheses 5 and 6 showed no correlation ($R^2<0.02$). So both speculations could be ruled out. Nor could any correlation be identified between the responses to hypotheses 2 and 6 ($R^2=0.004$), which means that those experts in favor of P-recovery are not also in favor of government intervention. In contrast, many experts who believe that there will soon be more than 30 % P-recovery also believe in the short-term economic viability of the relevant processes.

4.2 Potentials of P-recovery from wastewater and sewage sludge

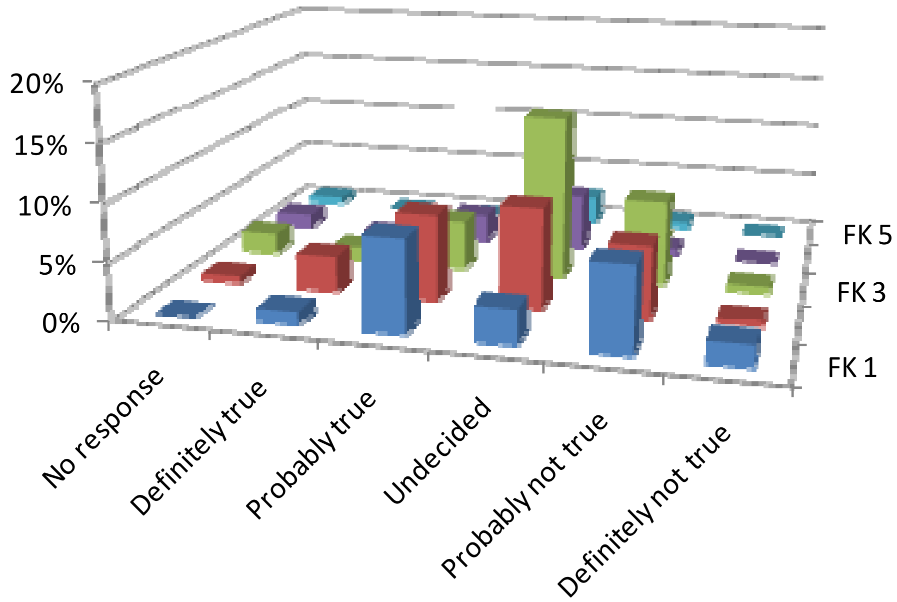
After stating that a variety of approaches to P-recovery from wastewater already exists, some of which have even proven their practical applicability, we asked the experts for a comparative evaluation of different alternatives (see Figure 4). More than half of them (53 %) fully or predominantly agreed that the precipitation of phosphates from the liquid phase of sewage treatment (e.g. sludge liquor) is the most important route for P-recycling (hypothesis 8). Only 22 % disagreed. P-recovery from the effluent of sewage treatment plants (after selecting a suitable precipitation, crystallization or adsorption agent; hypothesis 9) received fewer votes (49 % pro vs. 32 % con). The implication of this weaker support – that the internal streams of a wastewater treatment plant (including sludge and sludge liquor) are the preferable targets for P-recovery – is well supported by the very positive evaluation of hypothesis 10 (71 % agreement and only 8 % disagreement). This stated that the targeted precipitation of phosphate directly from sludge with subsequent separation of the P product is a promising solution to the problems with spontaneous struvite sedimentation occurring in many treatment plants. Moreover, if P needs to be precipitated anyway, it makes sense to think about its recovery at this state of the process.

Figure 4 Survey results for hypotheses set „Potential of P-recovery from wastewater and sewage sludge“



If P is to be recovered from sludge rather than its liquor, there is the additional problem of toxic organic compounds and heavy metals contaminating the sludge and, perhaps, the P product. In order to decontaminate the product, the phosphate needs to be redissolved and selectively precipitated – a complex and costly process. According to the survey results, the respondents appear to be rather ambivalent about this effort at first sight. Only 31 % are ready to justify the higher cost with the higher yield of P associated with this process (hypothesis 11); 30 % do not share this view. However, closer inspection shows that if the evaluation is restricted to the respondents with high expertise, two distinct groups can be identified – one in favor of and one against the additional effort (see Figure 5). Analyzing the correlation between the results of hypotheses 10 and 11 shows that those in favor of P precipitation from sludge are clearly more likely to accept the higher cost for the purification of the product than those voting against P precipitation from sludge in the first place ($R^2 = 0.263$). In other words the votes diverge depending on the beliefs or interests of the respective respondents. A divergence according to nationality, which would reflect different stances with regard to the need for P-recovery technologies to be economically viable or the use of untreated sludge in agriculture, could not be detected.

Figure 5 Dependence of the evaluations of hypothesis 11 on the respondents' expertise (FK 1 = high expertise ... FK 5 = low expertise)



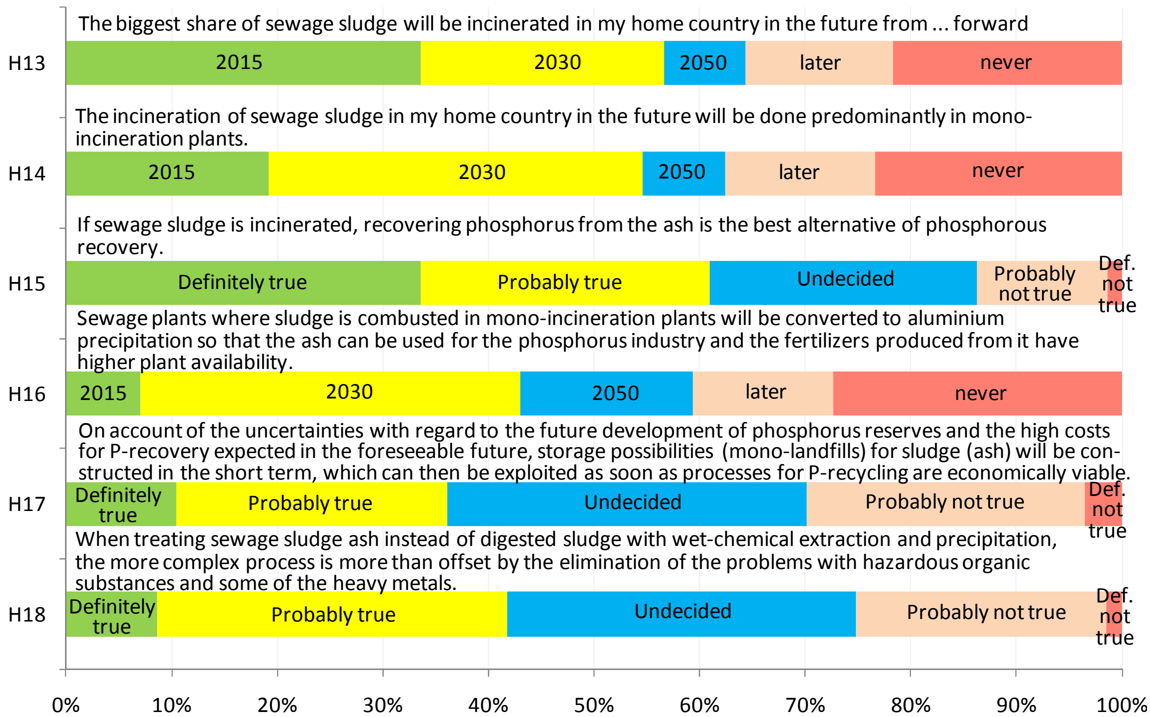
In contrast to hypothesis 11, the share of proponents of the more costly process increases to 45 % (and that of the skeptics declines to 22 %) if the higher cost is associated with higher quality and a better plant availability of the P product (see hypothesis 12).

As a preliminary conclusion with regard to P-recovery from the internal streams of a WWTP, the experts appear to prefer the less costly approaches even at the expense of lower yields. If, however, pollutants contained in the sludge are considered a problem, they then seem ready to employ more advanced and costly processes. This ambivalence also appears to be reflected in the evaluation of hypothesis 7, which shows no clear preference (40 % pro vs. 30 % con) for the trade-off between achieving a high rate of P-recovery through the broad implementation of more simple technologies and the more selective implementation of more complex processes with higher efficiency.

4.3 Potentials of P-recovery from sewage sludge ash

All the technical approaches discussed so far can be employed for the recovery of P regardless of what happens with the sludge afterwards. An additional set of P-recovery techniques can be used if the sludge is – or has to be – incinerated prior to the deposition of its ash in landfills (see Figure 6). Against this backdrop we asked the experts in hypothesis 13 from which year on they think the majority of sewage sludge will be incinerated in their home country. 34 % chose the earliest possible point in time, 2015, and 23 % believe this will happen by 2030. Only a small minority (8 %) chose 2050, whereas 35 % think incineration will prevail later or even never. If only the experts with higher than average expertise are considered, a remarkable 80 % see incineration as prevailing by 2015 or 2030, while only 17 % believe this will occur later or never. A country-specific evaluation of the votes shows that respondents from countries which are currently completely or partially obliged to incinerate sludge (e.g. Switzerland, the Netherlands, Austria and Germany) show an average preference between 2015 and 2030. By contrast, respondents from countries with no such obligation (such as Canada, Sweden, the UK, and the US) have their average preference between later than 2050 and never. Most respondents (70 %) consider sludge incineration as a viable option for developed countries while only 30 % and 5 % do so for emerging or developing countries, respectively. Interestingly, the shares of respondents believing in the prevalence of the mono-incineration of sewage sludge by 2015, 2030, and so on (hypothesis 14) were almost identical to those for hypothesis 13. In fact, the high correlation between the votes on hypotheses 13 and 14 (R^2=0.55) appears to imply that if sludge is incinerated, this will most probably take place in mono-incineration plants.

Figure 6 Survey results for hypotheses set „Potentials of P-recovery from sewage sludge ash“



If sewage sludge is incinerated, a clear majority of 61 % of the experts consider it very or fairly useful to recover P from the ash (hypothesis 15), while only 14 % hold the opposite view. At first sight, this vote seems to contradict the vote on hypothesis 12, which showed no clear preference for either the wet-chemical extraction of P from sludge or the thermal-metallurgical treatment of sludge ash. However, this can be understood if it is acknowledged that, in the former context (in hypothesis 12), the additional cost of incineration is assigned to the recovery of P, while in the context of hypothesis 15, incineration has to be done anyway and so the cost is not assigned to P-recovery. Evidently, incineration is recognized as able to eliminate certain problems with hazardous substances and some heavy metals right from the start. Consequently, 42 % of the respondents prefer (and only 26 % oppose) P-recovery from sludge ash over P-recovery from sludge even if the more complex process of wet-chemical extraction and precipitation has to be used (hypothesis 18).

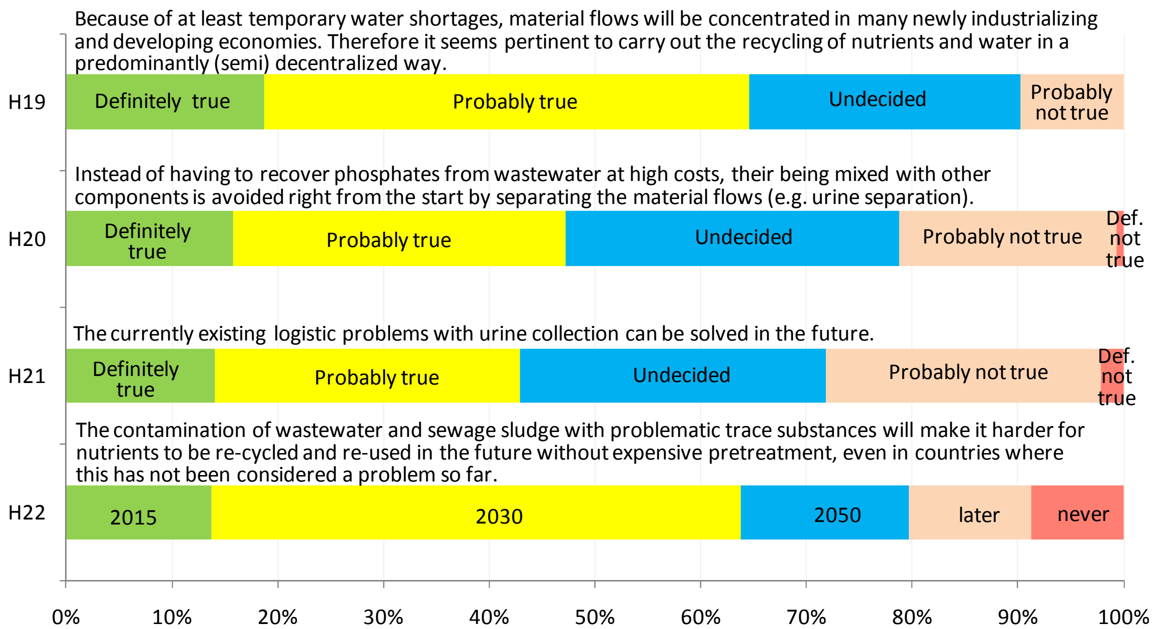
One way to recover P from sewage sludge ash is by the further treatment of the ash in the phosphorus industry, especially by applying the Thermphos process. However, this process is not able to handle ash containing iron, which represents the majority of ashes. Also iron-rich ashes may be less suitable as fertilizers. We therefore asked the experts if they think that the P precipitated in WWTPs will be converted to aluminum salts (hypothesis 16). 42 % think this will happen by 2030 while a considerable 28 % doubt it will ever occur. It is unclear whether the opponents of aluminum salt precipitation do not consider iron a problem, or view aluminum as an inadequate substitute. In some countries like the UK, dispersing aluminum as a component of fertilizers and in the context of food production appears to be socially unacceptable.

Another even more indeterminate vote (36 % pro vs. 30 % con) resulted for the question whether ashes should be disposed of in landfills devoted exclusively to this material in those cases where P-recovery cannot be carried out in the near future (hypothesis 17). The lack of a correlation between the opponents of specific landfills for P-rich sewage sludge ashes and the proponents of the economic profitability of P-recovery by 2030 (see hypothesis 5) shows that the opponents of hypothesis 17 are indeed critical of the concept of specialized landfills rather than the precondition that P-recovery may not be possible in the near future.

4.4 P-recovery in the context of a system transformation in water and wastewater management

The spread of sanitary systems in newly industrializing and developing countries is posing new challenges to urban water and wastewater management, especially where there are simultaneous water shortages (see Figure 7). With respect to developing and newly industrializing countries in the context of temporary water scarcity, almost two thirds (64 %) of the respondents agree (and only 10 % disagree) that recycling nutrients and water will be carried out in a predominantly (semi) decentralized way (hypothesis 19). However, the experts are clearly more skeptical with regard to the separation of material flows (e.g. urine separation) right from the outset (hypothesis 20). Only 47 % were in favor of, and 22 % against this option. These results correspond quite well with hypothesis 21, according to which 43 % of respondents are confident and 28 % are more or less skeptical that the currently existing logistics problems with urine collection can be solved in the future. The agreement with this hypothesis even increases to 49 % if only the votes of respondents with high expertise are counted. 63 % (multiple answers possible) believed countries with a scarce water supply are regions with potential for separating material flows at source (hypothesis 23) . Agreement is lower (53 %) for industrial countries in general, and decreases even more for newly industrializing (40 %) and developing countries (34 %). Only 6 % think that material flow separation will not take place anywhere.

Figure 7 Survey results for hypotheses set „P-recovery in the context of a system transformation in water and wastewater management"



A significant challenge to the recovery and reuse of nutrients and water is posed by the contamination of wastewater and sewage sludge with problematic trace substances. Almost two thirds of the experts (64 %) are convinced that by 2030 at the latest, recycling water and nutrients will not function without expensive pretreatment even in countries where this has not been considered a problem so far. Only 20 % believe that this will become relevant long after 2050 or never.

5 Discussion of the Results and Conclusions

In our survey we found a strong agreement (92 %) with the need for P-recovery despite the fact that supplies of geological P will not be exhausted in the short term and the conviction that P-recovery will become economical as early as 2030. To some extent this is due to the selection of experts, who may not be representative for the majority of actors in the P sector. Agreement would probably be lower if representatives for all the actors in the field of P-recovery had been included. However, among the survey participants the majority think in the long term and are informed about alternatives.

The fact that 60 % see industrial countries as the primary regions for the diffusion of P-recovery technologies, while only 30 and 10 % see newly developing economies or developing countries, respectively, as primary markets stands in stark contrast to the fact that developing countries actually have a greater need for a reliable P source. This may be because experts think primarily in terms of industrial recovery technologies developed for central sewerage systems, which can hardly be financed in developing countries. In fact, it may be more useful for developing countries to engage in better wastewater treatment and use the sludge directly in agriculture (if it is not too heavily polluted). More generally, however, and especially in many industrialized countries, the contamination of wastewater and sludge with heavy metal ions and toxic organic substances will soon lead to the phase out of the direct use of sewage sludge in agriculture.

At first sight, the strong belief in both the short-term economic viability of P-recovery processes and the need for regulatory support appeared contradictive. The lack of a correlation between the responses to hypotheses 5 and 6 showed that this view was not shared by the respondents. They considered economic viability and governmental support neither as strictly complementary nor as mutually exclusive. However, several comments were made to the effect that giving support and direction in the early phase of technical development would certainly favor earlier competitiveness in the market.

Basically three starting points for the recovery of P in a sewage plant were distinguished in this study. The first approach, recovery from the plant effluent, is favorable insofar as most wastewater contaminants have been removed by this point and, except for the dilution of the nutrients, the recovery process is fairly simple. This is also why the nutrient-containing effluent of the sewage plant is also able to be generally used as irrigation water for agriculture. In fact, however, P is eliminated from the wastewater (and effluent) stream in all larger sewage plants, which only makes it possible to recover a small proportion of the P contained in the wastewater. It could therefore be argued that P should not be eliminated from the wastewater stream, which would increase the potential of P-recovery from the effluent and diminish problems otherwise arising in the sludge stream. However, this raises the question of whether precipitation in the effluent is sufficient to meet the strict limit values for P elimination prescribed for large sewage plants today (or in the future).

For this reason, P-recovery from the side streams of the sewage plant (including sewage sludge and its liquor) is assigned a higher priority than P-recovery from the plant effluent. This is all the more valid since high P concentrations often give rise to problems in the sludge stream, especially after biological P elimination and sludge digestion. With regard to the remaining alternative options of P-recovery – precipitation from sludge water and leaching from the sludge itself – the former receives more support from the experts because it employs less advanced and less costly processes and can be applied in a wide range of sewage plants. It is this type of process that has become profitable in certain niche markets in the case of the Ostara and Airprex processes.

Since most toxic substances are bound in the sludge and P is integrated in the sludge, the recovery of P from sludge is more difficult and costly. Although this approach shows a greater potential with regard to the recoverable quantity of P (80 % instead of 40 %), it is chosen only if it yields better quality fertilizers with fewer contaminants and better plant availability.

Because the integration and binding strength of P is even greater in sewage sludge ash, the recovery of P by means of extraction and re-precipitation is even more costly. However, there are also several arguments for the recovery of P from ash. First, with a recovery share of 90 %, the potential of this recovery route is even larger than recovery from sludge. Second, the high temperatures characterizing the incineration process also destroy toxic organic matter in the sludge. Third, sludge incineration is already compulsory in many countries; in this case, the cost of incineration is not assigned to the recovery of P. Fourth, if the sludge ash is subjected to a thermal-metallurgical process, most heavy metals can also be removed. In this case, the treated ash can be directly used as a fertilizer. Since no waste is formed in this process, the saved cost of sludge or ash disposal in landfills make this process even more favorable. This explains why P-recovery from sludge ash is considered an alternative with greater potential than P extraction from sludge. Another favorable route for P-recovery from ash is to use this ash as a substitute for phosphate rock in the Thermphos process yielding P for the chemical industry. This process seems to be profitable for both the phosphorus user and sewage plant operator. However, the need for iron-free ashes as input for the P plant limits the applicability of this route at present. Aluminum could be used as a substitute for iron, but the survey experts are not sure about the acceptability of this approach.

Although our survey experts were in favor of semi- and decentralized approaches to the recycling of nutrients and water, they were less optimistic with regard to the separation of material flows, which would facilitate the recycling process from the outset by enabling substances to be recovered from specific streams before they mix. Apparently they consider the collection and treatment of different material streams to be a challenge that is not easy to surmount without the mobilization of substantial resources. This is probably why they consider industrialized countries more promising in this respect than newly industrializing or even developing countries. In contrast to this, Tilley et al. (2009) have shown that precisely the lower state of economic development in countries like Nepal offers opportunities in this respect. It is easier to establish a semi-central system of collection and conversion of urine into fertilizer if urine collectors and suppliers do not have too high requirements with respect to the performance of the processes and the possible profits.

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