Summary of the 9th International Phosphorus Workshop (IPW9)

ETH Zurich, 8 – 12 July 2019

https://plantnutrition.ethz.ch/ipw9.html

The 9th International Phosphorus Workshop brought together over 200 participants from 31 countries worldwide, with over 80 plenary and parallel session presentations and over 100 posters, to discuss the questions: "**Putting phosphorus first? How to address current and future challenges**".

The first IPW workshop took place in 1995 in Ireland, and since then in Northern Ireland, the UK, the Netherlands, Denmark, Spain, Sweden and Germany.

Recent IPWs, as conference conclusions, have defined **research needs to reduce phosphorus losses from agriculture** (7th IPW, Uppsala, Sweden, 2013, detailed in Sharpley et al., see SCOPE Newsletter n°128) and research needs into **interactions with soil organic carbon** (8th IPW, Leibniz Science Campus Phosphorus, Rostock, Germany, 2016 detailed in George et al. see SCOPE Newsletter n°128 and n°122).

The 8th IPW also identified the need for changes in agricultural policies, for a regulatory framework to place recycled phosphorus on the market (now addressed in Europe by the new EU Fertilising Products Regulation, June 2019, see ESPP eNews n°34) and the importance of price and economic instruments (in Leinweber et al., see SCOPE Newsletter n°128)

IPW9 included working groups on four themes: phosphorus resources and cycles, recycling phosphorus from wastewaters as fertilisers, phosphorus efficiency in agriculture, environmental challenges of phosphorus management.

This SCOPE Newsletter summarises information from a limited selection of the presentations and posters at IPW9, aiming to indicate some of the new information and ideas presented. Some conference **conclusions** are also summarised, as identified by ESPP.

The 10th International Phosphorus Workshop will take place **in 2022, in Scotland**, James Hutton Institute.

IPW8: summary in SCOPE Newsletter n°122, programme & abstracts https://wissenschaftscampus-rostock.de/files/Dateien/Veranstaltungen/IPW8/IPW8_2016%20Program%20and%20Book%20of%20Abstracts.pdf

IPW9, ETH Zurich, 8 – 12 July 2019 https://plantnutrition.ethz.ch/ipw9.html

Contents

Site visits 2
Holistic view 2
Phosphorus excess or phosphorus insufficiency? 3
Fertiliser innovation 4
Animal feeds 5
Long-term field trials 5
Phosphorus management policies 6
Phosphorus recycling 6
Conclusions 8

Site visits

IPW9 offered six **site visits**, looking at P losses from land with high livestock density, mitigation of soil erosion, P nutrient needs in forests, fertiliser application rates and guidelines, nutrient recovery from source-separated urine, biochar from sewage sludge and aquaculture.

The visit to the **Agroscope Agricultural research station in Reckenholz, Zurich,** supported by Hauert, saw how data necessary to improve fertiliser guidelines and agricultural methods can be gathered by long-term trials including lysimeters to monitor nutrient losses.

The biochar installation visited, at the Zurich University of Applied Science (ZHAW) Wädenswil site, was a **laboratory scale pyrolysis furnace** (Pyreg, capacity 2l/h, not operating when visited), which is testing pyrolysis of source-separated solid fraction of sewage and other organic materials. The visit was led by **Andreas Schönberg, ZHAW** and was supported by Hach,

At the same site, the **full-scale testing pilot for aquaculture** has developed nutrient removal systems for closed, intensive aquaculture systems, enabling compatibility with demanding nutrient discharge constraints for inland aquaculture development in Switzerland. Nutrients can be removed using biological nitrification – denitrification reactor and chemical P-removal, so enabling safe recycling of water. Water demand per fish produced is reduced by a factor of 50-100 and nutrient emissions by a factor of 2-20, depending on the technical setup. Complete nutrient and water recycling from aquaculture into hydroponic plant production is also being operated at the demonstration scale (aquaponics). The visit was led by **Ranka Junge, ZHAW.**

Holistic view

Astrid Oberson, ETH Zurich, Chair of the Conference Organising Committee, outlined the history of the International Phosphorus Workshop (see above) and introduced the question "Putting phosphorus first"? She underlined the interactions between use of phosphorus, lack of recycling, phosphorus losses, eutrophication and biodiversity.

Claudia R. Binder, École polytechnique fédérale de Lausanne, presented phosphorus flow and stock studies for Switzerland, possibly the only country for which such information is today available over time series. This shows that **in Switzerland, phosphorus use efficiency in agriculture has improved over the past 10-20 years**, whereas the quantities lost in waste management have increased (e.g. sewage sludge ashes going to landfills, or meat and bone meal ash). Phosphorus losses significantly increased, however, as a consequence of the Swiss bans on agricultural application of animal by-products and sewage sludge (2001, 2006). This will be resolved with implementation of the 2016 regulation requiring phosphorus recovery from these two streams.

Helen Jarvie, CEH, Wallingford, UK, emphasised the environmental challenges of phosphorus deficiencies and excesses in relation to agriculture, eutrophication and water resources. Improved stewardship of phosphorus will be vital in addressing these challenges. This will require collaboration across all sectors of society, to create a more circular P economy, and increase our phosphorus use efficiency through the entire food system: from farm to fork, to wastewater management and disposal.

Andrea Ulrich, previously with Phosagro, discussed phosphate rock reserves quantity and fertilizer quality. Estimations of reserves have historically varied, and so have supply lifetime estimates, which have often been larger in the past than today. However, moving towards circularity is important both to reduce resource consumption, and to address quality questions.

China is the largest producer of phosphate rock. However, Morocco, which is the second largest producer is the biggest exporter (over 30% of world market).

The new EU Fertilising Products Regulation sets a cadmium limit for CE-label fertilisers of 60 mgCd/kgP_2O_5. It is estimated that only around 20% of phosphate rock mined today has cadmium above this limit. Other countries, both in the EU and elsewhere, already have lower limits (e.g. China, Israel, Morocco, Russia, Saudi Arabia, South Africa, USA).

Different solutions exist to supply fertilisers with lower cadmium levels: sourcing from low-cadmium rock resources (both igneous and sedimentary), cadmium removal processes or use of secondary raw materials as inputs (recycling, because these generally have low cadmium content).

Geneviève Metson, Linköping University, Sweden, underlined the need for better data on phosphorus flows, including over time to enable monitoring of changes and analysis of actions. Data needs to be linked to phosphorus management science.

Collaboration with stakeholders is necessary, in addition to engagement across different branches of science, in order to enable transparency and agreed understanding of data, to propose feasible actions and move them towards implementation. This requires long-term engagement, beyond three year project funding logic.

Hansjörg Grützmacher, ETH Zurich, gave an exciting vision of the wide possibilities offered by phosphorus chemistry, still today largely unexplored. Most phosphorus chemical molecules are still not yet discovered! **New applications of phosphorus chemistry include as catalysts or as photo-initiators for medical applications or 3D-printing**. Phosphorus-based photo-initiators for tooth filling amalgams have enabled the replacement of 10 000 t/y of mercury-based fillings worldwide. A new phosphorus photo-initiator material is being developed to treat aneurisms and so reduce risks of strokes. Phosphorus based catalysts are being used to split water in hydrogen production, replacing platinum.

Another area of work is to try to **find solutions to replace PCl_3 as an intermediate in organic phosphorus chemistry** (PCl_3 is produced as a reactive 'transfer' molecule from elemental phosphorus P4 = white / yellow phosphorus). This would avoid halogenated chemical handling

A precursor molecule with a much higher phosphorus content is PH_3 (88 wt%) which is relatively easy to produce from red phosphorus. However, its toxicity and tendency to explode on contact with air requires the improvement of procedures for safe handling and especially the development of chemical transformations which lead to clean and full conversions into desired products. This remains a formidable challenge for synthetic chemistry.

Phosphorus excess or phosphorus insufficiency?

Fien Amery, ILVO Belgium, presented a study by the Flemish Land Agency (VLM), looking at different soil phosphorus test methods and relations to crop yields, based on 11 long-term field trials and a two-year greenhouse trial. It was concluded that extraction with ammonium lactate and acetate at pH 3.75 (P-AL, Egner et al 1960) was the most reliable indicator, and that P-AL levels in the range 110 – 160 mgP/kg are adequate to achieve 95% of maximum possible yield whilst limiting phosphorus leaching to groundwater.

Silvia Renata Motta, ERSAF, Italy, presented a simplified P balance model to estimate the phosphorus surplus on agricultural soils in Lombardy, which considers the organic and inorganic P sources and the crop P uptake. **Significant values of P surplus were found in areas of high livestock density**. Phosphorus in agricultural soils shows levels from 1.8 to 280 mgP-Olsen/kg because of past and ongoing N-based organic fertilization, resulting in a serious P soils enrichment that can contribute to the eutrophication processes.

Raniero Della Peruta, Agroscope, Zurich, presented modelling of manure trade and transport, based on data from farmers (HODUFLU platform), agricultural census and land use data. It was concluded that optimising local manure trading could reduce manure surplus (excess above nutrient needs: average across Switzerland: 5 kg/ha/yr) by at least 20%. **Increasing the number of manure trading partners within local networks** (ideally up to 6 farms) would have a much bigger impact than increasing the transport distance (optimal range was only 5-10 kms), so this addresses local, rather than regional, manure surpluses.

On the other hand, **Cathal Buckley, Teagasc, Ireland**, indicated that a survey of farms in 2017 showed that nearly two-thirds of all farm (across a sample of 45,157) **had P soil fertility levels below guideline recommendation levels for agronomy (under-fertilisation)**. This is a significant increase up from 40% of farms in 2007. Also, 30% of soils surveyed in 2007 were P enriched (over-fertilised) and this has declined to 19% in 2018. Overall, the number of fields at optimal soil P levels declined from 30% in 2007 to 22% in 2018. Suggesting there is significant room for improved matching of fertilizer supply to crop demand.

Finally, **Michael Kreuzer, ETH Zurich,** illustrated the challenge that manure distribution can pose even very locally, with a case study from Swiss alpine pastures (Tessin, 1 400 – 1 900 m altitude). **Because the cows graze higher areas, but tend to defecate in lower, flat areas, phosphorus is depleted in the former** (leading to invasion by low-nutrient *Narcus stricta* grass). Solutions can include active fencing and increasing the number of watering places. Studies show a more even spread of cow dung over a lowland pasture.

Paul Murphy, University College Dublin, indicated that the nitrogen surplus on dairy farms in Ireland varies by a factor of six, showing the potential to improve nutrient use efficiency. Based on the Teagasc National Farm Survey, **benchmarking of N and P efficiency and of dairy farm profitability** was developed. Farms with high livestock density achieve can high nutrient efficiency, because levels of nutrients exported in milk are optimised. However, densely stocked farms may be less resilient to bad weather years, because of their own grass production is then insufficient, and they then have to import feed: they are effectively optimised for normal or good weather conditions.

The **conclusion was that no one recommendation fits all**. Regions with high livestock concentrations show considerable phosphorus surpluses and accumulation in soils, whereas in other regions and in organic farming, phosphorus is currently applied insufficiently to maintain productivity.

Fertiliser innovation

Merrin Macrae, Waterloo University, Canada, presented field studies in the Lake Erie catchment. Results showed the significance of winter phosphorus losses, that is in periods where crops are not taking up phosphorus. Losses can be as dissolved or particulate P. Although most water moves off land in tile drainage, the dominant pathway for phosphorus losses can be in surface runoff. **Cover crops can reduce or increase phosphorus losses in winter, possibly because of cell lysis** (in frost, cells of dead or living plant material in the soil can be broken down, releasing phosphorus), so species selection is important. No-till does not increase P losses in tile drain runoff if fertiliser is injected not surface placed. Subsurface fertiliser placement reduces P losses (up to -60%), by decoupling from preferential transport (losses in runoff through gullies or cracks in soil). Maintaining low soil P levels is therefore important in cold regions where snowmelt is significant.

Therese McBeath, CSIRO Australia, noted that, on average, only around 70% of phosphorus applied in Australia (mineral and organic fertilization) ends up in crops, but there are also areas with a P deficit. P-efficiency can be improved by using the right fertiliser in the right place. With legumes, tests of **targeted placement tests below the soil surface has shown up to +15% yield increase**, by improving root access and avoiding having the fertiliser in a zone prone to drying. Liquid fertilisers can improve P use efficiency in calcareous soils, but foliar application does not always improve yields. In pastures, on the other hand, the current practice of early-season surface application of maintenance inputs (before growth starts) remains the most efficient strategy identified.

Antonio Delgado, University of Seville, Spain, summarised **tests of sodium phytate as a fertiliser**. Much of the phosphorus in some foods, especially grains, is in this form, which is considered to be not plant available. Soil inoculation of phytase releasing bacteria enabled up significant P uptake from phytate, but this was negatively impacted when iron oxides were present in the growing media.

Other presentations from the **University of Seville** addressed **how organic phosphorus compounds present in soil can impact behavior (sorption dynamics) of mineral fertilisers** applied to a Mediterranean soil.

Ana Robles Aguilar, Gent University, Belgium (research done at Forschungszentrum Julich), presented pot trials of narrow-leaf lupin (*Lupinus angustifolius*) treated with potassium phosphate or struvite as fertiliser (with control = no phosphate addition), in soil pH 4.5, 6.5, 7.5, looking at release of organic acids by the roots, and at root structure. Results showed that plants invested more in roots in suboptimal conditions for P uptake (no P fertiliser, alkaline soil), that lupins released more carboxylates when fertilised with struvite than with soluble phosphate fertilisers, and that, for lupins, **struvite showed a higher PUE (P uptake efficiency) than potassium phosphate in acid soils, similar at pH 6.5 and lower in alkaline soils**.

Silke Ruppel, Leibniz Institute of Vegetable and Ornamental Crops, Germany, presented trials of the bacterium *Kosakonia radicincitans* as a biostimulant. In a commercial formulation, AbiVital®, the bacterium is injected into seeds or spread onto leaves of young plants. The bacterium was originally isolated from winter wheat, and today production is scaled up to 5 000 litre fermenter. The bacterium has been shown to be effective, in pot and field trials, for e.g. wheat, maize, rape, kohlrabi, peppers, tomatoes, radishes … It improves growth via several mechanisms including biological nitrogen fixation, improving plant health, improving plant hormonal status, and by making phosphorus more available for plant uptake, e.g. from sources such as phosphate rock or from calcium, iron or aluminium bound phosphorus in soil.

Animal feeds

Michael Oster, Leibniz Institute for Farm Animal Biology (FBN), Dummerstorf, Germany, summarised farm animal-related work underway in the PEGaSus [project](). **Nearly half the variation in blood phosphorus levels in pigs is thought to be due to genetic factors**. Physiological studies revealed genes which are responsive to divergent dietary P supplies in tissues of interest, i.e. gut, kidney, bone, and parathyroid glands. Improving phosphorus use not only reduces the phosphorus levels needed in feed, but may also reduce phosphorus levels in manure. Data from micro-CT (micro-computed tomography) measurements revealed that trabecular bone but not cortical bone is susceptible to dietary challenges.

Solveig Vollmar, University Hohenheim, Germany, summarised work underway investigating the genetics of phosphorus use efficiency in poultry (Japanese quail used for practical reasons). Heritability of P use was shown by Zhang 2003 to be 0.2, that is sufficient to suggest that breeding for the trait could be feasible. Current studies show that **the P use efficiency trait is correlated to other traits, such as growth, feed intake or bone mineral traits**, and gene marker tests suggest that it is polygenic (not a single gene). One chromosome marker (chromosome 3) has been identified which is significant for both P and calcium use. Further studies need to investigate whether this is linked to gut microbial community. A challenge in such genetic studies is the difficulty of reliably measuring P use efficiency in livestock.

Brad Harrison, Reading University UK, presented results from a survey of UK dairy farmers and feed advisors. Results are based on 141 farmers responses (out of 2 000 questionnaires sent out) and 33 nutritionists. Respondents may thus be not representative of most farmers. Even amongst respondents, results show a lack of information and over-use of P in diets: **three quarters of respondent farmers did not know how much phosphorus was contained in their feed rations**, 40% of farmers and 50% of nutritionists fed P levels higher than NRC recommendations (National Research Council) and 80% of farmers used inorganic phosphate feed supplements.

Long-term field trials

Bettina Eichler-Löbermann, University of Rostock, Germany, underlined the importance of long-term field trials in understanding and improving fertilization. At the Rostock long-term trial single and combined organic (cattle manure or bio-compost) and inorganic (TSP or ash) P treatments are tested since 1998. In the topsoil, P pools tended to be higher after application of organic fertilizers whereas in the subsoil highest P contents in the labile P pools were found after application of TSP. Thus, it seems that **P can be retained in the organics in the topsoil**. This may partly explain differences between P budgets and soil P tests (P is moving to subsoil). Also, activities of soil enzymes involved in P cycling were higher in treatments with organic fertilizers.

Michela Battisti, University of Turin, Italy, also presented long-term field trials, since 1992 near Turin, comparing mineral fertiliser application to bovine slurry and to bovine manure, for different cropping systems. For the same net phosphorus balance (+20 kgP/ha) Olsen P in the topsoil (30 cm) after 20 years carried from 7 to 74 ppm, and was higher with manure, and similar for slurry and mineral fertiliser. Soil **Olsen P after 20 years also depended strongly on the cropping system**, in particular the nature of crop residues returned to the soil (crop residues with a high C/P ratio induced slower soil P mineralisation).

Klaus Jarosch, University of Bern, Switzerland, presented a long term field trial comparing 'organic' and conventional cropping systems. The conventional fields respected Swiss fertiliser recommendations, leading to a positive phosphorus budget (P applied > P offtake in crops). However, not all surplus P was recovered in the topsoil. This is probably because of P transfer into deeper soil layers. The **organic fields showed a negative P budget** which suggests a risk that these fields may face phosphorus limitation in the long run. Additionally, there are indications that the fertiliser applied on these fields is only slowly available to plants.

Phosphorus management policies

Bernou van der Wiel, Rhine-Waal University of Applied Sciences, Kleve, Germany, presented work underway to develop regional phosphorus flow analysis (SFA Substance Flow Analysis). A literature analysis identified local or regional nutrient flow studies, mostly in intensive agriculture areas. This analysis showed the need to include the whole agri – food– waste system and focus on N, P, K and C as optimal nutrient use efficiency relies on obtaining the optimal stoichiometric balance. A **case study is underway in the Kleve district, Germany, with the objective of engaging in particular farmers, food companies (including supermarkets) and waste management**.

Samia Richards, James Hutton Institute, Aberdeen, Scotland, summarised studies on the fate of phosphorus in septic tank discharges. Older septic tanks (> 10 years) showed reduced soil pH and increased BAP (bioavailable phosphorus = measured measured by iron oxide test). The rate of bioavailable phosphorus increase in soil ranged from 0.5 to 12.5 mgBAP/kg/year in the soakaway zone, indicating progressive saturation with P, and increasing risk of P reaching ground or surface water. Modelling suggested that **30 – 50 % of inflow phosphorus might reach water from a new septic tank within 20 years** (installed with a soakaway according to current Scotland guidelines).

Jessica Stubenrauch, and Katharine Heyl, FNK Leipzig / Berlin and University of Rostock, underlined that nearly half of the EU's phosphorus footprint is due to imports of agricultural products. The analysis of legislation in three countries (Germany, Nicaragua, Costa Rica) showed the necessity to implement **frugality strategies** in addition to efficiency and consistency strategies in P governance. It was underlined that **the current EU CAP (Common Agricultural Policy) subsidy system exacerbates nutrient mismanagement**. Voluntary certification standards and market instruments (e.g. payments for ecosystem services) are important, but inadequate. **Command-and-control legislation** / legally binding economic policy instruments will also be necessary to implement P sustainability.

Felix Ekardt and Beatrice Garske, FNK Leipzig/Berlin and University of Rostock, emphasised that 70% of global agricultural land use is for livestock production (including producing fodder). Impacts are considerable, not only on phosphorus, but also on greenhouse gases and on other important environmental challenges, including atmospheric ammonia and particulates, water use, biodiversity. Economic instruments can be highly effective in drastically reducing livestock production and diet as well as cutting the use of fossil fuels in all sectors, but such instruments must have a broad geographical and sectoral scope. Furthermore, complementary regulatory instruments and border adjustments for imports and exports may be appropriate.

Phosphorus recycling

Anders Nättorp, FHNW Switzerland, showed how phosphorus supply risk triggered an increased awareness and developments towards sustainable mineral phosphorus use in Europe. He described five types of recovery processes developed for sewage sludge, but also applicable to MBM and manure, with respect to TRL, yield, product properties, environmental impact and cost. The cost represents a few percent compared to existing wastewater treatment. Legislative (obligatory recovery, new fertilisers regulations) and technical developments should lead to an exponential increase (10 000 tP/y to 100 – 150 000 tP/y) technically recovered phosphorus in the coming decade. The foreseeable amount of 150 000 tP/y is still only a tenth of European phosphorus imports, but studies show that Europe has a substantial agricultural phosphorus oversupply and unused nutrients in wastes. Therefore, high volumes of technical phosphorus recovery could potentially achieve a circular P supply for mineral phosphorus in Europe. **He underlined the urgency of the climate collapse and the need for action in the agricultural sector which will be heavily influenced and is also crucial for climate mitigation**.

Oscar Schoumans, Wageningen University and Research, The Netherlands, presented the SYSTEMIC project studying and testing five full scale nutrient recovery from anaerobic digesters with a further 10 outreach locations.

He summarised the Groot Zevert case-study, The Netherlands, treating around 100 000 t/y of pig manure. **Currently the plant pays around 25€/tonne to transport manure to Germany**, up to 400 km. A proposed digestate treatment process will extract

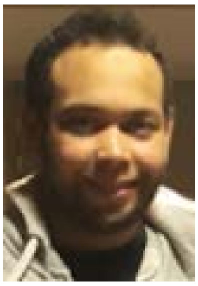
P as calcium phosphate or as struvite, which will be tested for possible use in mineral fertiliser production by ICL, and nitrogen will be transferred to a liquid concentrate. The remaining, low nutrient solid, can then be used locally as an organic soil improver.

A range of phosphorus recycling technologies, under development to recover phosphorus from sewage, were presented including:

- **Daniel Klein, Emschergenossenschaft, Essen, Germany**: EuPhoRe process, being optimised and tested within the Phos4You project (see summary in SCOPE Newsletter n°129). A 100 kgDM/h (dried sewage sludge) pilot has been operated with a number of runs since January 2019. After optimisation of some technical issues, it is intended to start continuous operation in summer 2019. Depending on the input material, the quality of the processed ash can be variable. The objective is to achieve accordance with fertilisers regulations specifications, in order to be able to **use the ash directly as a component of mixed fertilisers.**

- **Else Bünemann, FiBL Switzerland**: **alkaline pyrolysis of sewage sludge, using a potassium donor**, was tested (note for information: batch and fluidised bed oven, 100 kg/h, initial test one week). This follows initial pyrolysis tests, which found that sewage sludge biochar had very low P availability when the sludge came from works operating chemical P-removal. After process optimisation, the alkaline pyrolysis product showed up to 80% P-use efficiency in pot trials (independently of soil pH) and in one field trial. This could be an energy-efficient solution for small WWTPs to recycle P from sewage sludge. However, a possible problem is again that heavy metals are only partly removed.

- **Mohamed Amine Saoudi, IRSTEA, Rennes, France**: **bio-acidification upstream of sewage sludge anaerobic digestion**, also within the Phostep project. This is achieved by providing a substrate for bacteria. A standard commercial carbon source was used as substrate for experimental purposes, the intention is to use organic waste materials. The biological process achieved pH4 after 24 hours, resulting in dissolution of around 75% both phosphorus and iron, and over 60% in liquor after centrifugation. A cation exchange resin was used to remove 80% of the iron (recovered in regenerate, possible reuse for P-removal not yet assessed) then struvite was precipitated for P-recovery. Methane production was around twice that of sewage sludge alone, and +20% higher than the carbon substrate plus sludge mixture (not bio-acidified), so that this could partially offset process costs. To date, this has been tested at lab scale (3 kg/day, batch).



- **Tobias Hartmann, University of Hohenheim, Germany**: laboratory scale partial replacement of rock phosphate by ash from gasification of sewage sludge (P-removal mainly using iron precipitation) for the production of superphosphate. Pot trials using the resulting fertilizers showed that **at least 8% of P from rock phosphate may be substituted without affecting yield or P removal of maize but that substitution higher than 16% resulted in reduced availability of P in the fertilizers and reduced P removal by plants**. The authors suggest that buffering capacity inhibits dissolution of P by acid in the synthesis, and are working to adjust the acid application.

- **Janet Hering, Eawag (Swiss Federal Institute of Aquatic Science and Technology)** explained the interest of **urine separating systems** for toilets, in that urine contains around 60% of phosphorus and over 95% of nitrogen in human urine and faeces. The Eawag spin-off VUNA has developed a process to produce a liquid fertiliser from urine: AURIN. The process involves, after separate urine collection, biological conversion of ammonium to nitrate, active carbon filtration (to remove pharmaceuticals) and then **distillation** to reduce the volume and sanitise pathogens. Around 10 litres of urine generate 1 litre of Aurin. The product was licenced for use as a fertiliser in Switzerland in 2018. The next step is final process adjustment for industrial manufacturing and market roll-out.

- **Ruiz-Navarro Antonio, CEBAS-CSIC, Spain**, presented the BIOFORG project underway (with SUEZ, until 2021), investigating **PSM (phosphorus solubiliser micro-organisms)** and **enzymes (phytase, phosphatase)** to improve plant availability of phosphorus fertilising materials in soil, with organics from waste streams as a carbon source. Objectives are to assess different microbial strains and enzymes for solubilising both organic and inorganic (struvite) phosphorus inputs, and to look at possible delivery routes, e.g. coating of struvite with humic substances.

Conclusions

Emmanuel Frossard, ETH Zurich, Switzerland, and **Christian Stamm, Eawag, Switzerland**, summarised the conference and proposed conclusions, on behalf of the conference organising committee and the other workshop moderators:

Claudia Binder, EFP Lausanne, Switzerland; Phil Haygarth, Lancaster University, UK; Astrid Oberson, ETH Zurich, Switzerland; Alan Richardson, CSIRO, Australia; Christian Schaum, Bundeswehr University Munich, Germany; Oscar Schoumans, Wageningen University and Research, The Netherlands; Kai Udert, Eawag, Switzerland.









Overall, IPW9 showed the **wide range of questions and themes relevant to phosphorus stewardship**, including food, soil and agriculture, health, animal feed and genetics, eutrophication, nutrient recycling technologies and innovative industrial applications of phosphorus chemistry.

However, to combine these elements into functional systems, **approaches and collaboration networks need to widen** to integrate among others consumers, farmers, or scientific disciplines currently underrepresented in the field such as social scientists or economists.

Photos above: Grace Crain.

A positive sign is the number of young scientists engaging with phosphorus, proposing innovative approaches, new ideas and new research.

IPW9 concluded that **significant progress has been made** since IPW1 in 1995: see for example the progress papers published after IPW7 and IPW8, both summarised in ESPP's SCOPE Newsletter n°128:

- *"Future agriculture with minimized phosphorus losses to waters: Research needs and direction", A. Sharpley et al., AMBIO 2015, 44 (Suppl. 2): S163–S179* *http://dx.doi.org/10.1007/s13280-014-0612-x*
- *"Handling the phosphorus paradox in agriculture and natural ecosystems: Scarcity, necessity, and burden of P", P. Leinweber et al., Ambio 2018, 47 (Suppl. 1): S3–S19* *http://dx.doi.org/10.1007/s13280-017-0968-9*

The four interactive workshops within the conference identified the following questions:

Phosphorus scarcity / optimizing regional and national phosphorus cycles

Q1: What are the main drivers / incentives to obtain a circular P- economy? (*Drivers circular P economy*)

Q2: How to increase P use efficiency at different spatial scales? (*Scales of P use efficiency*)

Q3: What is the impact of P recovery from different from all types of waste streams on the P cycle? (*P recovery and P cycle)*

Sourcing phosphorus fertilizers

Q4: What are the interaction biosolids/wastewater treatment and technology development for P recovery (central/decentral/on site etc.)? (Interactions technologies)

Q5: What are promising business models for recycling P that induce societal acceptance for P from waste streams? (*Promising business models)*

Q6: How to reduce the impurities in recovered P to acceptable levels? (*Impurities*)

Efficient phosphorus use in agroecosystems

Q7: How to better verify 'P value' form waste products from economic, environmental and political perspectives (integrating benefits for environment and society)? (*P value from waste)*

Q8: How to promotion of best agronomic practice for P efficiency considering low P and high P systems? (*Promoting P-BMP)*

(*Context:* Pathways for greater grower awareness of tools, genotype and crop selection, and knowledge based advice.)

Q9: How to achieve system-wide and long-term consideration of P within crop/farm/landscape/ global systems linked to C & N cycles? (*Systems perspectives*)

(*Context:* Balance across animal-plant-soil-aquatic systems.)

Environmental phosphorus problems

Q10: What will happen to the P cycle with climate change? (*Climate change)*

Q11: How can we achieve a systems perspective to determine change? (*Systems view*)

Q12: How do we integrate socio economic perspectives into the P cycle change? (*P and socio-economics)*

Further information about the 9th International Phosphorus Workshop is available here: https://plantnutrition.ethz.ch/ipw9.html

The 10th International Phosphorus Workshop will be announced at, and other nutrient related events, here: www.phosphorusplatform.eu/events

Key points raised by the presentations and discussions at IPW9, as identified by ESPP, are as follows:

- **Awareness** of phosphorus sustainability challenges (resource limitations, environmental impacts, circular economy), awareness of legacy P (in both aquatic systems and in soil) and of time and spatial scale, and interest in agricultural **phosphorus use efficiency**
- Understanding the phosphorus cycle, including **phosphorus flow analysis**
- Increase in available **data on P in the environment**
- Understanding **links between phosphorus in soil, phosphorus losses, fertilisation**
- Improved agronomic **fertilisation recommendations** (4R stewardship = Right product, Right rate, Right place, Right time) and wider acceptance of biology-based approaches (**organic soil amendments**, crop rotation, inter- or cover copping,)
- Information and technology development for **P- recovery**
- Nutrient **circular economy policies** and first regulations requiring P-recovery

Important **challenges still to be addressed** include:

- Need to **widen the approach** to integrate consumers, farmers, social scientists and economists.
- Phosphorus sustainability must take account of specific nutrient, agriculture, soil and food challenges of **developing countries**.
- Wide spatial and time approach is necessary to take into account phosphorus cycles and legacy phosphorus, including **understanding the phosphorus cycle at the global level**
- Interactions between phosphorus management and **climate change, climate resilience**
- Importance of **long-term field trials** to support agronomic understanding and recommendations to policy makers and to farmers
- For recycling, move from 'waste processing' to production of a **market-orientated** phosphorus product
- **Livestock production** today generates major environmental problems and, including unsustainable nutrient management. Spatial concentration of livestock production accentuates this.
- A key primary driver for phosphorus use, efficiency and impacts is human **dietary choice**. Need to engage with the food industry.
- Need for further work to **assign an economic value to phosphorus use** and phosphorus losses, in order to support policy making, economic instruments
- **Regulation is necessary** to ensure implementation of nutrient sustainability and environmental protection, which are not necessarily "economic" (especially when 'externalities' are not integrated)

Publication of more complete and formal conference conclusions is planned by the IPW9 Organising Committee.