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BOOK OF ABSTRACTS

THE GERMAN FUNDING MEASURE REPHOR – REGIONAL PHOSPHORUS RECYCLING

Sophia Schüller, Johannes Pinnekamp

Research Institute for Water and Waste Management at the RWTH Aachen University (FiW) e.V.

The Regional Phosphorus Recycling (RePhoR) measure, funded by the German Federal Ministry of Education and Research (BMBF), aims to contribute to the implementation of the new Sewage Sludge Ordinance through innovative economic solutions for regional P recycling. The resulting increased use of secondary phosphorus from the recycling economy should significantly reduce the loss of phosphorus and Germany's dependence on phosphorus imports. To this end, various technologies for P recovery from wastewater, sewage sludge or sewage sludge incineration ash are being implemented on an industrial scale, thus providing scientifically sound knowledge and practical experience under real conditions. Innovative and holistic regional utilization concepts for the locally produced sewage sludge are being developed and implemented that close the gap between P-recovery and P-recycling and thus return the recovered phosphorus to the nutrient cycle via agriculture or as a raw material to industry. The addressed regions for P-recycling differ in size, quantity and composition of the sewage sludge and structure of the catchment area (e.g., rural regions and metropolitan areas), so that transferability of the results to other regions is possible. The funding measure consists of 7 collaborative projects, which work with different processes and products and investigate the respective economic viability and technical feasibility until 2026.

Since mid-2023, the projects have entered the final implementation phase, in which the large-scale demonstration plants will be completed and put into operation. The results are compiled and synthetized by the scientifically accompanying transfer project TransPhoR. The cross-cutting issues are particularly important as they identify overarching challenges and barriers to market entry. In particular, numerous legal challenges were compiled, from approval processes of the plants to organizational forms of the operating companies and the end of waste status of the ashes and recyclates as a prerequisite for the marketability. In order to clarify the “end-of-waste status”, a type of guideline is being developed together with a lawyer, which will deal with the legal requirements and process steps that must be taken to enable the determination of the waste status of phosphorus recyclates in specific individual cases. Furthermore, sales markets and their quality requirements are considered, both for the products and by-products of the recycling process. In a further overarching topic, standardized criteria for the comparability of life cycle assessment studies are developed. This includes a compilation of criteria for the economic evaluation of different processes. The aim here is to create a procedure for assessing the economic efficiency of phosphorus recovery concepts (standardized calculation method). A concept for the standardized profitability analysis was developed, which is aimed at a neutral and comparative evaluation of the various project procedures with regard to the costs incurred within the defined balancing framework.

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Institutional website: https://www.fiw.rwth-aachen.de/en/references/transphor

Project website: https://www.bmbf-rephor.de/en/

THERMODYNAMIC MODELLING OF PROCESSES FOR PHOSPHORUS RECOVERY FROM SEWAGE SLUDGE

A Kotze[1,2], C Dorfling[2], S Arnout[1], E Nagels[1]

1 InsPyro, 2 University of Stellenbosch

Phosphorus recovery from sewage sludge is a critical aspect of sustainable waste management and resource recovery, especially as regulations with regards to phosphorus recovery are becoming stricter. As a result, several processes aimed at recovering phosphorus from sewage sludge are under development. One example is the novel FlashPhos process which aims to recover phosphorus in elemental form. Other processes recover the phosphorus as fertilizer or phosphoric acid. Each process has certain benefits and disadvantages such as energy cost, use of chemicals, and possible product applications. In order to aid process development and inform process selection, it is necessary to understand and compare the relative performance of these processes. This study aimed to evaluate the robustness of phosphorus recovery processes against variations in sewage sludge feed composition and to understand the impact of these variations on phosphorus recovery efficiency and energy consumption.

Using advanced thermodynamic modelling tools, FactSage 8.2 and METSIM, three phosphorus recovery processes; a complete reduction process (FlashPhos), a calcination process and a leaching process, were evaluated. A theoretical mass and energy balance was constructed and the results analyzed to assess their performance under different sewage sludge feed compositions derived from literature data. The modelling focused on determining the phosphorus recovery rates and the associated energy requirements, with particular attention to the organic and inorganic fractions of the sewage sludge.
Preliminary results reveal that the feed composition significantly influences both phosphorus recovery and energy consumption in all processes. Notably, the organic content of the sewage sludge is a major determinant of energy consumption for the reduction and thermo-chemical processes. Processes like the FlashPhos process demonstrate varying efficiencies based on the specific characteristics of the feed sludge such as basicity and phosphate content.

This study provides valuable insights into the comparative performance of different phosphorus recovery processes, identifying key factors affecting energy use and recovery rates. By understanding these relationships, feed compositions can be selected or optimized to enhance the efficiency and sustainability of phosphorus recovery operations.

DAIRY PROCESSING SLUDGE, A VALUABLE SOURCE OF PHOSPHORUS AND OTHER PLANT NUTRIENTS - CAN HYDROTHERMAL CARBONIZATION IMPROVE ITS MANAGEMENT PRACTICES?

Marzena Kwapinska[1], James J. Leahy[2]

[1] *Post-doctoral Researcher, Dairy Processing Technology Centre, University of Limerick, Ireland, marzena.kwapinska@ul.ie*

[2] *Professor, Department of Chemical Sciences, Bernal Institute, University of Limerick, Ireland, j.j.leahy@ul.ie.*

Dairy processing sludge (DPS) as a byproduct of wastewater treatment processes in dairy (milk) processing companies is used in agriculture as fertilizer (biosolids) [1]. An important feature that makes DPS favourable for application in agriculture is its very low concentration of heavy metals [2]. However, DPS presents challenges in terms of its management due to its high moisture content (80 to 90 % of water thus plant nutrients are very dilute), prolonged storage required, uncontrolled nutrient loss and accumulation of certain substances in soil in the proximity of dairy factories. Additionally, the content of nutrients varies between different DPS substantially [2], as it strongly dependent on the type of products being produced in the dairy processing plants and treatment methods applied.

Hydrothermal carbonization (HTC) breaks up the physical/ chemical structure of the sludge; oxygen is partially removed, and the organic fraction is rearranged into a carbonaceous solid product which is less hydrophilic [3] thus water can be much easily removed. The purpose of the study is to investigate the potential of HTC as a conversion technology for DPS. Laboratory scale HTC of two different types of DPS brown sludge and white sludge from different milk processing plants was carried out at 180, 200 and 220°C for 1 hour. The properties of the resulting hydrochar and HTC liquid (separated by filtration) were examined. The distribution of plant nutrients between the two products was measured. Total phosphorus and plant available phosphorus in hydrochar were measured. The properties of hydrochar were compared against requirements for organo-mineral and inorganic fertilizer according to the European Fertilizing Products Regulation (2019/1009). The HTC treatment, although it is energy intensive, enables production of slurry that is easier to separate into solid hydrochar with concentrated phosphorus and the HTC liquid. HTC has the potential to improve DPS management practices providing that the HTC liquid could be valorised at wastewater treatment plant.

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BIOLOGICAL PHOSPHORUS REMOVAL IN A SWEDISH CONTEXT – EFFECTS OF NATIONWIDE IMPLEMENTATION

Sofia Högstrand[a*], Magdalena Svanström[b], Karin Jönsson[a]

[a]*Department of Process and Life Science Engineering, Lund University, Sweden*
[b]*Division of Environmental Systems Analysis, Chalmers University of Technology, Sweden*
**Corresponding author: sofia.hogstrand@ple.lth.se*

Enhanced biological phosphorus removal (EBPR) has been implemented in full scale in wastewater treatment plants (WWTPs) since the 1970s although the extent of implementation varies between countries. In Sweden, around 30 out of 430 WWTPs serving more than 2000 population equivalents (PE) operates using EBPR to varying degree, the rest depend on conventional chemical precipitation (CP) for phosphorus removal. The effluent requirements on phosphorus are generally very strict in Sweden and treatment requirements down to 0.3 mg P/l are common. CP provides an easy way of adhering to these demands, however, due to recent concerns regarding possible chemical shortage, the interest in EBPR has increased.

Here, we are exploring the environmental implications of nationwide implementation of EBPR instead of CP. The study is based on a project initiated by the Swedish EPA on the possibilities of increased implementation of EBPR in Sweden [1], and a life cycle assessment (LCA) comparing EBPR to CP on the WWTP-level [2]. Futures thinking and scenario analysis are applied by changing parameters in the foreground (type of configuration) and background (external factors such as chemical availability, phosphorus effluent requirements, etc.).

On WWTP-scale, the LCA results indicated increased greenhouse gas emissions from the EBPR compared to CP, although further refinement of the underlying process model is needed through calibration of hydrolysis rates and verified methane emissions. For CP, more heavy metals are found in effluent and sludge which is connected to precipitation chemicals. CP facilitates a greater recovery of biogas, but environmental benefits depend on assumed use of biogas. Both configurations performed equally well in terms of freshwater eutrophication in the base case. However, in a scenario with chemical shortage, the impact on eutrophication from CP plants was substantially higher than from EBPR.

Assuming these results are linearly scalable and sufficiently representative of Swedish conditions, preliminary calculations render the amount of precipitation chemicals saved to exceed 25 000 tonnes/year if most CP plants are converted to EBPR plants. This shift could, however, increase direct greenhouse gas emissions for Sweden by approximately 0.17% of total consumption-based climate emissions and increase energy requirements by some 0.010% of total Swedish electricity demand. Furthermore, this shift could mean a decrease in biogas production potential, by the amount that is currently flared at WWTPs. However, should the shift not be undertaken, and an extended, national chemical shortage occur, more than 800 tonnes extra of phosphorus risk being emitted to sensitive and phosphorus-limited recipients annually, corresponding to 340% of the current Swedish phosphorus emissions from municipal WWTPs and 2.9% of the total annual load of phosphorus to the Baltic Sea. A shift to EBPR could also decrease the amounts of heavy metals in the sludge by approximately 7, 6 and 2 tonnes annually of zinc, copper, and chromium, respectively, as well as allow for the potential production of more than 8000 tonnes of struvite.

Further research should include a thorough economic assessment of the different scenarios as part of the basis for future decision-making and policy implementation.

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PURALOOP, A RECYCLED PHOSPHATE FERTILIZER FROM ORGANIC WASTE STREAMS.

AGRONOMIC TRIAL RESULTS

Authors: Cristian Terrones

ICL Growing Solutions - The Netherlands.

Phosphorus for fertilizers comes primarily from phosphate rock, a non-renewable resource. Europe imports most of its phosphorus, with around half lost as waste (van Dijk et al., 2016). To address this, the EU promotes circular economy practices in managing the phosphorus supply chain.

Phosphorus is being recovered from sources like wastewater treatment plants (WWTP), manure, and municipal waste. Recovering phosphorus from WWTP sludge is a major focus, but it also contains pollutants that need treatment (Shaddel et al., 2019).
Incinerating the sludge produces sewage sludge ashes (SSA), which can replace phosphate rock in fertilizers.

ICL has established a phosphate recycling unit at its plant in Amsterdam, to partially replace the imported phosphate rock with locally recycled phosphate and use it in the production of complex fertilizers. The phosphate recycling unit can also use other sources such as struvite and precipitated calcium phosphates. This pioneering process enables circular phosphate farming, i.e., using a valuable ingredient more than once and increasing recycling rates for food production. By replacing phosphate rock with SSA in the Triple Super Phosphate (TSP) fertilizer production process, a fertilizer (marketed as 'Puraloop') is produced with 38% P_2O_5.

When it comes to recycled phosphates, common concerns are how safe they are to use in agriculture and how efficient they are in contrast with conventional fertilizers. For this reason, a series of pot (5) and field (1) trials were established in Israel, Italy, Germany and Poland to compare this material versus conventional fertilizers (TSP). All pot trials had a RBD set up with 5 or 6 blocks and included both negative (no P) and positive (TSP) controls. The field trial had a RBD set up with 3 blocks and only included a positive control (TSP).

Overall, the results consistently showed that plant development was the same for both Puraloop and TSP treatments. The only significant difference was found in the absence of P fertilization, which resulted in less biomass and yield. This proves that Puraloop can be used as a P fertilizer for all crops to replace traditional sources.

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SOLUBILIZATION OF COLOMBIAN PHOSPHATE ROCK WITH BACTERIAL BIOGENIC ACID FOR POTENTIAL USE IN AGRICULTURE.

[1]Martha Natalia Echeverry Álzate, [2]Marco Antonio Marquez Godoy

[1]*Universidad Nacional de Colombia,* [2]*Universidad Nacional de Colombia.*

Phosphorus is an essential element for humans, plants, and animals, as it is involved in almost all metabolic chemical reactions and serves as an energy transporter in the form of ATP. Phosphorus is a finite and non-renewable resource, primarily exploited to meet the demand in the fertilizer industry. This article proposes a phosphorus solubilization process using biogenic acid produced by A. thiooxidans in a 5L reactor. Phosphorus solubilization of 98.5% and 98.3% was achieved for 20% and 30% phosphorus mineral concentration. However, reprecipitation of phosphorus was observed over time for the 20% and 30% concentrations due to sulfate depletion in the acid. FTIR analysis revealed the appearance of calcium sulfate (gypsum) bands during rock acidulation, characteristic of the calcite reaction, and the disappearance of calcite-ankerite and some phosphorus bands. Quartz and dolomite showed no changes, confirmed by XRD analysis. Comparing the chemical and biological processes, the biological process solubilized 44% more phosphorus than the conventional chemical process. This process opens the door for further research and optimization of biogenic acid processes to treat low-grade phosphorite and enhance its benefits.

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CIRCULAR NUTRIENT RECYCLING IN THE BALTIC SEA REGION

Lima, Priscila de Morais[1*]; Dzemedzionaite, Vaida[1]; Luostarinen, Sari[2]; Kuka, Katrin[3]; Foged, Henning[4]; Tamm, Kalvi[5]; Kuligowski, Ksawery[6]; Aronsson, Helena[7]; Skowron, Piotr[8]; Virtanen, Eetu[9]; Sindhöj, Erik[1].

[1]*RISE - Research Institutes of Sweden Uppsala, Sweden.*

[2]*LUKE - Natural Resources Institute Finland, Jokioinen, Finland.*

[3]*JKI - Julius-Kühn-Institute - Federal Research Centre for Cultivated Plants, Quedlinburg, Germany.*

[4] *Organe Institute ApS. Skødstrup, Denmark.*

[5]*METK - The Centre of Estonian Rural Research and Knowledge. Jõgeva maakond, Estonia.*

[6] *IMP - Institute of Fluid-Flow Machinery, Polish Academy of Sciences. Gdansk, Poland.*

[7] *Swedish University of Agricultural Sciences. Uppsala, Sweden.*

[8] *IUNG - Institute of Soil Science and Plant Cultivation. Puławy, Poland.*

[9] *HELCOM - Baltic Marine Environment Protection Commission - Helsinki Commission. Helsinki, Finland.*

[*] *Corresponding author: priscila.de.morais.lima@ri.se*

The Baltic Sea has been facing eutrophication due to excessive nutrient inputs, primarily nitrogen and phosphorus. This eutrophication leads to harmful algal blooms, oxygen depletion, and negative impacts on marine ecosystems and biodiversity (Devlin & Brodie, 2023).

To combat eutrophication, more resource-efficient food systems are needed (Meybeck et al., 2012). In this sense, the Circular Nutrient Recycling in the Baltic Sea Region (CiNURGi) project focuses on nutrient recycling to reduce losses and enhance recovery from various sources. By improving infrastructure and technologies, CiNURGi aims to maximize nutrient recovery from biomasses and resource streams, contributing to sustainable, climate-neutral food production and reducing nutrient pollution in the Baltic Sea (INTERREG, 2024).

The project aligns with regional and European strategies, including the HELCOM Baltic Sea Regional Nutrient Recycling Strategy and Baltic Sea Action Plan, the EU's Circular Economy Action Plan under the Green Deal, the Integrated Nutrient Management Action Plan of the Farm to Fork Strategy, and the EUSBSR Policy Areas Nutri and Bioeconomy (RISE, 2024).

The project's primary activities consist of establishing sustainable nutrient recycling standards, enhancing regional nutrient balances, advocating for the utilization of recycled nutrients, investigating potential business prospects, and improving policy alignment in the Baltic Sea Region. Led by the RISE (Research Institutes of Sweden), the initiative is backed by a consortium comprising 24 partners and 13 affiliated organizations across Denmark, Estonia, Finland, Germany, Poland, Latvia, Lithuania, and Sweden.

The expected outcomes include enhanced efficiency in nutrient use, support for climate-neutral food production, reduction in nutrient pollution in the Baltic Sea, and economic opportunities in nutrient recycling industries.

While the CiNURGi project is focused on the Baltic Sea Region, it has potential for collaboration with the Mediterranean region. Through joint research and knowledge exchange, both regions can explore nutrient recycling technologies and innovative solutions to address issues like nutrient losses, soil health, and sustainable agriculture. CiNURGi's strategies and standards could serve as a model, promoting cross-regional cooperation by aligning with Mediterranean policies on nutrient management.

In summary, CiNURGi addresses environmental management and sustainable agricultural practices in the Baltic Sea Region, emphasizing nutrient recycling and circular economy principles to contribute to environmental sustainability and economic development. While CiNURGi's direct impact is in the Baltic Sea Region, its principles and experiences can be valuable for fostering connections and collaboration with the Mediterranean region. By sharing knowledge, aligning policies, and exploring joint initiatives, CiNURGi can contribute to a more sustainable and interconnected approach to nutrient management across different seas and ecosystems.

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ADVANCING NUTRIENT RECYCLING FOR SUSTAINABLE AGRICULTURE IN SWEDEN AND BEYOND

Dzemedzionaite, Vaida[1*]; Lima, Priscila de Morais[1]; Sindhöj, Erik[1], Luostarinen, Sari[2]; Laakso, Johanna[2].

[1]*RISE - Research Institutes of Sweden, Uppsala.*

[2]*LUKE – Natural Resources Institute Finland, Jokioinen.*

[*]*Corresponding author: vaida.dzemedzionaite@ri.se*

More sustainable and efficient nutrient management practices are needed to reduce the negative impacts on the environment and to save finite resources, such as phosphorus and nitrogen. Therefore, there’s an urge to minimize the external inputs in agriculture. A study in Sweden showed that recycling organic and human excreta could cover around 75% of crop nitrogen and 81% of phosphorus needs, whilst simultaneously exceeding crop potassium needs by 67% (Akram et al., 2019). Organic fertilizers improve soil and plant health; however, they have drawbacks such as imbalanced nutrient ratios and high-water content.

The EU-funded Circular Nutrient Recycling in the Baltic Sea Region (CiNURGi) project aims to promote the development of a circular economy for nutrients. The emphasis is on improving current infrastructures and technologies to maximize nutrient recovery from biomasses and resource streams coming from agriculture, municipalities, and industry. A more efficient use of nutrients and recycled fertilizer products would pave the way for climate-neutral food production, an increased food security in the Baltic Sea Region (BSR), and reduce eutrophication in the Baltic Sea (INTERREG, 2024).

One of the project aims is to assess the potential for nutrient recycling (NR) to improve national and regional nutrient balances in the BSR. This was done by collecting the relevant biomass data in the countries surrounding the BSR. For Sweden, the data was collected, and numbers estimated on livestock manure, municipal sewage sludge, and municipal biowaste. Data of regionally available recyclable nutrients was collected using the EUROSTAT European database (2020) and SCB national statistics of Sweden (2020). Data included quantity of relevant recyclable biomasses, such as nitrogen (N) and phosphorus (P) content and their spatial distribution according to region of origin.

Results indicate that livestock manure in Sweden with total values of 108346 t/year of N and 17387 t/year of P could reduce the import of mineral fertilizers. Agricultural land in Sweden has an input of about 190 200 tons of mineral N fertilizer and 37 500 tons of P, of which 14 400 tons are imported as mineral fertilizer (Lorick et at., 2021). As for municipal waste streams, data showed that wastewater sludge and source-separated biowaste cover 14160,70 t/year of N and 6465,01 t/year of P. Lastly, industrial waste streams had smaller amount of N (379,03 t/year) and P (85,10 t/year).

In conclusion, there is the potential to use recycled nutrient fertilizers in Sweden that would reduce dependency on synthetic fertilizers, leading to more circular approach as well as other recycling benefits. Collecting biomass data in Sweden could be replicated in Mediterranean countries to promote the use of recyclable nutrients.

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PHOSPHORUS RECOVERY BY ELEMENTAL SULPHUR ADDITION TO MUNICIPAL BIOSOLIDS AND ITS ANAEROBIC MICROBIAL REDUCTION TO SULPHIDE

Samantha Gangapersad, Tian Zhao, Dr. Susan Gaskin, Dr. Sidney Omelon

McGill University

We investigated the recovery of insoluble phosphorus from biosolids produced at municipal wastewater treatment plant in Ottawa, Canada: the Robert O. Pickard Environmental Center (ROPEC). ROPEC biosolids, containing low solubility iron and aluminium phosphates are applied to farmland. We hypothesized that iron phosphate could be dissolved by reduction of elemental sulphur by endogenous biosolids microbes. The sulphide would precipitate insoluble iron sulphides and consequently dissolve iron phosphate. Optimization of the molar ratio of elemental sulphur (S) to biosolids total phosphorus (TP) (0, 0.5, or 1), incubation temperature (22 °C, 32 °C, or 42 °C) and time (24 h, 96 h, 168 h) to maximise orthophosphate liberation was examined employing design of experiments to optimize the number of experiments required. The orthophosphate concentration increased with time for 32 °C and 42 °C incubations, but less significantly at 22 °C. Only samples treated at 32 °C and 42 °C showed evidence of iron phosphate dissolution with x-ray diffraction. Maximum orthophosphate release occurred after 168 h with 0.5-1 M S/TP at 32 - 42 °C. An experiment under optimum conditions, 168 h with 0.5 M S/TP at 32 °C, was repeated and confirmed the maximum orthophosphate release. The experiments are currently being repeated with a second batch of ROPEC biosolids to confirm repeatability of results. Further analyses, including sulphide and sulfate quantification is currently being conducted to understand the reaction mechanisms responsible for orthophosphate release at 32-42 °C and at 22 °C. The results of the second set of experiments and the sulphide and sulfate analyses will also be presented. Subsequent experiments will investigate the re-precipitation of the orthophosphate released through sulphur addition, in a bioavailable form.

THE EFFECT OF EXTREME HEAT EVENTS ON PHOSPHORUS SOLUBILITY IN SOILS

Iris Zohar, Yael Kirshenbaum, Shani Tischler, Maria Khoury, and Hasan E. Ganem

Department of Environmental Sciences, Tel-Hai College, Upper Galilee, Israel

Extreme heat events influence soil temperature and biogeochemical processes, including contradicting effects on P solubility. The endothermic behavior of minerals and oxides results in decreased solubility with increased temperature, while high temperatures stimulate bio-mineralization. The soil humidity also affects the temperature impact on each mechanism and other soil fertility indices. Although climate change projections indicate elevation in frequency and amplitude of extreme temperature events, effects on soil P availability were hardly investigated.

We sampled adjacent alluvial soils of four different managements in a Mediterranean climate five times during the year of 2022 (spring, summer before-, during- and after a heatwave, and winter): orchard soil in between dripline and in between soil beds, exposed and bare, uncultivated soil and uncultivated, shaded soil of natural vegetation.

The two exposed soils (in-between beds and uncultivated) attained a summer water content of < 10%, and the two shady ones (dripline and natural vegetation) summer water content was 15-40%. The exposed soils, where soil temperature rose above 50 °C, responded more strongly to the heat event, while the shady, moist dripline soil showed a minor effect of elevated air temperatures. The general trend of inorganic P solubility was common to all soil managements: it increased with summer heat, but surprisingly, the highest levels were recorded in winter. Elevated levels of total nitrogen (TN) solubility, phosphatase mono- and di-esterase activity, and pH were recorded in the summer and decreased compared to the winter. Altogether, the N/P ratio fluctuated during the year in all soil managements. The dissolved organic carbon (DOC) displayed summer peaking in all soil managements while its' aromatic fraction ($SUVA_{254}$, i.e., specific absorption at 254 nm) decreased concomitantly, evidencing the summer heat contributed to C transformation to labile forms, susceptible to loss to the atmosphere. Enhanced enzymatic activity simultaneously with enhanced P and N solubility in > 50 °C dry and exposed soils suggests residual extracellular enzymes were at play during heat events. Geochemical calculations suggest P mineral phases transferred to more soluble phases; however, determining the equilibrium of soluble P with mineral phases during temporal extreme heat events requires more research. In a previous controlled laboratory experiment with the same soil type, in wet and dry conditions, we found P solubility first reflected the response of mineral phases to elevated temperatures, then, after about three weeks and three heatwaves, changed trend and displayed a substantial increase with temperature, altogether fluctuating remarkably. Our conclusion from the field and laboratory studies is that soil P minerals usually govern soluble P in the alluvial soil investigated. Nevertheless, a series of extreme heat events stimulate the enzymatic activity that overwrites trends of the abiotic system. This research demonstrated unstable soil fertility conditions during the heatwave period, governed by biogeochemical processes involving elemental interlinkages. More research is required to decipher further biotic and abiotic P controls induced by extreme temperature events in this soil and other soil types to formulate adjusted site-specific P management in future climates.

THE U.S. SCIENCE AND TECHNOLOGIES FOR PHOSPHORUS SUSTAINABILITY (STEPS) RESEARCH CENTER

Jacob L. Jones

Kobe Steel Distinguished Professor of Materials Science and Engineering, North Carolina State University, and Director of the Science and Technologies for Phosphorus Sustainability (STEPS) Center

Phosphorus (P) is a critical component of cellular structures like DNA and processes like energy transfer and underpins the productivity of food systems as a key nutrient in fertilizers. Yet many challenges exist around the availability, application, management, and disposal or reuse of P: P is sourced from non-renewable phosphate rock, is inefficiently utilized in food systems, and accumulates in terrestrial systems such as soils and freshwater sources, the latter of which causes harmful algal blooms and hypoxia of marine life. Without intervention, the environmental, economic, and sustainability issues involving phosphorus will escalate with continued world population growth. In fact, a paradigm shift is needed in how we discover and develop materials, technologies, and strategies to control, recover, reuse, and manage phosphorus such that the solutions can have a transformative impact on improving the circularity of the P cycle.

This presentation will introduce the **Science and Technologies for Phosphorus Sustainability (STEPS) Center**, a 2021-class, NSF-supported Science and Technology Center (STC). STEPS is a **convergence research center** that addresses the complex challenges in phosphorus sustainability by integrating disciplinary contributions across the physical, life, social, and economic sciences. STEPS draws from atomic and molecular insights (e.g., chemistry, materials research, biochemistry, bioengineering) to develop materials and technologies that are deployed at the human scale (e.g., environmental and agricultural engineering, plant biology, crop and soil sciences) while considering supply-chain logistics, life cycle, and other regional and global issues (e.g., ecology, economics, sociology, policy). STEPS further leverages disciplinary contributions that transcend length scales and serve as integration mechanisms within the Center (e.g., science of team science, data science). Some specific research projects undertaken by STEPS will be highlighted, including examples relevant to Europe and the theme of ESPC5.

EVALUATING CURRENT SOIL P MANAGEMENT STRATEGIES AND ITS IMPLICATIONS FOR SOIL HEALTH MONITORING

Elise Van Eynde[1], Arthur N. Fendrich[2,3], Gerard Ros[4], Felipe Yunta[1], Philippe Hinsinger[5], Anna Muntwyler[6], Panos Panagos[1]

[1]*European Commission, Joint Research Centre (JRC), Ispra, VA, Italy*
[2]*Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ-UPSACLAY, Gif sur Yvette, France*
[3]*Universite Paris-Saclay, INRAE, AgroParisTech, UMR SAD-APT, Palaiseau, France*
[4]*Wageningen University and Research, Environmental Systems Analysis Group, Wageningen, the Netherlands*
[5]*Eco&Sols, Univ Montpellier, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France*
[6]*Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland*

The EU Farm to Fork Strategy aims to reduce phosphorus (P) losses and P fertilizer use by at least 50 % and 20%, respectively, by 2030. In addition, the Zero Pollution Action Plan targets to minimize soil nutrient losses. More recently, the proposed Soil Monitoring and Resilience Law includes soil P excess as a soil health indicator. Given these recent developments in agro-environmental EU policies targeting soil P and agricultural P management, we will present an evaluation of current P management strategies (i.e. mining, build-up and maintenance) across the EU based on soil P concentrations and target levels. Next, we will present the results when linking current P management strategies to observed changes in topsoil P concentrations.

In the framework of the 'Land Use and Coverage Area frame Survey' (LUCAS) topsoil survey, about 6000 grassland and cropland soils were collected in 2009/2012, re-visited and re-analysed in 2015 and 2018 following the same laboratory methodologies. For this work, P-Olsen concentrations were measured based on extraction with $NaHCO_3$.

The results from different years were used to calculate changes in P topsoil concentrations. Using exploratory analysis and statistical regression models, these changes were linked to current P surplus estimates, and other soil and management characteristics.

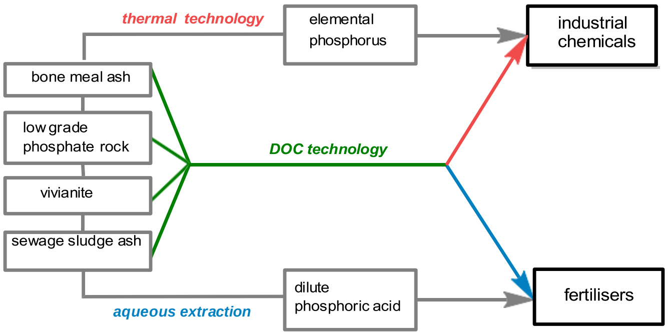
The model results aide in evaluating the gap between agronomic soil P concentrations and crop and nutrient management approaches, and the implication for soil health monitoring. Our results can contribute to EU and regional policies (e.g. for the Mediterranean regions) for sustainable phosphorus management, by showing spatially explicit trends and highlighting areas that might benefit from a change in P management.

NON-AQUEOUS PROCESS FOR SOLUBLE PHOSPHATE FERTILISER AND ORGANIC PHOSPHATES

Kirill Nikitin, Simon Hodge, Declan Gilheany, Rajan Choudhary

School of Chemistry and School of Agriculture, UCD Dublin, Ireland

Our interdisciplinary project SINFERT is focussed on a novel non-aqueous liquid-phase extraction of phosphorus. The impetus to seek such a different process are the limitations of thermal methods and acid extraction methods for treatment of medium/low grade ores and contaminated solid waste streams as illustrated below. Our aim is to address the phosphorus depletion challenge and creating efficient and commercially viable recovery of phosphate from a range of waste streams.



The technology comprises of a solid/liquid phase process, DOC, leading to a range of pure phosphorus compounds. The process incorporates an interim purification stage based on the unique chemistry of phosphorus which allows its selective recovery.

The effectiveness of industry equivalent DAP and MAP phosphate fertiliser synthesized in our lab has been evaluated in greenhouse trials (image above) on barley, oats and wheat, and found unfettered positive effects on plant growth in each case.

The value of DOC process for the chemical industry is the possibility to bypass white phosphorus *en route* to most industrially relevant phosphorus compounds including trialkyl- and triarylphosphate esters, plasticizers, flame retardants and phosphines. The objective is to combine the key DOC chemical step with other industrial steps to form a sustainable efficient closed-loop technology. SINFERT is a new ESPP member seeking effective collaboration with industrial and specialised academic stakeholders.

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IMPACT OF CLIMATE CHANGE ON P LOSSES: EMPIRICAL MODELLING OF HISTORICAL DATA AND FAR FUTURE PROJECTIONS IN HYDROLOGICALLY DIVERSE AGRICULTURAL CATCHMENTS

Golnaz Ezzati[1], Adrian. L. Collins[2], Per-Erik Mellander[1]

1 Agriclutral Catchments Programme, Teagasc, Johnstown Castle, Wexford, Ireland

2 Net Zero and Resilient Farming, Rothamsted Research, North Wyke, Okehampton, UK

Water quality in European rivers is degraded by pollutant loss to waters and excessive phosphorus (P) from agricultural lands is a particular problem in the freshwater systems. In view of the more frequent occurrence of extreme hydrological events, managing P loss in agricultural landscapes has become a particular pervasive challenge. Climate change will likely exacerbate nutrient and contaminant losses due to intensified hydro-meteorological drivers. Therefore, development and implementation of robust mitigation strategies will require an improved understanding of the timings and conditions that trigger losses.

The influence of the changing weather patterns on P loss events was assessed in six agriculturally-dominated hydrologically diverse catchments (ca 3-30 km^2) in Ireland. Empirical modelling was applied on 12-year of 10-min water quality and weather data to associate events of P losses with historical extreme-weather events. The influence of climate change on occurrence and timing of such triggering events for far-future was further assessed using downscaled intermediate and severe concentration pathways scenarios (i.e. RCP4.5 and RCP8.5 respectively) based on river discharge, temperature, and precipitation.

The modelling of high-resolution monitoring data revealed that having a "very wet day" (rainfall exceeding 5mm) following to five consecutive days of rainfall cumulating 5 mm would explained up to half of the flushes of P into surface water bodies across all catchments. Three time periods of 2010-2040, 2040-2070, and 2070-2100 in two emission scenarios of RCP 4.5 and 8.5 were compared. The results suggested a stepwise upward trend in rainfall which would double in the severe emission scenario. While the response of each catchment to climate change was controlled by soil chemistry, drainage network, hydrological connectivity, and farming, there would be an up to 2.4 times increase in the number of P losses events as we move towards the end of the century.

Extreme rainfall and increased hydrological connectivity within the studied catchments resulted in P loss incidents but due to the diversity in site characteristics, the frequency of P loss events differed across catchments and also within projected climate change scenarios. Hence, climate smart agro-environmental management measures are needed that are catchment-specific, resilient, and tailored to different environments and hydrometeorological consideration.

The study was carried out as part of the Water Future Project funded by the Irish Environmental Protection Agency and in collaboration with Agricultural Catchments Programme (Ireland).

POWER TO P

Innovative Phosphorus Recovery from Sewage Sludge Ash

Jesper Hoejer

Clean Matter Aps. Denmark

Phosphorus is an essential nutrient for all living organisms and a critical component of fertilizers, yet it is a finite resource with limited global availability. Most of the world's phosphorus supply is imported from Morocco and Russia, making it a strategic and vulnerable resource. The innovative technology developed by Clean Matter addresses this challenge by recovering phosphorus from sewage sludge ash (SSA) using a patented electrolysis process powered by green energy. This method not only closes the phosphorus cycle but also offers a sustainable and environmentally friendly solution to phosphorus recovery.

Technology Overview

Clean Matter's Power-to-P technology involves mixing SSA with water and processing it through an electrodialysis reactor. This reactor utilizes a patented dual-chamber electrolysis system, where a membrane separates the anode and cathode chambers, allowing for the efficient separation of negatively charged phosphorus and positively charged heavy metals. This process recovers up to 90% of the phosphorus from the SSA in the form of phosphoric acid, a vital component for fertilizers. Additionally, the purified ash can be repurposed as a cement-like additive, partially replacing traditional cement, thereby contributing to the circular economy.

Environmental and Operational Benefits

The Power-to-P technology operates solely on ash, water, and electrical power, eliminating the need for chemical leaching agents or solvents. This approach not only simplifies the operation and reduces potential chemical hazards but also minimizes the transport and disposal of harmful substances. The process has demonstrated remarkable efficiency in removing contaminants from the SSA, achieving up to 99% removal rates for elements like zinc, strontium, and selenium.

Business Model and Development Plan

Clean Matter plans to build, own, and operate Power-to-P plants adjacent to sludge incineration facilities. By partnering with domestic financial and operational entities, Clean Matter aims to generate revenue from ash gate fees, the sale of recovered phosphorus at market prices, and the sale of minerals and heavy metals extracted during the process.

The development roadmap includes establishing a prototype facility in Denmark by 2024, capable of processing 1 ton of SSA per day. By 2025, a modular pilot plant with a capacity of 25 tons per day (comprising five 5-ton modules) will be operational. The goal is to scale up to an industrial-size plant in Germany by 2026, ensuring significant impact on phosphorus recovery and sustainable waste management.

Impact on CO2 Footprint

The Power-to-P technology significantly reduces the carbon footprint compared to conventional phosphate rock mining and other phosphorus recovery methods. For instance, the CO2 equivalent per processed ton of SSA is drastically lower at 5 kg, compared to 400-600 kg for the current technologies involving chemicals. This substantial reduction underscores the environmental benefits and sustainability of the Power-to-P process.

Conclusion

Clean Matter's innovative approach to phosphorus recovery from sewage sludge ash represents a groundbreaking advancement in sustainable resource management. By leveraging green energy and patented electrolysis technology, Clean Matter not only addresses the critical issue of phosphorus scarcity but also contributes to the reduction of hazardous waste and CO2 emissions. With a clear development plan and a strong business model, Clean Matter is poised to make a significant impact on the circular economy and global phosphorus supply chain.

Blending circular fertilisers towards plant requirements -

Potatoes and strawberries are making the most of summer with a cocktail of circular fertilisers

R. Devlamynck, B. Everaert, J. Claerbout, E. Tardy, I. Verleden, D. Huits

Provincial Research and Advice Centre for Agriculture and Horticulture (Inagro vzw), Rumbeke-Beitem, Belgium, reindert.devlamynck@inagro.be.

Nitrogen (N) and phosphorous (P) flows exceed the planetary boundaries and situate themselves in the high-risk zone[1], resulting in eutrophication, greenhouse gas emission, and loss of biodiversity. Transitioning from nutrient removal toward nutrient recovery has the potential to reduce the fossil inputs from fertilization, while creating a market for new fertilizing products.

These fertilizing products are the result from technologies like solid/liquid-separation, P-precipitation, drying and incineration of sludge, composting, anaerobic digestion, ammonia stripping, reversed osmosis and pyrolysis. The individual products have been proven to have a good fertilizing value in several field trials all over Europe. It is a given that none of these products perfectly match the plant requirements, and mixing with other fertilisers (animal manure, synthetic, or organic) can help match the nutrient content more closely to the crop requirements.

In the ambition to recover as many nutrients as possible, mixing the circular fertilisers is an interesting option. Inagro is involved in two projects (Interreg NWE - ReNu2Cycle, and VLAIO LA - Hermest) where blends are made to fertilize open field crops (potato), hydroponics (Belgian endive, tomato, and lettuce) and container fields (strawberry).

During the poster or oral presentation we can present the methodology from a field trial in potato with 4 different blends:

1. Ammonium sulphate + zeolites
2. Ammonium sulphate + mineral concentrate
3. Pig urine + mineral concentrate
4. Liquid fraction + mineral concentrate

The field trial was planted in June 2024 and will be harvested in October. As a result, only the field observations can give an indication of the success of the experiment.

In line with this experiment, we will present the strawberry trial that started in June 2023. Unique is the foliar fertilization in this experiment, meaning that the circular fertilisers have to be able to pass a spray nozzle.

Three nutrient mixes were made that were theoretically similar to a control medium, but with the inclusion of liquid fraction from pig manure, ammonium sulphate, and biological effluent from pig manure. All these nutrient sources contain predominantly ammonia instead of nitrate. For that reason, we had to exchange nitrate into ammonium in the recipe. The conclusion from the experiment in 2023, is that the mix with biological effluent showed a slightly, yet significant lower fruit yield. Both other treatments showed no significant differences.

Finally, Belgian endive, which is cultivated in a hydroponic, which will be tested this summer.

At poster presentation we will provide a step by step guideline of how the selection process works for creating these blends and indicate the implications, and how these differ between open field crops, container field and hydroponic. The focus will lay on the applicability of circular fertilisers in three different systems. These insights can push forward the transition from synthetic/mineral to circular fertilisers in both arable as well as greenhouse crops.

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REDUCTIVE P-RECOVERY FROM EXCESS SLUDGE IN WASTEWATER TREATMENT PLANTS

Joachim Clemens, Christine Oeppert

SF-Soepenberg GmbH, Emil-Fischer-Straße 14, D-46569 Hünxe

In some European countries, laws require P-recovery from wastewater or sewage sludge. In Germany, sewage sludge that contains more than 2% P in the dry mass must be recycled. It is assumed that most of these sludges will be treated thermally, and P is recovered from the ash. However, if the sludge contains less than 2% P in DM, no P recycling from the sewage sludge is required. P can be recovered from wastewater or intermediated sludges on the wastewater treatment plant to match this criterion. But since recently these technologies have not been efficient enough to reduce the overall P concentration below 2% P in the sewage sludge because only dissolved P can be recovered. During the last years, different methods have been developed to disintegrate the sludge to increase dissolved P for better P recovery. Most of these technologies focus on the biological bound P.

We present a disintegration technology that releases P from iron phosphates. By reduction of FeP in excess sludge P is released and can be removed in form of Calcium- or Magnesiumphosphates. Dependent on the recovery requirements, the reduction phase and intensity are adapted. The technology was continuously tested in a pilot installation that treated wastewater from 5000 inhabitant equivalents in Germany for three months. The P was recovered in form of struvite.

During the test, the disintegration was adapted to the German legislative requirements: The aim was to produce a sewage sludge with concentration of P<2% (DM). The original concentration of P was 3.8% (DM). During the whole time, the P concentration in the sludge was 1.8% P (DM). In between, the reduction parameters were changed, and P concentration decreased down to 1.2% P (DM). The recovered struvite was a fine crystalline product and showed only few impurities.

PHOSPHORUS CIRCULARITY IN THE ENERGY TRANSITION: EXPLORING THERMAL TREATMENT APPLICATIONS IN WASTEWATER TREATMENT AND AQUACULTURE PRODUCTION FOR SLUDGE VALORISATION

Maja Arsic[1], Alexander Ilyushechkin[2], San S. Hla[2], Cathryn A. O'Sullivan[1], Anton P. Wasson[3], Diogenes L. Antille[3], Rebecca E. Haling[3]

[1]CSIRO Agriculture and Food, Queensland Biosciences Precinct, St Lucia, QLD 4067, Australia
[2]CSIRO Energy, 1 Technology Court, Pullenvale, QLD 4069, Australia
[3]CSIRO Agriculture and Food, Black Mountain Science and Innovation Precinct, Canberra, ACT 2601, Australia

Developing safe and effective circular phosphorus (P) products and value chains requires navigating complex interactions within waste, energy and environmental policy and regulation, and identifying alignment with emerging innovation opportunities between waste engineers and agricultural scientists to shift from P recovery to P reuse (Arsic et al. 2023). A systems perspective can link the international sustainability and energy transition policy drivers with regional and industrial regulatory drivers for environmental management and emissions reporting, which shape the market appetite and technical pathways for nutrient capture and reuse (Arsic et al. 2022).

This presentation applies a socio-technical systems perspective to outline the drivers and implications for nutrient and carbon circularity in the context of the energy transition, using Australia as a case study. Thermal treatment technologies are used as an example in the wastewater treatment and aquaculture sectors, as both industries are exploring thermal options for sludge management. From an energy transition perspective, thermal technologies are gaining interest due to their potential for renewable energy/bioenergy, reducing Scope 3 emissions via transportation, waste heat applications, or biogenic carbon for decarbonising heavy industry. From a sludge management perspective, thermal technologies provide industrial solutions for emerging organic contaminant environmental regulations (e.g., PFOS and PFAS) in sewage sludges, or reducing costs associated with transport and application of sludges with high water content and labile nutrients near environmentally sensitive areas (aquaculture).

From a circular P perspective, thermal treatment processes affect the total and soluble P fractions in the processed sludge material. Results are presented from experiments on a range of sewage and aquaculture sludge materials. When sewage sludges were processed under three conditions (incineration, pyrolysis, gasification) at two temperatures, the highest soluble P fractions occurred under high temperature pyrolysis (citric acid soluble). The addition of specific potassium salts greatly increased the P solubility in sewage sludge chars. Thermal treatment of aquaculture sludges increased the total P in the ash product, but decreased soluble P concentrations. Applying a socio-technical systems perspective can provide insights into facilitating the development of viable circular P products in the context of international and regional sustainability transitions.

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INVESTIGATIONS ON THE PHOSPHORUS RELEASE BEHAVIOR FROM SEWAGE SLUDGE IN INERT AND REDUCING CONDITIONS

Eric Franke, Sergei Shalnev, Ronny Schimpke, Steffen Krzack and Martin Gräbner
TU Bergakademie Freiberg, Institute of Energy process Engineering and Chemical Engineering, Fuchsmuehlenweg 9D, 09599 Freiberg, Germany.

Thermochemical conversion processes of carbonaceous materials have been subject to intensive theoretical and practical studies within the last decades.[1] Especially in the last years because of political and social pressure towards a shift from fossil carbonaceous feedstocks towards renewable energy and carbon matter sources the studies of the thermochemical conversion behavior of alternative feedstocks like e.g. plastic waste[2], biomass[3] or even nuclear graphite[4] gained increasing importance. In this field, especially biomasses like sewage sludge (SS) are an interesting feedstock since a simultaneous chemical recycling of carbon and valuable elements like phosphorus is possible resulting in a common circular phosphorus and carbon economy.

In this work, the phosphorus release behavior of five different sewage sludge (SS) samples is investigated in a simulated gasification environment, with the further aim of phosphorus separation from syngas and recycling in gasification processes. In a first step, the samples were analyzed in an inert atmosphere using a thermogravimetric analyzer coupled with mass spectrometry (TG-MS). It is demonstrated that the main pyrolysis, which consists mostly of hydrocarbon fragmentation, is finished at temperatures below 550 °C. No correlations between the elemental sewage sludge composition and the pyrolysis behavior could be detected. Nevertheless, the feedstock composition plays an important role in terms of the phosphorus release behavior.
Depending on the composition, the phosphorus release starts at temperatures ranging from 969 °C to 1052 °C. Phosphorus is predominantly released in elemental form.
Additionally, up to 98.2 % of the phosphorus in the samples can be released while its release ratio (PRR) correlates positively with the aluminum content and negatively with the iron content of the samples. In a second step, the original samples, their pyrolysis residue coke and their ash were treated in both inert and forming gas (FG) atmosphere, latter composed of nitrogen with 3.75 vol.-% H2. It was found that the phosphorus is mainly reduced by carbon from the feedstock leading to its release into the gas phase,

since no phosphorus release took place in the case of ash treated in inert conditions up to 1450 °C. Switching to FG atmosphere, phosphorus was also released, leading to the conclusion that strong reducing conditions have to be present to release gaseous phosphorus. In a last step, sewage sludge coke was treated with different mixtures of carbon monoxide and carbon dioxide as well as mixtures of carbon monoxide and nitrogen. It was found that the oxygen partial pressure has to be substantially low to sustain phosphorus release.

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AQUA2®N – INNOVATIVE TECHNOLOGY TO REMOVE AND RECOVER NITROGEN FROM WASTEWATER

Sido Altenburg, Yariv Cohen

EasyMining Services Sweden AB

Nitrogen recovery from wastewater is crucial for enhancing sustainability in agriculture and reducing environmental impact. EasyMining's Aqua2®N technology presents an innovative, circular solution to this challenge by removing up to 95% of ammonium nitrogen from concentrated ammonium streams, such as reject water, sludge condensate, and other industrial applications, and converting it into liquid ammonium sulphate. The Aqua2®N process is a two-step chemical system where ammonium nitrogen is first precipitated and then converted into ammonium sulphate, while regenerating the precipitant for reuse in the process. This system drastically reduces greenhouse gas emissions, and the process does not release nitrous oxide.

The Aqua2®N technology is robust, energy-efficient, and scalable, making it an ideal fit for wastewater treatment plants (WWTPs) handling streams with high concentrations of ammonium nitrogen. Additionally, the process reduces the carbon footprint associated with traditional fertilizer production by recovering nitrogen directly from wastewater, transforming WWTPs into nutrient factories. Its integration into existing WWTPs enhances plant efficiency and capacity, helping operators meet strict future EU regulations on nitrogen emissions and discharge. Aqua2®N addresses this issue by recovering ammonium and returning it to the production cycle as a high-quality fertilizer. By offering a turnkey solution that includes design, construction, and commissioning, Aqua2®N supports the shift toward sustainable agricultural practices and a greener economy.

A CIRCULAR APPROACH TO PHOSPHOROUS RECOVERY: STRUVITE PRECIPITATION FROM BIOMASS WASTE

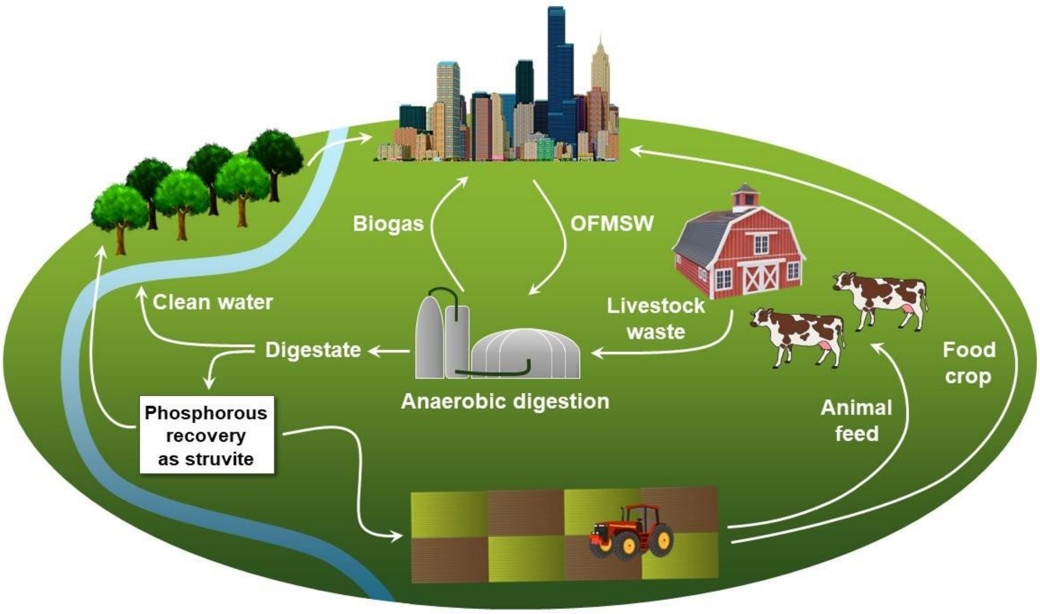
Alice Boarino, Elio Padoan, Luisella Celi

Department of Agricultural, Forest and Food Sciences, University of Turin, Largo Paolo Braccini 2, 10095 Grugliasco, Italy

The European Commission classifies phosphate rock as one of the 20 Critical Raw Materials, because of its great importance and high supply risk. Phosphorus is in fact a vital element without valid alternatives for the entire global population, but its production is concentrated in only three main countries (USA, China and Morocco).

Moreover, phosphorus use efficiency is tremendously low: 80% of P is lost in the supply chain from mine, to crop fertilization, to food production. The main losses end up in water bodies via run off and wastewater, resulting in local accumulation and environmental issues like eutrophication. The transition towards a more circular use of this nutrient has therefore become urgent and inevitable.

A promising approach is to recycle phosphorous from digestate produced during anaerobic digestion of biomass wastes. Digestate is normally separated into solid and liquid fractions. The solid can be further treated by composting or other methods, while the liquid is often disposed of. A smart strategy to avoid N and P discharge in water bodies is to precipitate ammonium and phosphate from the digestate liquid fraction as struvite, a natural mineral with composition NH4PO4Mg·6H2O, which can be used as slow-release fertilizer. Herein, phosphorous was recovered from the digestate of two different waste materials, yearly produced in huge quantities: livestock waste and the organic fraction of municipal solid waste (OFMSW). When the digestate is separated into solid and liquid fraction, phosphorus normally remains in the solid, while to be recovered as struvite it must be solubilized and moved to the liquid part. Therefore, various pre-treatments can be applied to the initial substrate before anaerobic digestion to solubilize the organic phosphorus, often consisting in strong acidic conditions. In this work, milder enzymatic and physical processes were tested, alone or in combination, aiming to optimize P solubilization and recovery as struvite in a more sustainable way. Different enzymes for organic matter degradation (cellulase, hemicellulose and protease) and phosphate hydrolyses (phosphatase and phytase) were tested, singly or merged with hydrodynamic cavitation. The effects of pre-treatments on the digestate composition were compared and evaluated to optimize the struvite production from the two different biomass wastes. Particular attention was paid both to the quality of the struvite achieved, in terms of yield, purity and slow-release capacity, and to the efficiency of nutrient removal from the digestate liquid fraction. This study aims to contribute to the transition towards a more circular and sustainable use of phosphorus, starting from the valorization of waste materials as a source of this nutrient essential for life.



B-FERST PROJECT: BIO-BASED FERTILISING PRODUCTS AS THE BEST PRACTICE FOR AGRICULTURAL MANAGEMENT SUSTAINABILITY

Cinta Cazador Ruiz, Javier Brañas Lasala

FERTIBERIA

B-FERST's main objective is to integrate the valorisation of bio-wastes in agriculture management plans creating new circular and bio-based value chains from bio-waste, municipal waste management, agri-food industries to fertiliser value chain, considering a bilateral interaction between farming and fertiliser sectors. It is focused on a paradigm shift in the fertiliser value chain with 8 specialised fertilisers, that combine biobased recovered nutrients with biostimulants and biodegradable coatings.

B-FERST project is being carried out by 11 entities and finishes in October 2024. It has achieved the following results so far:

- More than 150 biowastes have been identified from different sectors and areas in EU.

- A new decision tool to assess the suitability of biowaste to be implemented in the fertiliser industry value chain has been developed. Main hurdles and bottlenecks have been identified.

- Biostimulants and biodegradable coatings have been developed and validated from the technical, environmental, and industrial point of view.

- A first-of-its-kind Nutrient Recovery Demo Plant has been designed and built, able to solubilise nutrients from biowastes into available forms. It is based on an acid leaching process and a neutralization step that take place in a new double and thermally coupled reactor that saves energy and at the same time cathalises the neutralization reaction. It can produce 500 kg/h of dicalcium phosphate.

- A first-of-its-kind Coating Demo Plant has been built and can coat granules of fertilisers up to 1,5 t/h capacity. It has been designed to use biobased and biodegradable coatings, such as Non-Microbial Plant Biostimulants (NMPBs), Microbial Plant Biostimulants (MPBs) and Biodegradable Coating in multiple stages.

- Biobased fertilisers have agronomically been validated under relevant conditions in 4 field trials campaigns in Spain, Italy, Portugal and Poland. NPK fertilisers with biobased nutrients performed similarly as the conventional fertilisers, that demonstrated the feasibility of recovered nutrients. Moreover, NPK fertilisers with recovered nutrients and biobased coatings performed better than conventional fertilisers.

- The biodiversity assessment in soil demonstrated that generally the application of biobased fertilisers with MPBs has no effect on soil biodiversity. Furthermore, fertilisation, especially with the bio-based fertilisers without NMPB or MPB, seems to attract to the rhizosphere beneficial bacteria general (PGPR).

- The LCA demonstrated that the new biobased fertilisers contribute to the reduction of the carbon footprint compared to the conventional fertilisers.

As a conclusion, a new family of fertilisers with recycled nutrients and biobased coatings has been created and is ready to be industrially up-scaled.

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www.bferst.eu

PHOSPHATE AND AMMONIUM RECOVERY IN A THREE CHAMBERED MICROBIAL ELECTROLYSIS CELL

Míriam Cerrillo, Victor Riau, August Bonmatí

Sustainability in Biosystems, Institute of Agrifood Research and Technology (IRTA), Torre Marimon, E-08140 Caldes de Montbui, Barcelona (Spain), august.bonmati@irta.cat

An alternative to traditional livestock manure management is the implementation of circular agrosystems approaches. The recovery of phosphate, among other nutrients, helps closing natural cycles and take a step forward within the framework of closed-loop agriculture. In addition to more conventional nutrient recovery technologies, bioelectrochemical systems (BES) are emerging as candidates for the recovery of multiple resources from waste. BES are devices where exoelectrogenic microorganisms catalyse oxidation and/or reduction reactions in an electrode (anode and/or cathode, respectively) and, in combination with cation or anion exchange membranes, allow the recovery of nutrients [1]. In this work, a lab-scale three-chambered microbial electrolysis cell (MEC) has been operated in continuous mode for the recovery of phosphate together with ammonia from digested pig slurry, to obtain a concentrated nutrient solution as a potential source of fertilizer in the form of struvite [2]. Struvite is a salt composed of ammonia, phosphate, and magnesium (heptahydrate), and has been described as a slow-release fertilizer. The MEC was composed of an anode and a cathode compartments, separated by a recovery compartment delimited with a cation exchange membrane on the anode side and an anion exchange membrane on the cathode side. The digestate was first fed to the anode compartment to recover the ammonium, and then the anodic effluent was circulated to feed the cathode compartment and to recover the phosphate. In some of the assays, the digestate was acidified with H_2SO_4 to favour phosphate solubilization. The maximum average removal efficiencies for phosphate and ammonium were 36%±0% and 20%±4%, respectively. Salt precipitation was avoided in the reactor due to the pH of the recovered solution (<7). An increase of pH value to 8 outside the reactor would be enough to recover most of the potential struvite (0.21 mmol L^{-1} d^{-1}), while the addition of up to 0.2 mM of magnesium to the nutrient recovered solution would enhance struvite production from 5.6 to 17.7 mM, according to Visual MINTEQ software modelling. Phosphate solubilization is revealed as a key issue in the recovery of struvite from livestock manure in BES, as acidification with H_2SO_4 can interfere, on the one hand, with the growth of biomass in the anode compartment, and, on the other hand, with phosphate migration. Phosphate solubilization techniques compatible with BES performance should be evaluated to improve system recovery efficiency. However, the application of three-chambered MECs for nutrient recovery from high-concentration wastewater is a promising technology to avoid phosphate mineral extraction or ammonia production through industrial processes while closing natural nutrient cycles.

Acknowledgements.

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SOIL MOISTURE CONTENT GREATLY IMPACTS POLYPHOSPHATE FERTILIZER EFFECTIVENESS AND USE EFFICIENCY IN MEDITERRANEAN SEMI-ARID REGION.

Mohamed Chtouki & Abdallah Oukarroum

Plant Stress Physiology Laboratory, College of Agriculture and Environmental Science, Mohammed VI Polytechnic University, Benguerir 43150, Morocco

Water shortage and soil nutrient depletion are considered the main factors limiting crops productivity in the Mediterranean region characterized by longer and frequent drought episodes. In this study, we investigated the interactive effects of P fertilizer form and soil moisture conditions on chickpea photosynthetic activity, water and nutrient uptake, and their consequent effects on biomass accumulation and nutrient use efficiency. Two P fertilizer formulas based on orthophosphates (Ortho-P) and polyphosphates (Poly-P) were evaluated under three irrigation regimes (I1: 75% of field capacity, I2: 50% FC and I3: 25% FC), simulating three probable scenarios of soil water content in the Mediterranean climate (adequate water supply, medium, and severe drought stress), and compared to an unfertilized treatment. The experiment was conducted in a spilt-plot design under a drip fertigation system. The results showed significant changes in chickpea phenotypic and physiological traits in response to different P and water supply regimes. Compared with the unfertilized treatment, the stomata density and conductance, chlorophyll content, photosynthesis efficiency, biomass accumulation, and plant nutrient uptake were significantly improved under P drip fertigation. The obtained results suggested that the P fertilizer form and irrigation regime providing chickpea plants with enough P and water, at the early growth stage, increased the stomatal density and conductance, which significantly improved the photosynthetic performance index (PI_{ABS}) and P use efficiency (PUE), and consequently biomass accumulation and nutrient uptake. The significant correlations established between leaf stomatal density, PI_{ABS}, and PUE supported the above hypothesis. We concluded that the Poly-P fertilizers applied in well-watered conditions (I1) performed the best in terms of chickpea growth improvement, nutrient uptake and use efficiency. However, their effectiveness was greatly reduced under water stress conditions, unlike the Ortho-P form which kept stable positive effects on the studied parameters.

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"OPTIMIZING BIOLOGICAL NUTRIENT REMOVAL: TRANSFORMING LAB INNOVATIONS TO INDUSTRIAL SOLUTIONS FOR THE POTATO PROCESSING SECTOR"

Dorothee Göttert [a,*], Johanna Korte [b], Jana Weyns [c], Jan Dries [d]

[a,b,c,d] *BioWAVE, Biochemical Wastewater Valorization and Engineering, Faculty of Applied Engineering, University of Antwerp, Groenenborgerlaan 171, 2020 Antwerpen, Belgium*

* Corresponding author: Dorothee.Goettert@uantwerpen.be

In Belgium, over 6.2 million tonnes of potatoes were processed in 2022 alone, resulting in approximately 20 to 50 million liters of wastewater [1, 2]. This wastewater contains high concentrations of nitrogen (N), phosphorus (P), and carbon (C), posing a risk of eutrophication and rendering it unsuitable for direct discharge without treatment per Belgian discharge regulations (VLAREM II) [3]. However, these compounds also serve as essential nutrients for biological growth, making biological nutrient removal (BNR) particularly attractive to treat wastewater. Current industry practices focus on biological N and C removal through nitrification, denitrification, and anaerobic digestion; P is typically removed via chemical precipitation with metal salts. Although physicochemical P-removal is efficient and straightforward, it has significant drawbacks, including high chemical costs, additional sludge formation, increased effluent salinity, and the lack of P-recovery, making it incompatible with sustainable practices [4]. The objective of this research is to optimize current BNR processes for potato-processing wastewater by incorporating Enhanced Biological Phosphorous Removal (EBPR), which offers significant advantages such as eliminating chemical use, reducing sludge production and effluent salinity, and enabling P-recovery.

This study focuses on establishing a laboratory-scale Sequencing Batch Reactor (SBR) cycle adaptable to an industrial-scale system. This innovative approach replaces chemical precipitation with an anaerobic step at the start of the treatment cycle (Figure 1), creating a selective environment for polyphosphate-accumulating organisms (PAOs), which take up P from their environment and store it as intracellular polyphosphate [5]. Using industrial wastewater exclusively, the study assesses the stability of the microbial community amidst natural nutrient fluctuations. Involving multiple companies ensures robust results by testing the treatment method on wastewater and sludge from different potato-processing facilities and optimizing C-utilization, often the limiting factor for Bio-P removal; Table 1 highlights nutrient variability across different companies' feedwaters.

Research conducted on Company 1 wastewater spanned over 300 days, employing two 11L EBPR SBRs (A & B) to establish and evaluate various treatment cycle setups using seed sludge containing PAO activity. Identified functional SBR cycle configurations underwent rigorous testing to validate their nutrient removal efficiency and stability long-term. Additionally, multiple effluent-to-influent feedwater ratios were tested to optimize C-utilization. Despite challenges posed by intentional phase changes and significant variations in the wastewater composition, both reactors exhibited resilience and maintained operational stability. While SBR A and SBR B demonstrated nearly identical removal rates for C and N, approximately 97% and 98% respectively, they exhibited significant differences in P-removal efficiency. SBR A consistently outperformed SBR B across all effluent-to-influent feedwater ratios, achieving average P-removal rates of 92.2% compared to 78.5% (Figure 2). Preliminary results from ongoing experiments on Company 2 wastewater are promising; the treatment cycle developed during Company 1 testing has successfully established biological P-removal within just 60 days using sludge that initially lacked PAO activity (Figure 3).

To summarize, the experiments led to the development of a dynamic process cycle adaptable to industrial-SBR systems and fluctuating nutrient concentrations in potato-processing wastewater. These findings provide valuable information on the long-term performance and stability of the SBR cycle, laying the foundation for implementation and upscaling this biological treatment process to an industrial setting.

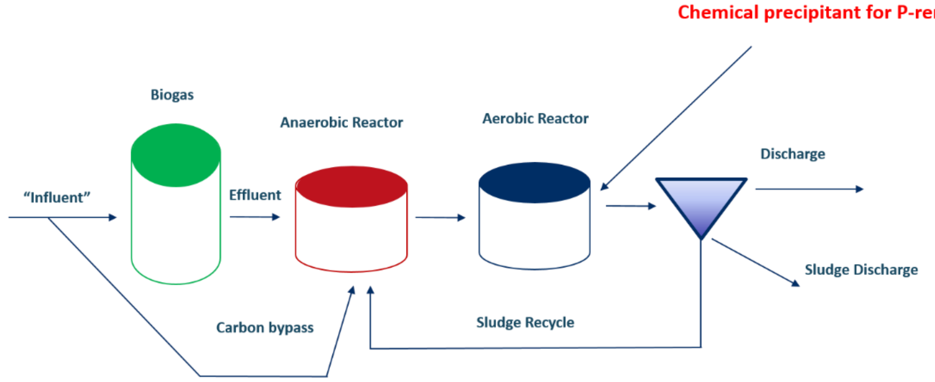

Figure 1. Typical treatment process for biological Nitrogen and Carbon removal, plus the addition of biological or chemical Phosphorous removal (in red)

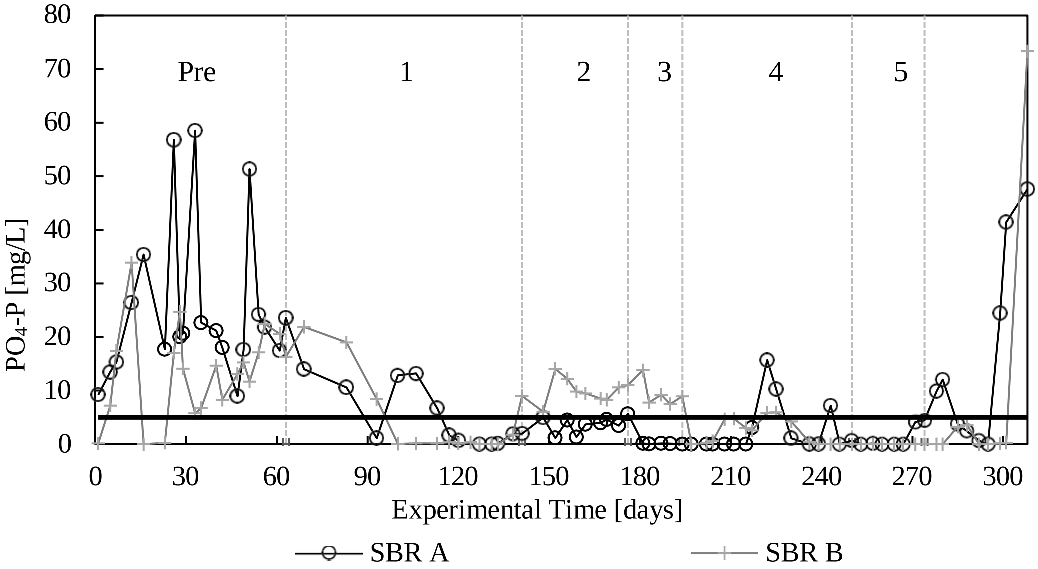

Figure 2. Effluent discharge concentrations of phosphate (PO_4-P) throughout the 308 days of experimental time with Company 1 for SBR A and SBR B, including feedwater ratio testing. Pre was adjusting the cycle time and feedwater volumes, phases 1-5 having strict effluent:influent feedwater ratios of 2:1, 2.5:1, 3:1, 3.5:1, and 4:1 respetively, and the post phase having double the amount of PO_4-P concentration, requiring drastic feedwater ratio changes.

Table 1. Potato processing effluent and influent wastewater

Parameter	Influent* Company 1	Effluent** Company 1	Influent* Company 2	Effluent** Company 2
COD (mg/L)	8163±1439	1125±505	4055±447	474±62
TN (mg/L)	188±62	425±97	114±23	129±20
TP (mg/L)	41±31	34±11	25±3	35±13

*Influent wastewater refers to the immediate potato processing wastewater that has undergone no treatment

**Effluent wastewater refers to the effluent from the anaerobic digester that still requires treatment to remove N and P

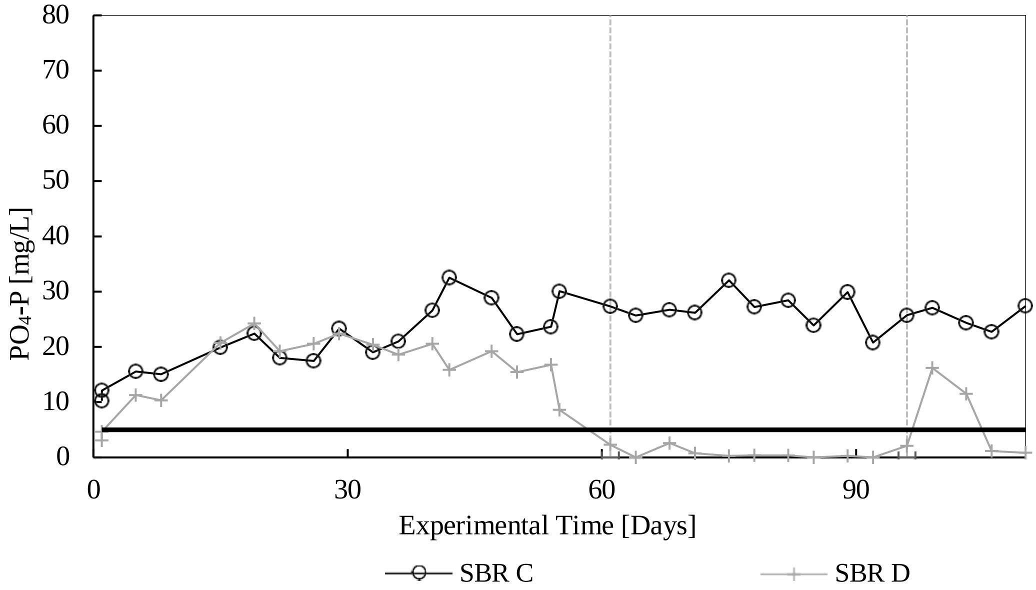

Figure 3. Effluent discharge concentrations of phosphate (PO_4-P) throughout 110 days of experimental time with Company 2 for SBR C (industry reference) and SBR D (experimental Bio-P), including feedwater ratio testing. Pre was the time it took for PAO activity to establish using sludge with no Bio-P activity, phases 1 and 2 are effluent:influent feedwater ratios of 2:1 and 2.5:1 respectively.

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PHOSPHORUS RECOVERY AS VIVIANITE FROM SLUDGE BY MAGNETIC MEANS

O. Grönfors*, V. Vuori*, A. Haarala*, B. Hansen**, J-C. Ades***

Kemira Oyj, Kemira Kemi AB**, Kemira Chimie****

Wastewater treatment plants (WWTP) are looking for phosphorus recovery methods meeting with the new purification requirements and being compatible with the existing processes. Kemira ViviMag® is one solution. ViviMag® is a new innovative technology to recover phosphorus and iron in the form of vivianite from sludge by magnetic means. The technology fits for WWTPs that use iron coagulants for phosphorus removal. Up to 60% of influent phosphorus can be recovered. Two industrial pilot scale trials have been done, and the third one is on-going. The aim of the trials is to verify the technology and demonstrate phosphorus recovery capabilities. A summary of all trials will be presented with high level conclusions of the performance of the technology.

Phosphorus recovery methods for municipal wastewater, sludge and incinerated ash have been developed over the decades. However there has been a technology gap to recover phosphorus directly from sludge from wastewater treatment plants (WWTP) using chemical phosphorus removal. This changed when the magnetic separation of vivianite was introduced.

With this new technology, ViviMag®, iron coagulants facilitate the phosphorus recovery. Both phosphorus and iron are recovered and can be reused as valuable nutrients in the food chain, for example as iron fertilizer against iron chlorosis in Mediterranean area.

The target of these trials was to assess the phosphorus and iron recovery from sludge by magnetic means. Two industrial scale pilot trials have been accomplished, one in collaboration with Veolia at Schönebeck WWTP in Germany and the other one with Vand Center Syd at Søndersø WWTP in Denmark. Schönebeck WWTP operated in Enhanced Biological Phosphorus Removal configuration but with increased iron dosage. The sludge used in the phosphorus separation was anaerobic digested. Søndersø WWTP is a biological plant with chemical phosphorus removal with iron coagulant.

Since Søndersø does not have a digester, phosphorus recovery was made on undigested sludge.

The third trial is on-going in the Netherlands at Hoensbroek WWTP in collaboration with Waterschapsbedrijf Limburg and Royal HaskoningDHV.

Magnetic separation is a selective method to recover vivianite, $Fe_3(PO_4)_2 \cdot 8H_2O$. A typical composition of the recovered material in these trials was 8-11% of P and 20-27% of Fe in dry matter. Separated vivianite is low in metal impurities and compliant with EU fertilizer directive requirements. Vivianite can be used as such or further processed.

Phosphorus recovery rate of 50% in Germany and 30-40% in Denmark was reached. The digested sludge contained 75-85% of P in vivianite whereas undigested sludge had 41-54%, indicating a higher recovery potential from a digested than an undigested sludge. The Dutch digested sludge contained 55% of vivianite and its phosphorus recovery rate will be demonstrated. (Figure 1)

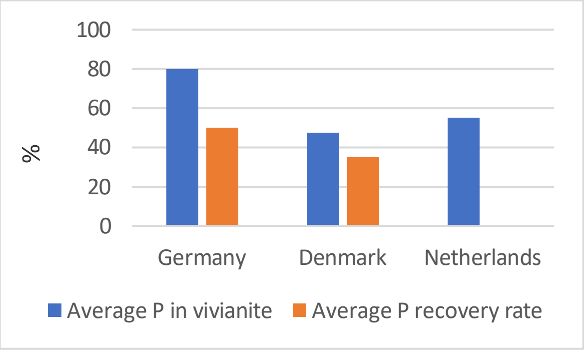

Figure 1 An average share of phosphorus bound in vivianite and average phosphorus recovery rates from studied sludges.

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MOBILE NMR SENSOR TECHNOLOGY: QUANTIFICATION OF PHOSPHORUS AND OTHER PARAMETERS IN ANIMAL SLURRY, FEED, AND SOIL

Morten K. Sørensen,[a,b,c] Michael Beyer,[a] Ole N. Jensen,[a] and Niels Chr. Nielsen[a, +]

[a]*NanoNord A/S, Skjernvej 3, DK-9220, Aalborg Ø, Denmark,* [b]*Department of Biological and Chemical Engineering, Aarhus University, Gustav Wieds Vej 10C, DK-8000 Aarhus C, Denmark,* [c]*Interdisciplinary Nanoscience Center (iNANO) and Department of Chemistry, Aarhus University, Gustav Wieds Vej 14, DK-8000 Aarhus C, Denmark.*
[+]*Present address: Interdisciplinary Nanoscience Center (iNANO) and Department of Chemistry, Aarhus University, Gustav Wieds Vej 14, DK-8000 Aarhus C, Denmark*

Sustainable management and recycling of phosphorus (P) requires accurate knowledge of the actual P contents in all stages of the nutrient cycles. In agriculture, this particularly involves the contents of P in the animal slurry, in the livestock feed, and in the arable soil. Unfortunately for farmers' economy and the environment, traditional laboratory methods are expensive, time-consuming, demanding on hazardous chemicals, and subject to high uncertainties due to unrepresentative samplings since only few samples can be analyzed in practice. On the other hand, optical methods like near-infrared spectroscopy (NIRS) are insensitive to P, and generally challenged by small penetration depths and inaccurate results for broad applications due to the intrinsic dependence on database calibrations.

Here we present mobile Nuclear Magnetic Resonance (NMR) sensor technology for quantification of P in animal slurry, feed, and soil. This enables simple, accurate, low-cost determination of total P contents. Using the newly developed Tveskaeg NMR sensor, on-site measurements can be performed in either *i*) a flow setup with animal slurry or other flowable samples pumped through the bore of the instrument, or *ii*) a sample-tube setup with samples prepared in stick tubes, which are inserted for measurements manually or using an automatic sample changer. Since NMR is based on "communication" with specific atoms through magnetic fields, the NMR sensor is extremely robust (no sensitive parts in contact with sample, no optical window to keep clean) and offers direct detection of P and other elements. For animal slurry, the accuracy for NMR quantification of P and nitrogen (N) has been shown to be similar to the accuracy obtained by traditional laboratory methods, and we expect this to be true also for quantification of P in livestock feed and agricultural soil. Furthermore, the NMR sensor technology offers quantification of other elements than P, and for other areas than agriculture. This includes for example N in animal slurry, aluminum and sodium in soil, protein in feed (upon digestion), protein and fat in milk (upon adding contrast solution), salt in food products and ingredients, as well as P and N at waste-water treatment plants. In agriculture, NMR sensor technology may facilitate the achievement of sustainable management and recycling of P.

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RECOVERY AND REUSE OF RESOURCES IN WASTEWATER STREAMS – BEST AVAILABLE KNOWLEDGE AND EXPERIENCE FROM PRACTICE

Christian Baresel*, Elin Flodin**, Elin Kusoffsky**, Linda Önnby*, Staffan Filipsson*, Linus Dagerskog***, Charlotte Bourghardt**, Ann Johansen**, Åsa Romson*, Maria Hübinette**, Elisabeth Kvarnström****, Emelie Persson*, Linus Karlsson*

** IVL Svenska Miljöinstitutet, ** RISE Research Institutes of Sweden, *** Stockholm Environment Institute, **** Ecoloop*

A recent project initiated by Swedish authorities provides a synthesis of available knowledge and experiences in Sweden regarding the recycling, recovery and reuse of resources from various wastewater fractions. It also provides a roadmap towards a sustainable and resilient society based on circular solutions in the wastewater sector.

Relevant parts of circular solutions were described and discussed in sub-syntheses with focus on availability of various resources in wastewater and societal needs, circular systems and techniques, policy and legislation, acceptance, risks and evaluation tools. Further, a scenario description of different future wastewater handling approaches and how they perform as a part of a circular society are presented and discussed. Literature data and knowledge from reference projects was gathered and summarized in collaboration with interested stakeholders. All project material was open for review and comments and was discussed at stakeholder meetings including relevant Swedish authorities. The extensive feedback has been used and implemented in the sub-syntheses and the final summary report.

As one conclusion, the project showed that there are already a lot of techniques and systems that could be utilised in this transition towards a more circular wastewater handling. At the same time, there is also a large potential for innovative solutions. There exist also good tools, such as LCA and other modelling that should be used when designing and evaluating circular solutions based on local conditions. The transition to more holistic and system-wide evaluation using existing tools is, however, needed. One example is that the social-technical perspectives of the wastewater systems is often underestimated.

There are a lot of hinders that makes the transition to circular solutions slow and tortuous. Among these, legislation and policy are one of the most important areas to improve. Unclear or outdated regulations is inhibiting investments and decreasing acceptance of products. In Sweden, the water fee for example does not include any costs for withdrawal or outlet of water – meaning that linear solutions have a head start against circular solutions that almost certainly will be somewhat more expensive, at least in an early phase of development and implementation.

The study suggests that the most compatible scenario for resource reuse and recovery from wastewater is based on source separation. But as these systems are far from being realistic in a large scale in all society within any near future, a combination of solutions is proposed. Transforming existing wastewater treatment plants to resource facilities and to aim for more source separated systems in new areas and areas undergoing maintenance. In this way, an increased resource utilisation from wastewater can be initiated immediately. As a result, the recovery and reuse of water, nutrients, energy and other resources can efficiently be implemented and dynamically adapted to technology progress and societal needs. This will indirectly also lead to lower drinking water production needs and reduced discharge of harmful substances to the environment.
Nutrient recovery will benefit largely from source separating systems, but will also be a sufficient part of the transition from wastewater treatment plant to resource facility.

REFERENCE VALUES FOR PHOSPHORUS EXCRETION IN LIVESTOCK FARMING: A SWISS PERSPECTIVE FOR SHEEP AND GOATS

Giovanni Lazzari and Patrick Schlegel

Ruminant Nutrition and Emissions Research Group, Agroscope, Tioleyre 4, 1725 Posieux, Switzerland

Complying with Swiss farm nutrient balance regulations and fertilization planning rely on accurate reference values for phosphorus (P) excretion of livestock. This study presents the method for deriving such values considering different production scenarios, using sheep and goats as case study. The P excretion was determined through a balance approach, calculating for a defined period, the difference between dietary P intake and P retention in growth, fetal development, milk production, and wool production (only sheep). Scenarios were defined for each animal category identified as dairy ewes (n=48), suckler ewes (n=12), dairy goats (n=48), fattening lambs (n=36), and goat kids (n=1). Those according to birth season (n=3), indoor basal diet type within (grass/maize silage vs. hay), body weight (BW, n=3, 60-90 kg for ewes, 50-75 kg for goats), milk yield (MY, n=4, 350-650 kg/year for ewes, 350-950 kg/year for goats), and slaughter age (SA, n=3, 100-180 days for lambs). For each category, a reference was defined according to performance (MY, BW, SA) including a weighted average of birth season and indoor diet. Feed and milk intake were estimated using INRA (2018) and Agroscope (2021) equations, with diets optimized to cover net energy and absorbable protein requirement. Mineral phosphates contributed to 13.7 %, 12.9 %, 10.5 % and 26.9 % of total P intake for dairy ewes, suckler ewes, dairy goats, and fattening lambs, respectively. Dairy ewes, suckler ewes and dairy goats allocated respectively 92.3 %, 81.9 % and 88.4 % of retained P to MY; 3.11 %, 7.34 %, 7.02 % to first-lactation BW gain; 4.45 %, 10.5 %, 4.62 % to fetal development; 0.10 %, 0.24 % to wool (only ewes). Reference values for P excretion by dairy ewes (500 kg MY/year, 75 kg BW), suckler ewes (75 kg BW) and dairy goats (550 kg MY/year, 60 kg BW) was 2.90 kg/year (78.2 % of intake), 1.67 kg/year (83.6 % of intake), and 1.57 kg/year (73.8 % of intake), respectively. Fattening lambs (140 days SA, 45 kg BW) excreted 0.28 kg P (60.7 % of intake), while pre-weaned goat kids (56 days SA) excreted 0.04 kg P (31.4 % of intake). Based on the modelled scenarios, correction factors to the reference values were

established to account for variations in farm characteristics. For dairy ewes, suckler ewes, and dairy goats P excretion varied respectively by 7.76 %, 7.89 %, 8.79 % per 10-kg BW difference and by 2.36% and 0.81% per 25-kg/year MY difference (dairy ewes and goats). For fattening lambs, P excretion varied by 17 % per 10-day SA difference. Overall, birth season and basal diet type affected the reference P excretion between -18.3 % to 13.5 %. These correction factors allow farmers to adjust the reference values to better reflect their specific production systems. The models demonstrate the impact magnitude of animal performances on P excretion in sheep and goats. The presented methodology and results provide a framework for realistic nutrient balance assessments and effective fertilization strategies, ultimately promoting optimal farm nutrient management and environmental stewardship.

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MAKING PHOSPHORUS FERTILIZER FROM DAIRY WASTEWATER WITH Fe DESALINIZATION TREATMENT RESIDUALS

M. Iggy Litaor[1], H. Ganem[1,2], M. Heeb[1,2]

[1]*MIGAL – Galilee Research Institute, Hydro-Geochemistry Laboratory, Israel*

[2] *Tel Hai College, Water Sciences Department, Israel*

Phosphorus (P) is a non-renewable nutrient that needs recycling, hence P recovery and reusing can improve the sustainability and nutrient management in agriculture. In this study, P was recovered by reacting iron-based desalinization treatment residuals (Fe-DTR) with organic matter-rich, high P concentration (60-100 mg L^{-1}) dairy wastewater. We optimized the chemical-physical process of loading P from the cowshed wastewater onto the Fe-DTR by testing in the lab the adsorbent dosage, particle size, pH, and temperature on P adsorption capacity and kinetics. The highest adsorption occurred at pH 3 and 25 ◦C (11,410 ± 11 mg P kg^{-1} Fe-DTR) after 3 h, significantly surpassing adsorption at pH 7 at 40 ◦C (10,834 ± 371 mg P kg^{-1} Fe-DTR). A probabilistic model suggested that combining low pH and high temperature could enhance P adsorption.

Lower pH increased adsorption by removing competing ligands, and higher temperature has led to endothermic behaviour, reducing solubility of calcium/iron phosphate phases. The pseudo-second-order model best described the adsorption rate with activation energy at pH 3 of 8,082 J mol^{-1} compared to pH 7 of 3,970 J mol^{-1}. A pilot instillation was constructed in the cowshed which consists of coaguflocculation module, automated mixing cell that control the pH and rate of reaction and sieving device that separates the Fe/O-DTR from the partially treated wastewaters. The resulting P-rich Fe/O-DTR was applied as fertilizer in screen house using romaine lettuce (*Lactuca sativa*) planted in perlite and in Typic Haploxerolls with limited P (< 10 mg kg^{-1}). The factorial design consisted of 2 substrates, 3 treatments, 8 repetitions with 5 pots per repetition to a total of 240 3 L pots. The treatments were 1) perlite with commercial fertilizer (N, P, K + Mg 5-3-8+6), 2) perlite with no fertilizers, 3) Fe/O-DTR (70 g per kg perlite) with N, P, K 8-0-6), 4) soil with commercial fertilizer (N, P, K + Mg 5-3-8+6), 5) soil with no fertilizer, 6) Fe/O-DTR (70 g per kg soil) with N, P, K 8-0-6). Lettuce dry biomass growing in perlite in both commercial and in the Fe/O-DTR treatments were quite similar (10.2 and 9.6 g pot^{-1}) whereas the lettuce in the control showed very limited

growth without nutrient addition (0.3 g pot^{-1}). Similar results were observed in the soil. Lettuce dry biomass growing in both commercial fertilizer and in the Fe/O-DTR treatments were quite similar (12.4 and 11.1 g pot^{-1}) whereas the lettuce in the control of the soil experiment showed less stress than the perlite because some natural P was available in the soil (7.6 g pot^{-1}). These results clearly showed that lettuce yield was similar across treatments, indicating that Fe/O-DTR can provide sufficient P to perform similarly to common fertilizers. Recovery and re-use of P using Fe-DTR may therefore improve the sustainability of nutrient cycling in agriculture.

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WASTE AS A REAL ALTERNATIVE TO MINERAL PHOSPHATE FERTILIZATION: A WHEAT POT-EXPERIMENT IN MEDITERRANEAN SOILS

Nieves Nuñez-Romero[1], Ana M. García-López[1], José M. Quintero[1], Isabel M. Becerra-Vela[1], Yasmina Jiménez[1], Ramiro Recena[1], Antonio Delgado[1]

nnunez1@us.es, adelgado@us.es

[1]*Department of Agronomy, University of Seville, Spain*

Phosphorus (P) is an essential nutrient for agriculture. Sustainable management of phosphorus in soils is key to achieving an environmentally sustainable agricultural system within a circular economy framework. To this end, fertilizers should be partially or completely replaced with residual biomass, such as post-harvest waste, livestock production waste, or food processing by-products. The objective of the work was to evaluate the effectiveness of **14 fertilizers** derived from waste/residues and to assess their use as alternatives to mineral P fertilizers. For this purpose, a wheat pot-experiment with two basic Mediterranean soils from olive groves was conducted in greenhouse facilities at the University of Seville.

The tested fertilizers included four sewage treatment by-products (**vivianite**, **struvite**, **sewage sludge**, and **compost**), **urban solid waste compost**, **vineyard** waste compost, two kinds of **olive pomace** (**'alperujo'**) —one traditional and one treated with microorganisms— **digestate**, three **vermicomposts** derived from horse manure, pruning residues, and the commercial 'Abono Max', as well as **fish meal** and the commercial organic fertilizer **'Moge'**. For comparison, controls with diammonium phosphate (DAP) at (25, 50, and 100 mg P kg^{-1}) were used alongside an unfertilized control. The results obtained in our experiment showed similar total biomass production between most of the fertilizers and mineral fertilization at 50 mg P kg^{-1} with values around de 16 g except 'alperujo' and Moge with a mean value of 8.1 g.

A similar trend was showed for grain yield with the highest values for vivianite and vermicompost. Besides, some fertilizers showed total P uptake by wheat similar to the P mineral fertilization at 50 mg kg-1, vermicompost of horse and struvite showed the highest value of P uptake in red soil by contrast vermicompost of vegetable, struvite, max and ‘alperujo’ showed the best behavior in white soil.

Fertilizers showed an agronomic replacement value (using as references for agronomic index total P uptake) between 70 and 120%. Micronutrients concentration in plants varied with fertilizers. Digestate showed in lower iron concentration (12.34 mg kg^{-1}).
According to the results obtained, most of the fertilizers assessed in this study offer viable alternatives to mineral P-fertilized soils, thus promoting waste recycling in a circular economy framework.

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POLYPHOSPHATE-ENRICHED BIOCHAR OPTIMIZES PHOSPHORUS AVAILABILITY IN ALKALINE SOIL AND USE EFFICIENCY BY TOMATO PLANTS

Rachida Naciri[1], Mohamed Chtouki[1], Loubna El Allam[2], Hasfa Hirt[3], Doha Belkachach[3], Abdallah Oukarroum[1]

1 Plant Stress Physiology Laboratory, college of Agriculture and Environmental Sciences, Mohammed VI Polytechnic University, Benguerir 43150, Morocco
2 Faculty of Sciences and Techniques, Sultan Moulay Sliman University, Beni-Mellal, Morocco
3 Faculty of Sciences, Mohammed V University, Rabat, Morocco

Phosphorus (P) fertilizer properties and nutrient management strategies considerably affect soil P availability and P uptake. Organo-mineral amendment was tested as an effective approach to optimize P use efficiency and consequently crop yield. In this regard, the present study aims to elucidate how enriched biochar (EB) with inorganic P fertilizers can improve biophysiological processes in tomato plants and nutrient use effeciency. In a greenhouse pot experiment, the impact of EB with two phosphorus (P) forms: polyphosphate (Poly-P) and orthophosphate (Ortho-P) through a sorption process on the soil proprieties, photosynthetic performances, plant growth, and nutrient uptake and acquisition was assessed. The results confirmed the positive effect of biochar plant growth and development. The application of polyphosphate enriched biochar improved significantly plant growth parameters (plant height, leaves number, surface area) and yield components and quality (flowers number, fruit weight and number, fruit total soluble sugar) as compared to the orthophosphate enriched biochar and the control (biochar non enriched) treatments. The adsorption properties of polyphosphate-loaded biochar were improved which resulted in a significant amelioration of nutrients availability in soil, its uptake and use efficiency by tomato plants. The obtained results showed that enhanced biochar with polyphosphate fertilizers could be a promising technique to optimize P use efficiency and promote plant growth and developpement.

DIGESTATE TREATMENT TO REDUCE EMISSIONS AND PRODUCE STRUVITE

Moscatelli Giuseppe*, Tagliavini Silvia, Piccinini Sergio

*Research Centre on Animal Production - CRPA, Reggio Emilia, Italy; * g.moscatelli@crpa.it.*

Introduction

An optimal management of agricultural digestates could contribute to a reduction in emissions. Not only, a digestate treatment also aimed at nutrient recovery could facilitate the relocation of surplus nitrogen and phosphorus from high livestock areas to areas instead characterized by chemical fertilizer demand.

Methodology

The objective of the Struvite project is to decrease the nitrogen (N) and phosphorus (P) content in agricultural digestates in order to reduce ammonia, methane and nitrous oxide emissions from both the storage and spreading phase compared to the raw dogestate. N and P recovered produce a renewable fertilizer (struvite - magnesium ammonium phosphate hexahydrate - $MgNH_4PO_4.6H_2O$).

To achieve this, a farm-scale prototype has been designed, implemented and installed after the biogas plant of a pig breading. Digestate is an optimal matrix because anaerobic digestion involves the mineralization of part of the organic nitrogen to ammonia nitrogen and organic phosphorus to inorganic orthophosphate.

The digestate treatment consists of a solid-liquid separation by screw press. The liquid fraction at pH 8.5 is then acidified (with 50% solution of H_2SO_4) up to pH of 7.5 in order increase the organic phosphorus form and after microfiltered at 40 micron to partially remove suspended solids and organic matter that hinders the struvite formation. At the end, in a crystallization and precipitation reactor, magnesium (a 15% solution of magnesium chloride $MgCl_2$) and a base (a 30% solution of NaOH to raise the pH to 9), are added to promote the struvite crystals development. Air insufflation to stripe CO_2 is also provided in the crystallization reactor to encourage the pH increasing.

Results

The supernatant was significantly depleted in nitrogen (-20%) and phosphorus (-73%) compared to the input digestate. The reduction of the orthophosphoric P-form, as % of the total phosphorus, in the precipitate compared to untreated digestate (8% vs 36%), concomitant with an increase in concentration of total phosphorus (2247 vs 725 mg/kg), indicated that orthophosphoric-P, in the form of struvite crystals, has been precipitated.

Methane and ammonia emissions from the storage phase of the treated surnatant fraction were 86% and 42%, respectively, lower than the emissions from the untreated digestate. Soil application of the treated digestate led to 19% reduction in the N emissions (counted as sum of N-ammonia and N-nitrous oxide) as compared to untreated digestate.

Conclusion

The prototype effectively recovers phosphorus and nitrogen from the digestate, providing technical feasibility. Precipitate containing struvite can be exploited by fertiliser producers as a “raw material” for the production of phosphate fertilisers to replace finite phosphate minerals. By reducing P, N and dry matter content in agricultural digestates, ammonia, methane and nitrous oxide emissions were reduced from the liquid digestate storage and soil application phase.

Future developments of the prototype are the inclusion of a filter press to better enhance the final product and the use of a magnesium and biochar composite to encourage the struvite crystallization instead of magnesium chloride.

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PHOSPHORUS RECOVERY FROM MUNICIPAL WASTEWATER: QUANTIFYING POTENTIAL ECONOMIC IMPACTS IN CANADA AND UNITED STATES COMMUNITIES

Edgar Martín-Hernández[a,b], Sidney Omelon[a], Céline Vaneeckhaute[b,c], Gerardo J. Ruiz-Mercado[d,e]

[a]*Department of Mining and Materials Engineering, McGill University, Montréal, QC H3A 0C5, Canada*

[b]*BioEngine - Research Team on Green Process Engineering and Biorefineries, Chemical Engineering Department, Université Laval, 1065 Ave. de la Médecine, Québec, QC, G1V 0A6, Canada*

[c]*CentrEau, Centre de recherche sur l'eau, Université Laval, 1065 Avenue de la Médecine, Québec, QC, G1V 0A6, Canada*

[d]*Center for Environmental Solutions and Emergency Response (CESER), US Environmental Protection Agency, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268, United States*

[e]*Chemical Engineering Graduate Program, Universidad del Atlántico, Puerto Colombia 080007, Colombia*

Implementing phosphorus recovery processes at wastewater resource recovery facilities (WRRFs) can contribute to developing a sustainable circular economy for this crucial, non-renewable nutrient for food production [1]. Additionally, the recovery and reuse of phosphorus would enhance the resiliency of food production systems, mitigating the risks derived from potential disruptions of the global phosphorus supply chains [2]. However, building phosphorus recovery processes at WRRFs creates economic impacts for the served communities. The magnitude of these economic impacts depends on the process scale and wastewater treatment system of each of WRRF, and the served population income level. Creating a sustainable circular phosphorus economy must consider equitable economic community burdens to avoid the emergence of underprivileged social groups.

This work quantifies the socio-economic impacts of phosphorus recovery at WRRFs considering the capacity and wastewater treatment system of WRRFs, and the regional demographic and economic characteristics across the continental United States and Canada. Phosphorus recovery from sewage sludge, biosolid ashes, and the aqueous phase of the digestate was considered [3]. The study examined several geospatial scales, from the micro-scale, comprising the analysis of individual WRRFs, a mesoscale comprised of the Canadian census divisions and U.S. counties, and the macro-scale, by considering the Canadian provinces and U.S. census divisions.

The economic impact of phosphorus recovery at the WRRFs in the population served by these facilities was estimated through the annual phosphorus recovery cost per capita and the household affordability index (HAI) of phosphorus recovery. The annual phosphorus recovery cost

per capita was estimated as the sum of the annual operating expenditures (OPEX) and the annualized capital expenses (CAPEX) over 20 years. The HAI was defined as the income percentage allocated to cover phosphorus recovery costs. Phosphorus recovery costs were also compared with the economic savings obtained from preventing the negative economic impacts produced by in-excess phosphorus releases, which were valued in 2022 at 102.0 USD per kilogram of phosphorus released [4].

The results obtained show that the capacity and wastewater treatment system of WRRFs play a major role in the cost of phosphorus recovery. The WRRF's wastewater treatment system limits the phosphorus recovery point and technology selection, while the WRRF capacity determines its economic performance. At the mesoscale, the difference in the wastewater treatment systems of WRRFs in urban and rural areas led the selection of the suitable phosphorus recovery processes for each WRRF. As a consequence, the results reveal significant differences between the macro-scale regions with the best and worst economic performances. Large capacity, advanced phosphorus recovery WRRFs in densely populated urban areas are more cost effective per capita than the small scale WRRFs with secondary treatment installed in sparsely populated regions. As a result, this work recommends inter-regional cooperative policies to distribute the economic impact and benefits of phosphorous recovery evenly by cost-sharing effective phosphorus recovery systems for different population centers with different economic resources.

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EXPLORING PLANT RESPONSES TO DIFFERENT PHOSPHORUS SOURCES IN ALKALINE-CALCAREOUS SOILS

Salma Qetrani [1*], Moussa Bouray[2], Abdallah Oukarroum[1*]

[1] *Plant Stress Physiology Laboratory, College of Agriculture and Environmental Sciences, Mohammed VI Polytechnic University, Benguerir 43150, Morocco*

[2]*Agricultural Innovation and Technology Transfer Center (AITTC), CAES, Mohammed VI Polytechnic University (UM6P), Benguerir 43150, Morocco*

**Corresponding author email: salma.QUETRANI@um6p.ma ; Abdallah.oukarroum@um6p.ma*

Phosphorus (P) is an essential macro-nutrient often limiting plant productivity in alkaline-calcareous soils due to prevalent sorption and precipitation reactions. Understanding the root-soil interface, specifically the rhizosphere, and its intricate mechanisms in plant P utilization is imperative. A greenhouse experiment investigated the impact of four P sources (Rock phosphate (**RP**), Orthophosphate (**OrthoP**), Polyphosphate (**PolyP**), and Triple superphosphate (**TSP**), compared to a control (**zero P application**), on various parameters using white lupin (*Lupinus albus*) as the indicator crop. Evaluations encompassed root morphological traits, plant growth, shoots and roots P uptake, and root exudates. The rhizosphere and bulk soils analysis included pH, bioavailable P, and enzyme activities (acid and alkaline phosphatases). Our results revealed significant differences among P sources in affecting shoot and root dry weights, with a substantial increase of 37% in root-to-shoot ratio observed in the RP treatment ($p<0.05$) compared to no P addition. Control and RP treatments exhibited similar trends in root morphological traits. At the same time, OrthoP and TSP led to reduced root parameters, except for an increase in the average root diameter by 14% and 21%, respectively. Acid phosphatase activity significantly surged in rhizosphere soil regardless of the P source applied, with the highest activity ($p<0.05$) observed under RP. However, alkaline phosphatase activity showed no significant variation except for RP. Furthermore, rhizosphere soil pH significantly declined, especially in RP-treated and control soils ($p<0.01$). Noteworthy positive correlations were observed between shoot P uptake and alkaline phosphatase in bulk and rhizosphere soils. In addition, Root P uptake positively correlated with plant growth parameters, rhizosphere soil pH, and alkaline phosphatase in the rhizosphere. Additionally, soil pH in both rhizosphere and bulk soils exhibited strong positive correlations with growth parameters. Polynomial

regression relationship of total organic acids from root exudates and shoot P uptake were negatively correlated (R^2=0.65). The study emphasizes the dependency of rhizosphere processes involved in plant P mobilization and acquisition on the type of P source used.

Keywords: Phosphorus mobilization, phosphorus use efficiency, P sources, rhizosphere processes, white lupin, alkaline soils.

EVALUATION OF PHOSPHORUS RECOVERY POTENTIALS IN SPAIN FOR THE PRODUCTION OF WHITE PHOSPHORUS WITH THE FLASHPHOS PROCESS

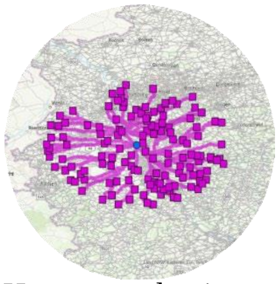
Lukas Pohl, Christian Schmidberger, Helene Umubyeyi, Lars Hufeld, Matthias Rapf

Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA), University of Stuttgart, Germany

Graphical Abstact

Urban wastewater treatment plants

Hotspot identification



Hotspot evaluation

White phosphorus (P_4) is a form of the element phosphorus (P) that is used in the production of flame retardants, agrochemicals, food and battery electrolytes [1]. Since the last P4-production ceased in 2012 the EU's demand is completely covered by imports. These supply dependencies prompted the EU Commission to list P_4 as a critical raw material [2, 3]. The focus on recycling in the revised Water Framework Directive and the implementation of government regulations requiring P-recovery, opened a window of opportunity to develop P-recycling products that reduce import dependencies and promote environmental benefits. Less than one sixth of the P-rich wastes generated could cover the EU's annual P_4-demand [4]. However, P-material flows are dispersed across the continent. An economical P_4-production in contrast requires the largest possible quantities of material in one facility.

To localize regions appropriate for a P_4-production, a material Flow analysis of P-rich waste streams was conducted in the EU27 + UK. Spatial potentials were calculated using GIS and thermodynamic modelling. For the evaluation, a matrix was created to rate logistical, economic and political circumstances. While the methodology was specifically tailored for the FlashPhos process, the underlying principles make it transferable to other P-recovery processes. Current subjects of the methodology are wastewater treatment plants >2000 population equivalents and rendering plants.

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SUSTAINABLE TECHNOLOGIES FOR NUTRIENT RECYCLING, RE-BLENDING, AND UPSCALING VIA MICROALGAE

Darren L. Oatley-Radcliffe

Faculty of Science and Engineering, Swansea University, UK.

Generation of industrial, agricultural, and domestic waste from human activities is on the increase. Waste generation in OECD countries has increased by 14% since 1990 and 35% since 1980. Recycling and reuse of waste materials is now considered key to develop and maintain sustainable products and processes, as well as making strides to the net zero carbon goals. For example, in Wales, municipal solid waste recycling rates have increased from ~8% in 2000 to around 66% in 2023 with Germany leading the EU field at 69.1% (2022) and the EU average at 48.6%.

One of the rising technologies in recent times to deal with organic waste (food, flowers, vegetables, fruit, kitchen waste, manures…etc) is anaerobic digestion (AD). In this process, organic materials are naturally broken down and generate biogas, consisting of methane and carbon dioxide, and digestate, a slurry rich in nitrogen and phosphorus. Current estimates suggest that the EU-27 (plus Norway, Switzerland, and the UK) will generate some 74 billion cubic meters of biomethane via this method by 2040. Digestate composition varies depending on the nature of the feed materials to the AD reactor. Typical values are nitrogen 2.3-4.2 kg/tonne, phosphorous 0.2-1.5 kg/tonne, and potassium 1.3-5.2 kg/tonne. As typically 90-95% of what is fed to the reactor exits as digestate, then this creates a lot of residual nutrients, including phosphorous. Typically, this digestate waste is used as a soil remediation agent or fertiliser. However, with the advent of nitrogen vulnerable zones, this method for disposal is becoming more difficult.

This work reports on several technology steps that have been successfully implemented at both pre-industrial and industrial scale to recover the nutrients from AD digestates. Raw digestate is treated with membrane ultrafiltration to produce a clarified liquor rich in P (also N and K) and a solid slurry for disposal. The liquor is then treated using membrane nanofiltration where the phosphorous is highly rejected (> 98%) and creates a P-rich fraction. Various diafiltration operations can also be conducted on the nutrient rich liquor to generate N-rich fractions, although somewhat diluted. The resultant liquors can easily be concentrated for transport by reverse osmosis if necessary. The recovered P, along with N, is then used as a feedstock to grow microalgae. Microalgae are photosynthetic organisms that consume P, N, and CO2 (as well as others) during photosynthesis to yield biomass. The biomass itself is rich in various products which can be fractionated and sold. These processes have been demonstrated at the Langage AD site (Plymouth, UK) and the Vale Europe Limited site (Clydach, UK), the latter operation has now been commercialised. Thus, using a circular economy approach, waste nutrients can be recycled and reused to generate carbon neutral/negative sustainable products.

ENHANCING PHOSPHORUS UPTAKE AND SOIL HEALTH: INNOVATIVE BIOCHAR FROM CATTLE MANURE AS A SUSTAINABLE FERTILIZER SOLUTION

Schönfeld, S.[a], Westenthanner, E.[b], Reiter, T.[b], Hartung, C.[b], Heuwinkel, H.[b]

a) Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT
b) Weihenstephan-Triesdorf University of Applied Sciences

After the 6th Assessment Report of the IPCC, the sector of Agriculture, Forestry, and Other Land Use was responsible for 13-21% of human-made greenhouse gases from 2010 to 2019.[1] Biochar is a way to reduce/compensate CO_2 emissions while simultaneously improving soil properties. Possible feedstocks for its production include all organic residuals, such as regionally abundant organic fertilizers. Thermo-catalytic reforming, a special type of pyrolysis, was developed by Fraunhofer UMSICHT and produces a certain quality of biochar.[2] It was now necessary to examine to what extent this biochar represents an interesting fertilizer. In a randomized pot experiment (n=4) with a silty loam (grassland soil, pH 5.0, Corg 2.8%, Nt 0.31%, CAL-P and K in supply levels A and B, respectively), the fertilizing effect on maize and rye grass growth was compared with products from other processing methods. Nutrients missing in the test group were added in a water-soluble form. The growth of the maize was regularly assessed. After 6 weeks at BBCH 32, the harvest of the maize plants took place. The first harvest of biomass of the rye grass experiment took place after 18 days. Five additional harvests were carried out after 26, 35, 43, 55 and 68 days. Dry matter content, the content of N, P, and K in the biomass, as well as the soil content of CAL-P, -K, and pH value were recorded. The significance of differences was tested using ANOVA in combination with a Tukey test ($\alpha = 0.05$).

The maize plants developed equally well with full fertilization and biochar, achieving the same mass formation and nutrient uptake, while unfertilized plants likely experienced more severe growth restriction due to P deficiency than K deficiency, despite very good N supply. In the first harvests of rye grass the biochar fertilised plants had the highest biomass production within the first four harvests. The last two harvest showed a decrease in the harvestable amount in all plants. There are no statistically significant differences in biomass production and the fertilizer replacement values for P, N and K are near 100%.

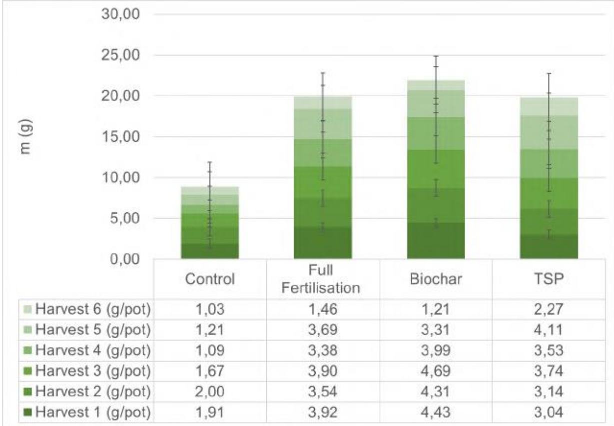

Figure 1(left) Rye grass before the third cut. (right) Harvestable amount of ryegrass (g/pot) during the six harvests done.

Table 1 Overview of some crop-relevant properties of the biochar produced from cattle manure in the trial. All data in mg per g dry matter.

Parameter	Value	Unit	**Parameter**	Value	Unit
Org. Matter	522	g/kg	**Total P**	0.15	g/kg
Org. C	393	g/kg	**Total K**	30	g/kg
Total N	10	g/kg	**Mg**	6.7	g/kg

Initial stages revealed that biochar (DE-BC) treatment significantly boosted biomass, indicating its potential for providing essential nutrients for rapid plant growth. The rye grass trial demonstrated that the phosphorus present within the biochar was plant available and resulted in similar P uptake then full fertilization. Based on the available nutrients, a fertilization profile was designed, in which mineral fertilizers are saved by using biochar, and at the same time, stable carbon is introduced into the soil. The investigation of phosphorus uptake showed that the test group with biochar exhibited improved uptake compared to full fertilization. Savings on mineral fertilizers did not affect the overall performance of the plants (see Figure 1).

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SYNERGIES FOR PHOSPHORUS RECOVERY AND THE DECARBONIZATION OF THE EUROPEAN STEEL INDUSTRY BY VALORIZATION OF RESIDUAL BIOMASS

Michael Renz

Instituto de Tecnología Química (ITQ), Universitat Politècnica de València – Consejo Superior de Investigaciones Científicas, Avda. de los Naranjos s/n, 46022 Valencia, Spain; email: mrenz@itq.upv.es.

The transformation of residual biomass such as the organic fraction of municipal solid waste (OFSMW) has been identified as an alternative phosphorus resource when processed by hydrothermal carbonization (HTC) with subsequent phosphorus extraction.[1] During the HTC process, the carbon content of the biomass is concentrated mainly by chemical dehydration reactions. Under process conditions organic phosphorus is converted into inorganic phosphates that remain in the solid carbonaceous product, the hydrochar, as ash content.[2] Afterwards, mineral acids, such as nitric acid, sulfuric acid or hydrochloric acid, can be used to dissolve and extract the phosphate salts. Under suitable conditions, the ash content is reduced which improves the properties of the hydrochar as renewable solid fuel.

This knowledge has been taken as basis for the design for the concept of the BioReSteel project (Research Fund for Coal & Steel (RFCS); EU).[3] This project has the aim to establish hydrochar as solid fuel for electric arc furnaces (EAF). Thereby, the ambition is to replace around 840 kt of fossil coal at today's production level from the EAF process, leading to a reduced fossil CO_2 emission of about 2.5 Mt per year. Taking into account that up to 3 wt% of the hydrochar produced from the OFMSW consisted of P_2O_5, this valorization pathway would recover more than 40 kt of calcium phosphate that is landfilled in diluted form at present.

In the present contribution the single steps of the phosphorus recovery are described in detail up to the production of a solid phosphate fertilizer. Influences of the biomass feedstock will be discussed as well as expansion of the overall process to other sectors of the metallurgical industry. In summary, it will be shown that the concept has a high potential for the recovery of phosphorus from residual, low-value and wet biomass driven by economical interests in important European industry sectors.

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CYTOGENETIC EFFECT OF NANO-PHOSPHORUS POLYMER PREPARED VIA GAMMA IRRADIATION ON *VICIA FABA* PLANT.

M. Salah[1], Soad Yehia[1] and Rania T. Ali[2]

1 Radiation research of polymer chemistry department, industrial irradiation division; National center for radiation research and technology, Egyptian Atomic Energy Authority P.O. Box 9621, Nasr City, Cairo, 11787, Egypt

2 Cytogenetics & Cytology department, Genetic engineering & Biotechnology division, National Research Centre, Dokii, Egypt.

Background: The trendy nano-fertilizers came to the front in modernized agriculture seeking for minimizing the soil suffocation with other chemical fertilizers in the bulk size. Nano-fertilizers are mostly absorbed by the plant due to their tiny size and complete dissolved in water, also it magnifies the benefit to the plant due to its high surface area. phosphorous (P) element is one of the essential nutrients required for all metabolic processes in planted crops. In this work, three concentrations of new nano-phosphorus prepared via Gamma irradiation from Cobalt 60 source at irradiation dose 5 KGy. This nano phosphorus coated with PVP as a shell form a new composite supplies plants with P element needs to be revised for its safety usage in agriculture. **Methodology:** phosphorous and the mixed Zinc-phosphorous elements were prepared in nano-composite forms coated with PVP as a shell and then characterized by HR-TEM, UV and FT-IR to emphasize their new sizes and shapes, then, they were examined for their cytotoxicity in three concentrations (0.5, 1 and 2%) on *Vicia faba* plants; after three hours of direct roots treatment. cytotoxicity test concerned the mitotic index, phase index, abnormal mitosis and the type of the aberrations at each phase. **Results**: The tested NPs exerted mito-accelerating effect on root meristematic cells. However, concentration-dependent genotoxicity was also an evident.as the treatment with P NPs induced a concentration independent (fluctuated) abnormal mitosis. The observed chromosomal abnormalities were mainly of chromosomal kinetic abnormality which refers to the turbogenic on the spindle apparatus to organize in a normal way. All in all, the treated plants can complete its division cycle to reach the final mitotic stages without cell death which indicates that the examined products in determined concentrations may have genotoxic effect but not cytotoxic effect. **Conclusion:** The examined nano-composites may recommend to be used in the lowest examined concentrations in order to minimize its harm effect on the plant cell and keep their benefits to the environment. It also recommended to count the Zn/P mix NPs over P separately as it induces an intermediating cytogenetic effect on mitosis apparatus of *Vicia faba* plant.

A NOVEL APPROACH FOR EFFICIENT EXTRACTION OF P FROM ASHES GENERATED FROM BIOWATE INCINERATION

Guozhu Ye[1*], Elsayed Mousa[1], Bruno Valentim[2], Georgeta Predeanu[3], Hayati Olgun[4], Barbara Białecka[5], Elza Bontempi[6], Luminița-Georgeta Popescu[7]

[1] *Swerim AB, Aronstorpsvägen 1, 974 37, Luleå, Sweden*

[2] *Department of Geosciences, Environment and Spatial Plannings, Faculty of Sciences, Earth Science Institute-Porto Pole, University of Porto, Rua do Campo Alegre s/n, 4169-007 Porto, Portugal*

[3] *National University of Science and Technology POLITEHNICA Bucharest, Research Center for Environmental Protection and Ecofriendly Technologies, 1-7 Gheorghe Polizu Str., 011061 Bucharest, Romania*

[4] *Ege University, Solar Energy Institute, 35100 Bornova, Izmir, Turkey*

[5] *Department of Environmental Monitoring, Central Mining Institute – National Research Institute, Katowice, Plac Gwarków 1, 40-166 Katowice, Poland*

[6] *INSTM and Chemistry for Technologies Laboratory, University of Brescia, Via Branze 38, Brescia, 25123, Italy*

[7] *Constantin Brâncuși University of Targu Jiu, Engineering Faculty, 30 Calea Eroilor, Târgu Jiu, Gorj County, Romania*

The EU phosphorus need is dependent on imports from Kazakhstan (71%), Vietnam (18%), and China (9%). Due to its economic importance and supply risk, the EU included phosphorus (P) and phosphate rocks (PR) in the “2020 List of critical raw materials (CRM) for the EU”. One of the most sustainable options to secure future P supply within the EU is P recovery from the food production and consumption chain. A substantial P-source is the biowastes from the poultry litter. For example, with more than 375 million laying hens in the EU, which excrete between 0.10 and 0.45 kg P_2O_5 per chicken/year, one may estimate that there are about 16,350-73,575 tons of P available only in the hens' manure, which corresponds to about 10-15% of all P needed in the EU and UK. Incineration of this biowaste will enrich the P content by 6-7 times to P-rich ashes and at the same time produce green energy. This approach has been extensively investigated in an ongoing ERA-MIN3 project, PHIGO. The project aims to optimize the incineration step and to develop a sustainable technology for efficient P-extraction from the P-rich ashes, thereby enabling the closing of the P-loop in the EU P-strategy.

The PHIGO P-extraction concept has been developed and proven on a laboratory scale. Several preliminary pyrometallurgical tests have been carried out, and the results show that a P-recovery rate of over 85% P can be achieved. The recovered P-products have been characterized and their potential applications tested, e.g., fertilizer. The remaining inert material after the P-thermal extraction mainly consists of Ca_2SiO_4, which can be a degreasing additive in shaping mixtures and replacing raw clay.

This paper will highlight the major outcomes of the project with a focus on the P-extraction approaches. The developed P-extraction concept of the PHIGO project is based on experiences from the metal extraction processes. The obtained P can be recovered as element P (as white phosphorus) or fertilizer together with recovered K. The thermochemistry behind the PHIGO P-extraction concept, the experiment setup, and the test procedure will be described and discussed. The utilization of the obtained P-products will also be discussed.

Acknowledge

The authors acknowledge the ERA-MIN3 Joint Call (2021) for funding the PHIGO project "Thermal Processing of P-rich ashes aiming for HIGH-GRADE PHOSPHORUS Products" through Vinnova -Sweden (ref. 2022-00072), TUBITAK-Turkey (ref. 122N038), NCBR-Poland, UEFISCDI-Romania (ref. 310/01.03.2022 and 19848/02.08.2022). B.V. thanks FCT-Portugal (UIDB/04683/2020; UIDP/04683/2020), and E.B. the University of Brescia (Italy).

PHOSPHORUS RECOVERY FROM CATEGORY 1 MEAT AND BONE MEAL ASH ON PILOT SCALE

Vishal Zende[1], Isabelle Willems[2], Teresa Curtin[1], James J. Leahy[1]

[1]*Department of Chemical Sciences and Bernal Institute, University of Limerick, Limerick V94 T9PX, Ireland*

[2]*Research and Development Department, Prayon SA, Engis, 4000 Belgium*

This study explores the recovery of phosphorus from Category 1 meat and bone meal (MBM) ash, generated through a bubbling fluidized bed combustion process, via the dihydrate method to produce phosphoric acid. The pilot scale production of phosphoric acid from this MBM ash demonstrates an efficient recycling method that aligns with stringent EU regulations. According to the Waste Framework Directive, certain specified waste ceases to be waste when it has undergone a recovery operation, including recycling, and complies with specific criteria. While Category 1 MBM ash is typically disposed of by incineration or co-incineration, it remains classified as waste. However, this ash can be treated to produce phosphoric acid, which can then be converted into various phosphate salts. The conversion to phosphoric acid can serve as the new end-of-waste status for the ash. This innovative approach not only provides a sustainable solution for managing Category 1 MBM ash but also contributes to the circular economy by transforming waste into valuable products suitable for industrial applications.

The pilot test using Cat1 MBM ash lasted for 4 days and phosphoric acid with 28-29% P_2O_5 was produced. The impurity ratio is low (0.045) and heavy metal concentration is further reduced with Cd conc. < 0.2 ppm. The attack yields obtained are high with an average of 98.7%. The standard yields obtained on average on pilot scale are about 96-97%, hence the results are good. The process yields are of the same order of magnitude, a little over 98%. The washings are therefore effective. The losses are mainly due to co crystallized P_2O_5 losses (0.3%) while un-attacked losses are approximately 0.02%. The acid is further concentrated to a P_2O_5 content of 54% without any decantation problems in a vacuum evaporator.

The successful recovery and conversion of Cat1 MBM ash into high-purity phosphoric acid illustrates a viable pathway for including this material in CMC 13 of the EU Fertilizing Product Regulation. The demonstrated ability to meet safety and quality standards supports the potential regulatory acceptance of Cat1 MBM ash derivatives for industrial applications.

FOOD, FEED AND FERTILIZER IN TIMES OF CONFLICT AND CRISIS

Serina Ahlgren*, Elin Kusoffsky* (submitting), Priscila de Morais Lima*, Johanna Olsson*, Solveig Johannesdottir*, Rasmus Einarsson**, Verena Germann**, Jennifer McConville**, Erika Öhlund***

RISE Research Insitutes of Sweden, ** SLU Swedish University of Agricultural Science, * Swedish Defence Research Agency*

Production of food and people's access to food are global problems including food supply and security for the poorest, a national security issue, and at the same time also a matter of environmental sustainability and resources use (Irani & Sharif, 2018). As Swedish food system is largely dependent on imports there are an urge to look into ways of making the food supply system more resilient (Kummu et al., 2020). The project "Production and supply of domestic and sustainable fertilizers for food security in uncertain times", explores ways to a more sustainable and resilient food system, with focus on nutrient supply. Fertilizers and feed are some of the most important inputs to agriculture and our food system, and in Sweden a large majority of the fertilizers are imported. Hence, the project aims to address critical environmental challenges in Sweden related to nutrient management in crisis situations.

To achieve this goal, the activities of the project include: examining fertilizer requirements during both short-term and long-term crises; identifying existing nutrient flows and technologies, and exploring domestic fertilizer production possibilities; investigating realistic supply options and assessing barriers and constraints; conducting a Sustainability Assessment, focusing on environmental impacts such as eutrophication, acidification, air pollution, climate change, and biodiversity loss.

As the project is still ongoing and will be finished at the end of 2025, the results are preliminary. In a first report published in Swedish, scenarios for different types of crisis situation have been explored in a stakeholder workshop. The scenarios explored how the nutrient flows would look in three different scenarios where the imported inflow of nutrients is in different ways limited due to crises situations. The report draws on the outcomes of the workshop with representatives from agriculture, authorities, technology providers and scientists.

Also as part of the project, current nutrient flows for Swedish conditions have been mapped. The results are presented as flow charts for nitrogen, phosphorus and potassium, giving a starting point on total use and reused amount in the current system, including human food and animal feed. The results will help pinpoint technology bottlenecks (such as energy efficiency and transport logistics) and potential conflicting aspects within the scenarios. This information will guide decision-makers in assessing the resilience and sustainability of the scenarios.

The project also explores possible long-term future scenarios where Sweden is less dependent of imported fertilizers. Achieving self-sufficiency will be beneficial and essential for sustainable food production in the future.

In conclusion, we want to enhance comprehension of the connections, synergies, and trade-offs between contingency and sustainability aspects for nutrient management as an essential part of food production.

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BOOSTING NUTRIENT RECOVERY FROM ANMBR EFFLUENTS BY MEANS OF ELECTRODIALYSIS TECHNOLOGY

P. Ruiz-Barriga[1], L. Ruiz-Cosgaya[1], J. Serralta[1], R. Barat[1], J. Carrillo-Abad[2] and A. Bouzas[*2]

[1] *CALAGUA – Unitat Mixta UV-UPV, Institut Universitari d'Investigació d'Enginyeria de l'Aigua i Medi Ambient – IIAMA, Universitat Politècnica de Valencia, Camí de Vera s/n, 46022 Valencia, Spain*

[2] *CALAGUA – Unitat Mixta UV-UPV, Departament d'Enginyeria Química, Universitat de València, Avinguda de la Universitat s/n, 46100 Burjassot, Valencia, Spain.*

[*]*Corresponding author: alberto.bouzas@uv.es*

Currently, there is an increasing interest in reclaiming nitrogen and phosphorus from industrial and urban wastewater for fertilizer production. Effluents from Anaerobic Membrane BioReactors (AnMBR) processes contain significant ammonia and phosphate concentrations that may prevent their discharge if direct reuse in agriculture is not allowed. Thus, a post-treatment step may be required to remove and recover nutrients. In this work, an electrodialysis (ED) process was applied to the effluent of an AnMBR (located at the Conca del Carraixet WWTP, València, Spain) to concentrate ammonium and phosphate for their subsequent recovery. However, in areas with high water hardness (as in València region), the precipitation of calcium compounds during ED hinders the production of a discharge-quality diluted stream and a high-nutrient concentrated stream. To address this issue two different ED alternatives i) a two-stage conventional ED process combined with a cation exchange resin pretreatment and ii) a selectrodialysis process (SED) were studied.

Two ED stacks provided by PCCell GmBH (Germany) – a conventional one and a SED stack – were used. The conventional ED and SED stacks allow working with a maximum of 10 cell pairs and 10 triplets of cell, respectively. Cation (PC-SK), anion (Acid_100_OT) and monovalent (MVK) exchange membranes with an effective area of 64 cm^2 were used. A 0.01M H_2SO_4 solution was used as electrolyte solution. A current of 0.24 A and a voltage of 7.5 V were used when operating in galvanostatic and in potentiostatic mode, respectively.

The first ED alternative involved the AnMBR effluent pre-treating with ion exchange resins to reduce inlet calcium concentration (ca. 85%), followed by a two-stage ED process. This approach achieved concentrations of 1233 mg NH_4-N/L and 135 mg PO_4-P/L in the concentrated stream. Diluted stream concentrations were 1.58 mgNH_4-N/L and 0.91 mgPO_4-P/L. The second ED alternative involved SED to separate divalent cations, preventing precipitation with sulphate ions. However, MVK membrane efficiency was lower than expected (27.6% of calcium), resulting in lower concentrations in the concentrated stream (587 mg NH_4-N/L and 80 mg PO_4-P/L).
Diluted stream values were 0.63 mgNH_4-N/L and 1.29 mgPO_4-P/L. Even so, SED concentrations are still suitable for recovery. Removal efficiencies were close to 90% in the diluted stream and energy consumption ranged from 0.6 to 1 kWh per cubic meter of AnMBR effluent treated in both experiments.

All in all, a multistage ED operation combined with a pretreatment to reduce calcium at the inlet of the ED process yields significantly promising results in diluted and concentrated streams simultaneously. SED showed encouraging results, however, further research is necessary to improve the MVK efficiency.

MOVING FROM WASTEWATER TREATMENT PLANTS TO BIOFACTORIES: SUCCESSES IN NUTRIENTS RECOVERY FROM URBAN WASTEWATER.

E. Marín[1], A. Egea-Corbacho[1], F.J. Delgado[1], M. Tena[1], P. Zamora1, N. Morales[1], J.R. Vázquez[1], E. Serrano[2], F. Rogalla[1] and V. Monsalvo[1].

[1]*Aqualia, Innovation and Technology Department, Madrid, Spain. eugenio.marin@fcc.es*
[2]*Aqualia, Innovation and Technology Department, Paris, France.*

The requirements set by laws and the growing emphasis on environmental stewardship are reshaping traditional wastewater treatment plants (WWTP) into greener and more efficient biorefineries, producing valuable bioproducts that are becoming more prevalent in our society. According to the legislation, it should be noted that the recent revision of Directive 91/271/EEC sets a new objective of energy neutrality and a greater reduction of nutrients discharged into the environment. To this end, more rigorous limit values for nitrogen and phosphorus are considered. Additionally, all WWTPs with more than 150,000 p.e. will be required to have nutrient removal. This change in legislation will result in higher operating costs at WWTPs by increasing the need for energy consumption to remove nitrogen and raising the dosage of chemical reagents to help precipitate the phosphorus present in the wastewater to ensure meeting the new required discharge parameters. The objective of this study is to provide high quality treated water and biofertilizers from domestic wastewater by means of two different scenarios. The first one shows the world's largest 100% solar anaerobic photobiofactory, based on the use of purple phototrophic bacteria (PPB) (CBE JU project DEEP PURPLE). The development of this technology has gone from TRL 5 during its pilot-scale piloting at the Estiviel WWTP in Toledo (Spain) to TRL 7 with the construction of the demonstrative plant at the Linares WWTP (Spain). Using the photobioreactor system with a treatment capacity of 350 m3/d (1500 p.e.), the effluent parameters (including TP) are systematically in conformity with values below those established by European legislation (TP < 2 mg/L, TSS < 15 mg/L, BOD5 < 23 mg/L and TCOD < 40 mg/L).
Furthermore, the flexibility of the process allows the treated water to be adapted for use in agriculture, minimizing the assimilation of nitrogen and phosphorus and turning it into an important resource as nutrient-rich irrigation water. In addition, phototrophic biomass has already tested to be a low-cost raw material in formulating biofertilizers with a CNP ratio of 100:15:13 and an NPK ratio of 100:98:25. While the second case is

based on obtaining a valuable product such as struvite (Aquavite®) recovered from the nutrient-rich waste streams of WWTPs (BBI B-FERST project). The recovery efficiency of phosphorus (III) oxide (P2O5) in Aquavite® production system was higher than 80% and the removal efficiency of ammonium (NH4+) was close to 40%. The treated flow rate was up to 100 m3/d, which produced an estimated 15 tons per year of enriched struvite in P2O5 (28%) that can be used as a raw material for the formulation for fertilizers. Both projects BBI DEEP PURPLE and BBI B-FERST provide true-to-scale solutions for the recovery of nutrients from urban wastewater, promoting the concept of circular economy.

Keywords

Biorefinery; Phosphorus recovery, Struvite; PPB; circular economy.

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EFFECT OF CLIMATIC EXTREMES AND AGRICULTURAL PRACTICES ON ANNUAL P EXPORT IN AN AGRICULTURAL WATERSHED

Monia Magri[1], Elia Gambarotto[1], Edoardo Severini[2], Bianca Maria Lecchini[1], Pietro Iavazzo[3], Silvia Motta[3], Daniele Nizzoli[1], Marco Bartoli[1]

[1]*Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parco Area delle Scienze 33/A, 43124 Parma, Italy;*

[2]*Department of Environmental and Prevention Sciences, University of Ferrara, Via Luigi Borsari 46, 44121 Ferrara, Italy;*

[3]*ERSAF, Via Pola 12, 20124 Milano, Italy;*

This study, conducted by Parma University and Regional Agency for Agriculture and Forestry Services of Lombardy (Northern Italy), investigates factors influencing phosphorus (P) transport in the Chiese River basin, situated in the Po River watershed. Here, large P surplus in soil and flood irrigation contribute significantly to P mobility, either in dissolved or particulate form, and eutrophication of inland and coastal waters. Climatic anomalies, including extreme rainfall, exacerbate further erosion and P transport mechanisms.

A phosphorus budget was constructed to assess P surplus in agricultural soils, considering inputs from fertilizers and manure, and outputs from crop harvest. This approach identified P-enriched soils prone to contaminate water and quantified potential P export to aquatic ecosystems. Monthly measurements of total phosphorus (TP), particulate phosphorus (PP), and soluble reactive phosphorus (SRP) concentrations and loads were conducted along the river course, with intensified sampling during extreme rainfall events to identify periods of high P mobility. The impact of flood irrigation on P export from dominant crops (maize and permanent meadows) was quantified across experimental plots, combining outlet channel concentrations and irrigation volumes scaled to the basin.

Manure spreading emerged as the primary P input term (>90%) to soils, with crop uptake removing approximately 25% of inputs, resulting in an annual surplus of 2600 tons P y^{-1} (62 kg P ha^{-1} UAA y^{-1}). Riverine TP concentrations peaked downstream, reaching 45 µg P L^{-1} for PP and 40 µg P L^{-1} for SRP in the lowland plain. During extreme rainfall events, SRP concentrations remained stable while PP concentrations significantly increase (up to 650 µg P L^{-1}). Annually, 36 tons P were exported at the river outlet, with 50% delivered during the 10 rainiest days.

Flood irrigation significantly increased P export, mainly as PP from maize culture and SRP in permanent meadows, with TP concentration ranging between 500 and 750 µg P L^{-1} in outlet channels, consistent across the tested crops. Despite uncertainties, flood irrigation potentially accounted up to 40% of annual P export at the river outlet.

The Chiese River basin has one of Europe's highest phosphorus (P) surpluses. Although only 1% of its potential P load is exported, extreme precipitation can significantly increase this proportion. Agricultural practices, especially flood irrigation, contribute to unsustainable P export.

This research underscores the need for sustainable practices to reduce nutrient pollution, particularly from manure and inefficient irrigation. Future studies should refine P management strategies tailored to local agriculture and climate to achieve sustainable water quality in regions like the Po River basin.

PHOSPHATE UPTAKE FROM WATER BY SORPTION PROCESS USING Zn-Al LAYERED DOUBLE HYDROXIDES

Inês D. Borges[a, b, c], Frederico Maria[b], Carlos M. Silva[c], Margarida J. Quina[a] Authors' names in size 12, centred

[a]University of Coimbra, CERES, Department of Chemical Engineering, 3030-790 Coimbra, Portugal; [b]Smallmatek- Small Materials and Technologies, Lda, 3810-075 Aveiro, Portugal; [c]CICECO-Aveiro Institute of Materials, Department of Chemistry, University of Aveiro, 3810-193 Aveiro, Portugal;

Population growth and unsustainable consumption patterns are placing high pressure on some of the finite natural resources of Earth. Phosphorus (P) is predicted to become depleted in mining sites within the next 50 to 100 years due to high rates of exploitation. However, excess phosphorus in soil and water can lead to eutrophication, which is characterized by excessive plant and algal growth, with negative impacts to the ecosystems. Thus, it is crucial to redirect P flows for reuse and recycling, with a particular emphasis on the production and application of fertilizers, while maintaining the mineral content in the food chain. Layered double hydroxides (LDH) are ionic lamellar clays with positively charged layers balanced by interlayer-charged anions, which have gained attention because of their high removal capacities of specific compounds in water through adsorption and/or anion exchange. This study aimed to evaluate the recovery of P from aqueous matrices using Zn-Al LDH with two different compositions. The effects of key variables of the sorption process, such as sorbent dosage, initial P concentration, contact time, initial pH, and presence of competitive anions (NO_3^-,Cl^-, CO_3^{2-}, SO_4^{2-}) were evaluated in batch tests. Zn-Al LDH material were prepared via the coprecipitation method and characterized by X-ray diffraction (XRD) and Fourier Transform Infrared spectroscopy (FTIR). The specific surface area of the started material was determined using BET method. The XRD analysis conducted after the sorption tests revealed that phosphorus was intercalated within the LDH structure. According to the results, the Langmuir isotherm adequately represented the sorption equilibrium for the evaluated materials, demonstrating a maximum sorption capacity of 89.3 and 92.3 mg/g. The sorption kinetics tests conducted over 24 hours, followed a pseudo-second-order reaction. The presence of competing anions, particularly carbonate, decrease the performance of both materials, due to the high stability that it lends to the LDH structure. In general, both materials exhibit promising

potential for phosphorus removal from wastewater. However, further research is necessary to validate these observations, namely testing these materials in real urban wastewaters. In addition, these materials will be further tested in the scope of releasing P for fertilization purposes.

IMPROVING PHOSPHORUS USE EFFICIENCY IN MEDITERRANEAN AGRICULTURE THROUGH INNOVATIVE AGRONOMIC PRACTICES AND BIOCHEMICAL PROCESSES

Abdallah Oukarroum[1] and Mohamed Chtouki[1]

[1]*Plant Stress Physiology Laboratory, College of Agriculture and Environmental Science, Mohammed VI Polytechnic University, Benguerir 43150, Morocco*

*Corresponding author email: Abdallah.oukarroum@um6p.ma

For long time, dry phosphorus (P) fertilizers were extensively used to meet crop' P-requirements and improve soil fertility and crop productivity under Mediterranean climate. However, the effectiveness of granular P-fertilizers as well as their P use efficiency (PUE) are drastically reduced in several cropping systems around the Mediterranean region. The PUE of the Mediterranean agricultural systems is currently below 25%. This figure is explained by the impact of climate change on the sustainability of the cropping systems and by the different P lose processes in soils, which increased the recalcitrant P-pools in the soil and reduced its availability for plants. Under these challenging conditions several agricultural practices and biochemical processes were adopted to improve the P use efficiency and crop responses to P fertilizers. The development of new P fertilizer formulas based on polyphosphate and orthophosphate molecules was tested as an innovative approach to enhance P releasing kinetics and availability in soil and consequently plant P-uptake and PUE. Several agronomic experiments were conducted on legume and cereal crops in Morocco revealed that the choice of optimal P fertilizer formulas, taking into consideration the pedoclimatic conditions, greatly improved plant physiological traits (photosynthetic yield), agronomic yield and quality, as well as the P uptake and use efficiency.

Moreover, the enhancement of phosphate rock effectiveness through biological and chemical processes such as phospho-composting and partial acidulation were tested as ecofriendly techniques to improve phosphate rock solubility and making it more convenient to wide range of soil and crops under arid and semi-arid conditions of Morocco. On other side, the integration of precision agriculture tools like high-frequent drip fertigation and the use of soil and plant sensing technologies such as electromagnetic induction systems and chlorophyll fluorescence spectroscopy has proved its highly significant contribution to improving the P use efficiency by plants.

The different experiments carried out in our laboratories and under field conditions were shown that phosphate fertilizer application rates and PUE can be greatly improved using a leaf P content prediction model based on chlorophyll fluorescence measurements and through the application of variable-rate P fertilizers using drip fertigation system.

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TO FAIR, INCLUSIVE, CIRCULAR AND HEALTHY CITIES: TRANSFORMATION OF PHOSPHOGYPSUM (PG) INTO COMMERCIAL PRODUCTS THROUGH SUSTAINABLE AND ZERO-WASTE PROCESSES

Vitor Correia(1), Pavlos Tyrologou(1), Anita Stein(1), María González-Moya(2), Andrea Prieto(2)

(1) European Federation of Geologists, (2) Idener.

The EU-funded FIC-Fighters project, which commenced in June 2024, aims to transform phosphogypsum (PG) waste into valuable resources. This initiative focuses on producing sustainable raw materials for various industries, including paper, cement, batteries, fertilisers, and detergents. Emphasising a circular economy approach, the project actively engages local communities through dialogue, fostering new economic models to manage waste that harms natural and cultural heritage.

The project serves as a platform for discussion and adoption of alternatives for wastes accumulated near urban areas for decades. By involving diverse local actors, industries, authorities, SMEs, research and technology development (RTD) centres, and universities, the FIC-Fighters project seeks to inclusively scale up waste recovery processes to Technology Readiness Levels (TRL) 6-7. The focus is on valorising phosphogypsum waste to generate sustainable raw materials, aligning with circular economy principles.

Over a 48-month period, various stakeholders will collaborate with the Circular Cities and Regions Initiative (CCRI) to realise new circular business models. Key activities include:

1. Building a Mobile Pilot Plant: A mobile pilot plant (TRL7) will be constructed, utilising optimised results and digital twin processes to demonstrate sustainable production of raw materials such as sodium sulfate, rare earth elements (REE) and phosphorus, aluminium hydroxide, ammonium sulfate, and precipitated calcium carbonate from phosphogypsum and other wastes.
2. Creating a PG Forum: Local discussions will be facilitated through a PG forum, complemented by workshops in seven case studies. These workshops

will involve citizen participation, addressing socio-economic, environmental, and regulatory aspects to foster trust and acceptance of new circular business models.

3. Ensuring Flexibility and Replicability: The project will involve seven case studies to explore the flexibility and replicability of valorisation processes. Additionally, a PG Exploitation Portal will be developed to identify, characterise, and engage all European cities facing similar challenges.
4. Knowledge Exchange and Community Building: Contributions to knowledge exchange will be made through clustering and CCRI events. A Community of Practice will be established, ensuring the results are publicly available and exploitable, with appropriate intellectual property (IP) protection.
5. Providing Circularity Guidelines: Guidelines for achieving circularity will be developed based on life cycle assessment (LCA), life cycle cost (LCC), social, and health and safety (H&S) studies.

By transforming phosphogypsum waste into valuable resources, the FIC-Fighters project not only aims to provide sustainable raw materials for key industries but also seeks to establish a model for circular economy practices, engaging communities and fostering inclusive, sustainable development.

ASSESSING AGRI-FOOD SYSTEM PHOSPHORUS FLOWS AT A LOCAL LEVEL: THE POTENTIAL FOR RECOVERY AND RE-USE IN RURAL INDIA

Diorbhail Wentworth [a] (presenting author, diorbhail.wentworth@ed.ac.uk)
Chandan K Basavaraj
Alfred Gathorne-Hardy[a,b]
Priyanka Jamwal[c]
Kate Heal[a]

Name of the Institutions in size 11, italics.

[a]The University of Edinburgh, School of GeoSciences, Crew Building, Alexander Crum Brown Road, Edinburgh EH9 3FF, United Kingdom

[b]The University of Edinburgh, Global Academy of Agriculture and Food Systems, Charnock Bradley Building, Easter Bush Campus, Edinburgh EH25 9RG, United Kingdom

[c]Ashoka Trust for Research in Ecology and the Environment, Royal Enclave, Sriramapura, Jakkur Post, Bangalore 560 064, Karnataka, India

India is the second-highest consumer of phosphorus (P) globally, following China. With a growing population and increasing P footprint per capita due to dietary shifts towards more meat consumption, India's demand for P will continue to rise. Over 90% of India's P fertiliser requirements, and consequently its food security, rely on imported P. Our substance flow analysis (SFA) of P in India's agri-food system, utilising national-scale datasets, revealed that equivalent to 20% of the current P applied in mineral fertiliser could be recovered from human excreta (urine and faeces). P recovery in this manner is anticipated to be particularly viable in India, given the large rural population engaged in agriculture often in proximity to large urban centres. However, the diverse physical, cultural and agri-food environments in India, necessitate the validation of these national scale results at local scales, through analysis of agri-food systems and their actors.

To ascertain the region-specific potential for P recovery and re-use we undertook a scaled down SFA of a rural location, Berambadi Gram Panchayat, in Karnataka, South India. The study area of 3,769 hectares (or 38 km^2) comprises seven villages with an approximate population of 5,200, and predominantly agricultural land. A combination of scaled down national data on P fertiliser use, sanitation, P excrement levels, dietary intake of P, P in crop residues, P in crop distribution wastes, and P in runoff and eroded soil was used along with the responses from 51 interviews, covering agricultural practices and sanitation habits, to complete the SFA. Of the 51 respondents, 24 were Scheduled Caste or Scheduled Tribe and eight were female. Respondents were predominantly farm owners, however six of the 51 worked as both farmers and farm labourers, and six were labourers without their own to land. We also conducted soil and water phosphorus sampling to inform the SFA and validate some of our results.

The SFA is ongoing; however, initial results indicate an increasing use of mineral fertilisers alongside a decrease in the use of animal manure, due to regulations prohibiting grazing on forest land making livestock ownership less viable. Additionally, the majority of households now have access to sanitation (newly built pit latrines) that will require emptying in the coming years. With a current lack of treatment facilities this could pose significant challenges or provide a valuable source of recoverable P if solutions are put in place, particularly if these can be incorporated into ongoing changes in fertiliser use practices. The Indian Government’s plans to reduce expenditure on fertiliser, with states and union territories encouraged to reduce their overall use of mineral fertilisers, offering 50% of the savings to develop alternative fertiliser systems and incentivise farmers and groups to reduce fertilizer use, could provide opportunities for investment in solutions that simultaneously address sanitation and nutrient recovery, understanding regional potentials could prove crucial for this decision-making.

MODEL-BASED OPTIMISATION OF PHOSPHORUS MANAGEMENT AND RECOVERY IN WRRFS: A PLANT-WIDE APPROACH

S. Jaray-Valdehierro*, B. Elduayen-Echave*,**, P. Grau**, T.Fernández-Arévalo*,**, E.Ayesa*,**

** CEIT-Basque Research and Technology Alliance (BRTA), Paseo Manuel Lardizabal 15, 20018 Donostia - San Sebastián, Spain. (sjarayv@ceit.es)*

*** Universidad de Navarra, Tecnun, Paseo Manuel Lardizabal 13, 20018 Donostia - San Sebastián, Spain*

Introduction

In the past, wastewater treatment plants (WWTPs) primarily focused on meeting specific effluent quality standards. Today, are evolving into Water Resource Recovery Facilities (WRRFs) due to resource concerns (WEF, 2014).

Mathematical modelling, such as Ceit's PWM methodology (Grau et al., 2007), enables a detailed characterization of (P) phosphorus-related processes and fluxes (Fernández-Arévalo et al., 2017; Lizarralde et al., 2019) and facilitates the formulation of effective P management strategies. Its applicability has been tested and proven over the years in numerous real WWTP.

The aim of this contribution is to is to show the potential of the tool for optimizing WRRF operation.

Material and Methods

The Plant-Wide Modelling concept enables the construction of unit-process models (UPMs) that describe dynamic processes in water sanitation systems and industrial activities, ensuring mass, charge and energy continuity (Grau et al., 2007). Users can construct comprehensive PW models by selecting transformations involved in the processes evaluated.

To analyse P management strategies using PWM, a mathematical model is constructed, calibrated, and validated. Secondly, a complete P mapping of the process is conducted.

Finally, operational strategies are assessed to establish optimal P management guidelines.

To demonstrates the tool's capabilities, results from a model-based scenarios analysis in the Sur WWTP are shown.

Table 1: Set of scenarios for the model-based analysis.

A	Baseline – Sur WWTP
B	Struvite precipitation unit
C	Redissolution tank to treat secondary sludge
D	Primary sludge added to the redissolution tank.

Results and Conclusions

The phosphorus mass fluxes through the complete WWTP are shown in Figure 1. Around 70% of the phosphorus is retained in the sludge. Several recycle points in the WWTP that contain phosphorus can been identified.

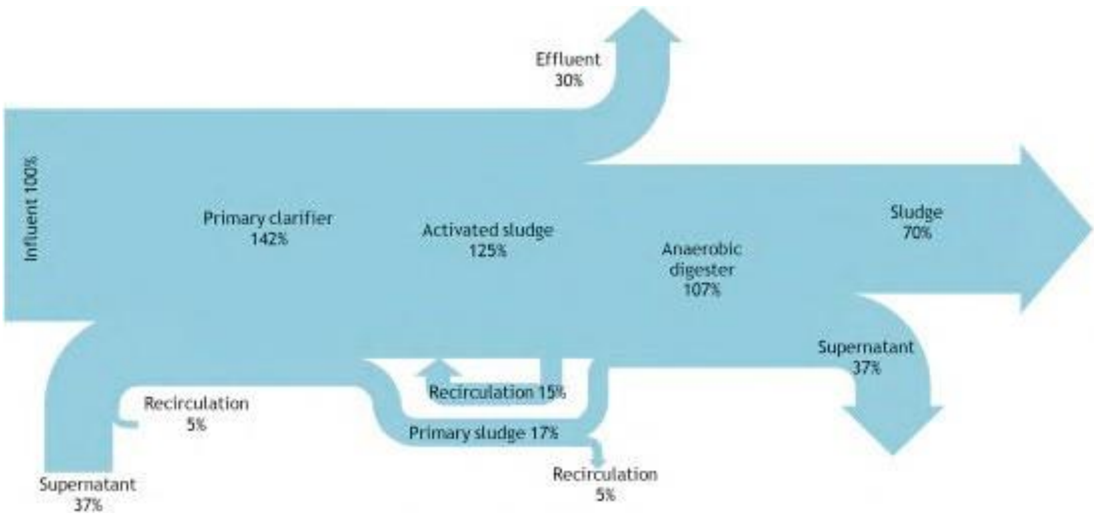

Figure 1: Phosphorus flux throughout the Sur WWTP

In the three new scenarios struvite is recovered. In Scenario C a very small amount of struvite is recovered, compared to scenarios B and D. This is because the dissolution of phosphate in the redissolution tank is very low if no primary sludge is provided.

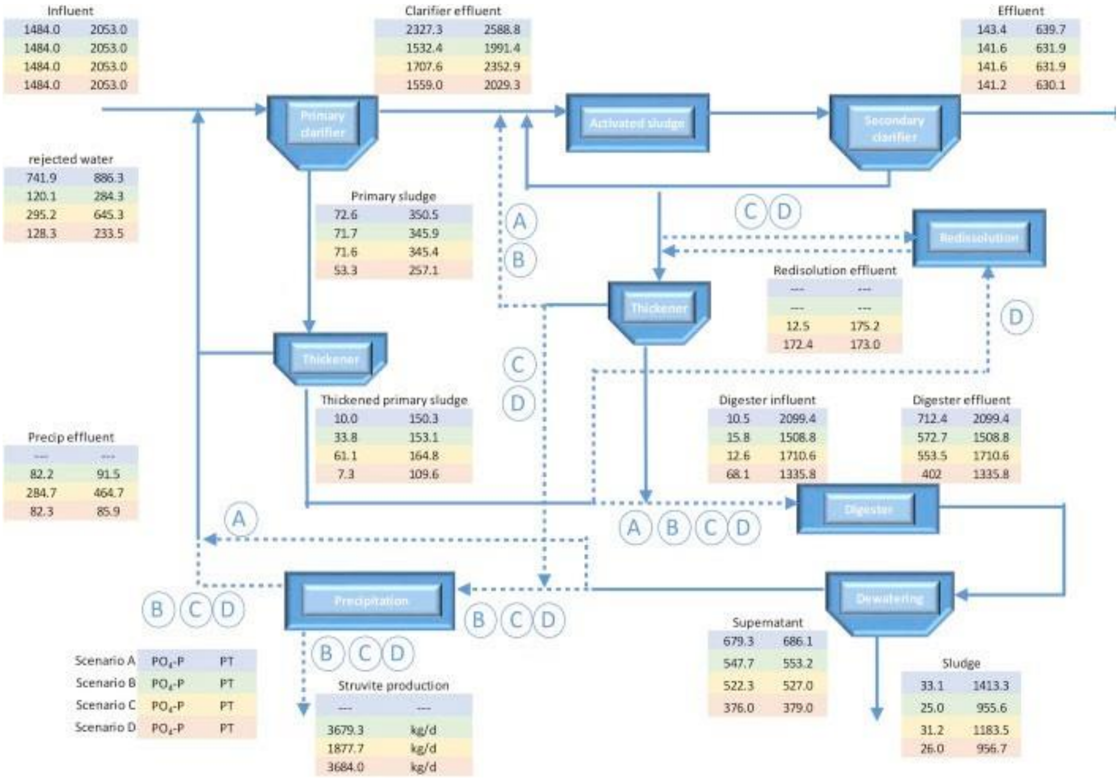

Figure 2: PO4-P mapping throughout the plant in the different scenarios

Conclusions

The PWM library developed by Ceit is a validated and highly useful tool for the design and optimization of strategies for nutrient recovery in urban and industrial processes.

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SUSTAINABLE P-PRODUCTS OBTAINED FROM URBAN WASTEWATER VIA CHEMICAL PRECIPITATION AND ADSORPTION

Andreia F. Santos[a], Paula Alvarenga[b], Licínio M. Gando-Ferreira[a], Margarida J. Quina[a]

[a] *University of Coimbra, CERES, Department of Chemical Engineering, 3030-790 Coimbra, Portugal;*
[b] *University of Lisbon, LEAF, School of Agriculture, Tapada da Ajuda, 1349-017, Lisboa, Portugal;*

Considering that phosphorus (P) and phosphate rock were reconfirmed in the 2023 Critical Raw Materials (CRM) list [1], reducing consumption by minimizing the input (e.g., in people and animal food) and recycling more by maximizing the recovery and reuse of P in the waste streams is important. Indeed, the CRM Act (in force on 23 May 2024) set goals to improve the sustainability and circularity in the European Union market. This includes measures to increase the collection of CRM-rich waste and ensure its recycling into secondary CRM [2]. Wastewater treatment plants (WWTP) are one of the potential hot spots to recover P. Thus, the main motivation of this project is to contribute with sustainable solutions to recover and recycle P and, subsequently, obtain products via chemical precipitation and adsorption to be introduced in the market. Two processes to recover P will be proposed: adsorption with a thermally modified low-cost adsorbent (eggshell), and chemical precipitation. The P-products obtained will be eggshell loaded with P after adsorption (and Ca-rich), and struvite (as pure as possible). In addition, the dewatered sludge, after thermal treatment to eliminate microbiological contamination, will also be considered in an agronomic assessment as an extra source of P and organic matter. Therefore, the main outcomes of this project will be a contribution to state of the art in respect of (i) the concentration of P in both fractions in Portuguese WWTP; (ii) the feasibility of P recovery from wastewater through adsorption and chemical precipitation and determine the optimum operating variables; (iii) understand the adsorption behavior in a pilot-scale adsorption column using eggshell as an adsorbent; (iv) increase the purity of struvite obtained from these matrices with an innovative approach to reduce the influence of calcium in the process; and (v) tune a suitable battery of tests to ascertain the agronomical value of the recovered products and its potential to replace commercial fertilizers, with a soil experiment using lettuce.

Overall, this project involves all the phases from the characterization of the wastewater streams and selection of the best hot spots to implement the technology, the development of the technology, optimization of the operating conditions and test the products in the final application. It is intended to contribute to environmental protection and economic development by reducing the risk of eutrophication and to the supply of a cost-effective fertilizer that recovers a finite and irreplaceable resource (P). This project has a high impact on society, contributing to three Sustainable Development Goals (SDG), namely SDG 2 (zero hunger), SDG 6 (clean water and sanitation), and SDG 12 (responsible consumption and production).

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CIRCULAR FERTILISERS FROM CIRCULAR SANITATION, COMMUNAL WASTEWATER, AND AGRI-FOOD INDUSTRY PROCESS WATER

Kimo van Dijk (1), Lotte Veenemans (1), Inge Regelink (1), Rene Rietra (1), Oscar Schoumans (1), Wim van Dijk (2), Willem van Geel (2), Alexander van Tuyll (3), Tiemen Nanninga (3), Hazel van Waijjen (3), Kees Roest (4), Frank Oesterholt (4)

1. Wageningen University & Research (WUR) – Wageningen Environmental Research (WENR), *kimo.vandijk@wur.nl*

2. Wageningen University & Research (WUR) – Wageningen Plant Research (WPR)

3. LeAF B.V.

4. KWR Water Research

Nutrient cycles in Europe and the Netherlands remain far from closed, with the largest leakages in the food system occurring via wastewater rather than animal manure. Despite various ambitions and targets, nutrients are still scarcely recovered and reused from wastewater as circular fertilisers. Instead, they are lost through incineration, sequestration or emissions to the environment. For instance, in the Netherlands, the nutrients in communal wastewater could replace approximately twice the phosphorus, half the nitrogen, and the same amount of potassium currently used in synthetic fertilizers if safely and sustainably recycled. Additionally, the agri-food industry process water and sludge could serve as valuable sources of nutrients but are also increasingly incinerated. It is essential to replace conventional synthetic fertilizers as much as possible, which are based on fossil energy (nitrogen) and mined resources (minerals like phosphorus), as well as organic fertilizers like manure that have negative impacts by indirect synthetic fertilizer use.

The production and use of sustainable circular fertilisers from wastewater face several barriers at the intersection of technology, knowledge, regulation, cooperation, and economics. This presentation will present the first outcomes of the Dutch public-private partnership project "Closing the Cycle of Nutrients from Wastewater and Process Water" (KNAP). This project focuses on recycled fertilisers from circular sanitation, communal wastewater, and agri-food industry process water (sludge), both in concept development and in practice.

Key conclusions on the agricultural value, quality, and safety of recycled fertilisers will be shared, with special attention to regulatory challenges at the Dutch and EU levels. A quality assessment system is under development in collaboration with more than 40 stakeholders from agriculture, fertiliser industry, the wastewater sector, the agri-food industry, technology providers, policymakers and knowledge institutes. Underlying activities will also be presented, including product portfolio and composition (agronomic parameters and contaminants), an agronomic field trial for 14 nitrogen-rich products, an agronomic pot experiment for 8 phosphorus-rich products, and emission measurements for nitrous oxide, ammonia, and nitrate.

In addition, practical solutions from several KNAP cases will be showcased, including the valorization of concentrated nitrogen-rich liquid fertilisers, solid mineral/phosphate-rich fertilisers from municipal wastewater, anaerobically digested black water and dewatered sludge, source-separated human urine mineral concentrate, and anaerobically digested food residues with on-site micro-digesters at retail, catering, and hospitality companies. Additionally, anaerobic and aerobic residual biomass from the treatment of agri-food industrial process water from the dairy, brewery, sugar, and potato processing industries will be discussed. To demonstrate the potential use of these recycled fertilisers and soil improvers in circular agriculture, two potential application routes will be examined: arable farming in the Dutch region of Flevoland and greenhouse horticulture.

The presentation aims to provide insights on how to implement circular fertilisers from wastewater systems. The underlying objectives are (1) to minimize the input of 'fossil' resources, including fertiliser and feed imports, (2) create added value by recycling and valorising nutrients from wastewater, (3) shorten nutrient loops in the food system as much and as locally as possible, (4) remove and control contaminants to enable safe circularity, and (5) and minimize emissions to land, water, and air at the source.

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SUSTAINABLE PHOSPHORUS MANAGEMENT IN ACID SOILS: A PATH FROM TRADITIONAL TO SMART APPROACHES

Seguel A[1], Montesano de Souza P[2], Palma, R[3], Cea P[4], Rojas N[4], Meier S[2]

[1] *Departamento de Ciencias Agronómicas y Recursos Naturales, Facultad de Ciencias Agropecuarias y Medioambiente, Universidad de La Frontera, Temuco, Chile.*
[2]*Instituto de Investigaciones Agropecuarias. INIA Carillanca, Casilla Postal 929 Temuco, Chile*
[3] *Instituto de Investigaciones Agropecuarias. INIA La Cruz, La Cruz, Región de Valparaiso*
[4] *Vicerrectoría de Investigación y Postgrado, Universidad de La Frontera, Temuco, Chile*

Phosphorus (P) is a crucial nutrient for plant growth, yet its management in agriculture, especially in acid soils, presents significant challenges. Traditional methods of P fertilization often lead to inefficiencies and environmental issues due to the finite nature of phosphate rock reserves. Despite its importance, there remain significant knowledge gaps in optimizing P use in agriculture, particularly in acid soils where up to 90% of applied phosphorus can be immobilized. This work outline a comprehensive approach to sustainable phosphorus management, transitioning from traditional practices to smart, innovative solutions. First, we investigated the phenological responses of wheat genotypes to varying phosphorus levels and water availability. This study aims to identify genotypes with enhanced P uptake and use efficiency, improving productivity in phosphorus-limited environments. Phosphorus addition promoted plant growth, particularly in early stages, by enhancing tiller development and nutrient and water uptake. These effects were crucial during anthesis and ripening, where P and water addition boosted key yield components, resulting in increased grain yield. Furthermore, water addition promoted phosphorus use efficiency (PUE) and water productivity (WP), indicating a synergistic relationship. Additionally, we focus on mechanisms underlying PUE, particularly the role of arbuscular mycorrhizal fungi (AMF) and root development. By studying these mechanisms, we aim to develop wheat varieties with enhanced P acquisition, facilitated by beneficial symbiotic relationships with AMF and optimized root architecture. These findings are crucial in breeding programs aimed at producing more resilient and efficient crops. Finally, we explore next-generation fertilizers, focusing on phosphorus-impregnated biochar. These smart fertilizers provide controlled-release of nutrients, reducing application frequency and improving nutrient recovery. Our experiments show that biochar-based fertilizers significantly enhance P availability and uptake, leading to better yields and reduced environmental impact.

Preliminary results from these approaches show promising improvements in phosphorus use efficiency. Wheat genotypes with enhanced root systems and favorable phenological traits exhibit increased P uptake and utilization. Phosphorus-impregnated biochar proves effective in controlled nutrient release, contributing to better crop performance and sustainability. Transitioning from traditional to smart approaches in phosphorus management is essential for addressing the complex challenges posed by acid soils and global food demands. Our research provides a robust framework for sustainable phosphorus management, leveraging advanced technologies and biological insights to enhance agricultural productivity and sustainability. This shift from conventional to innovative practices promises a future where agriculture is both productive and sustainable. To realize this vision, our future research will focus on scaling these solutions and integrating them into broader agricultural practices, ensuring their widespread adoption and impact.

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Keywords: Sustainable agriculture, Soil fertility, Acidic soils, Phosphorus-impregnated biochar, Crop productivity, Wheat.

OPTIMIZATION OF PHOSPHORUS MOBILIZATION IN BIOGAS DIGESTATE

M. Sc. Kea Purwing, PD Dr. Andreas Lemmer

University of Hohenheim, State Institute for Agricultural Engineering and Bioenergy

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Introduction

Mineral phosphorus (P) and nitrogen (N) fertilizers are used in agriculture to ensure food safety in Germany. Nowadays, P fertilizer is mainly extracted from phosphate rock, a finite and fossil resource with China, Morocco and Western Sahara as the main exporters [1, 2]. In addition to an increasing demand for food, society's growing need for energy, the scarcity of fossil fuels and climate change make it necessary to use renewable energy sources [3]. An important source of energy is biogas, which is produced by the anaerobic decomposition of biomass in biogas plants. Besides biogas as an energy source, biogas plants also produce digestate as a by-product. Digestate contains most of the nutrients from the biomass used and is therefore used as a fertilizer in agriculture. According to Roskosch, A., Heidecke, P. [4] the annual P-recovery potential in Germany is about 125.000 t/a for digestate, 444.000 t/a for manure and 50.000 t/a for municipal sewage sludge. Solely the P-recovery from digestate would meet the annual demand of 124.000 t/a [4]. Isolation of nutrients from digestate is crucial to make them transportable in order to close nutrient cycles and replace mineral fertilizer [5].

Digestate is often first separated into a solid and a liquid phase. Only a small proportion of the nutrients are separated in the solid separated fraction: Ammonia at around 18 %, potassium at around 17 % and P at around 30 % [6]. The present work deals with the isolation of P from the liquid separated fraction, with typical nutrient concentrations of N_{total} 4.9 kg/m^3, NH_4 3.1 kg/m3, P_2O_5 2.0 kg/m^3, K_2O 5.4 kg/m^3 and a dry matter content (DM) of 5.7 % [7].

The process principles for recovering P from the liquid separated phase are divided into concentrating processes and isolating processes. A typical process for isolating P is phosphate precipitation. In this process, the contained phosphates are first dissolved at low pH values (pH 4.7-5.0) with sulphuric acid (H_2SO_4), which leads to the dissolution of most of the contained phosphates into the liquid phase. The dissolution of phosphates enables the separation from organic particles by filtration. Afterwards the solved phosphates can be precipitated with divalent cations (Ca^{2+} or Mg^{2+}) at an alkaline pH value as phosphate salts [8]. The particle-free fermentation product is then alkalized with sodium hydroxide (NaOH), which leads to the precipitation of the phosphate salts.

In a further filtration step, these are isolated and the now P-depleted liquid digestate is transferred to an NH_3 stripper column, where air stripping takes place at 60 °C and pH 11. ASL is produced from the NH3 obtained using a vapor scrubber and sulphuric acid. What remains is a P- and N-depleted liquid, which is still rich in potassium. The NuTriSep Process of the company Geltz Umwelttechnologie GmbH is based on that principle [9]. Nowadays, large quantities of H_2SO_4 and sodium hydroxide solution (NaOH) are necessary in phosphate precipitation processes for pH-value adjustment [9].

The overall aim of this project is to optimize the process of phosphate recovery from digestate by completely or partially replacing H_2SO_4 and NaOH for pH-value adjustment by carbon dioxide (CO_2) and ammonia (NH_3). For this purpose, P-recovery is combined with both, the treatment of biogas and the recovery of N (Figure 1).

Research aim

The present work examines the possibilities of acidifying separated liquid digestate with CO_2 and the amount of P dissolved this way. For comparison, separated liquid digestate was acidified with sulphuric acid and the amount of dissolved phosphorus was determined.

Methods

Acidification with CO_2 takes place in pressure-stable reactors (500 ml). CO_2-acidification was conducted at 5 and 10 bar with 100 % CO_2 atmosphere for 30 min at 15.28 ± 1.12 °C. For better pumping probabilities the liquid separated digestate was diluted with distilled water at a ratio of 1:1. While acidification the pH was measured every 60 s. After acidification, the pressure was released and the sample was prepared for centrifugation (3500 rpm, 10 min) within 10 min after pressure release.

After centrifugation, the P content was measured both in the centrifugation supernatant and the centrifugation pellet. Untreated liquid separated fermentation residue of the same dilution (1:1 with distilled water) was used as control samples and additional acidification with sulphuric acid was carried out for comparison with CO_2 acidification. For titration 30 g digestate was titrated with 0.5 M Sulfuric acid to the respective pH value reached with CO_2 acidification (pH 6.09) with the titrator 785 DMP Titrino (Metrohm). P was measured with UV-VIS 1240 Spectralphotometer (Fa. Shimadzu) at 405 nm after addition of ammonium vanadate and ammonium heptamolybdate.

Results and Discussion

In Table 1 the analysis results of the initial substate (liquid separated digestate) are listed.

	P [g/kg FM]	P [g/kg DM]	FOS [mg/l]	TAC [mg CaCO3/l]	FOS/TAC
Value	0.755	10.080	3421	16263	0.210
σ	± 0.008	± 0.071	± 204	± 264	± 0.009

	NH4-N [g/kg FM]	NH4-N [g/kg DM]	TS [%]	oTS [%]	Ash [%]
Value	3.005	40.125	7.488	4.748	2.740
σ	± 0.024	± 0.325	± 0.023	± 0.011	± 0.011

By acidifying liquid digestate with CO_2, the pH value can be lowered from around pH 8 to pH 6 (Figure 2). Preliminary tests have shown that the pH-value is stable after 30 minutes of acidification. It can be observed that the CO_2 acidification of digestate stabilizes at higher pH-values compared to distilled water, where a pH value below 4 can be achieved. This can be explained by the strong buffering effect of digestate in the respective pH-range of predominantly by the bicarbonate buffer system and volatile fatty acids [10].

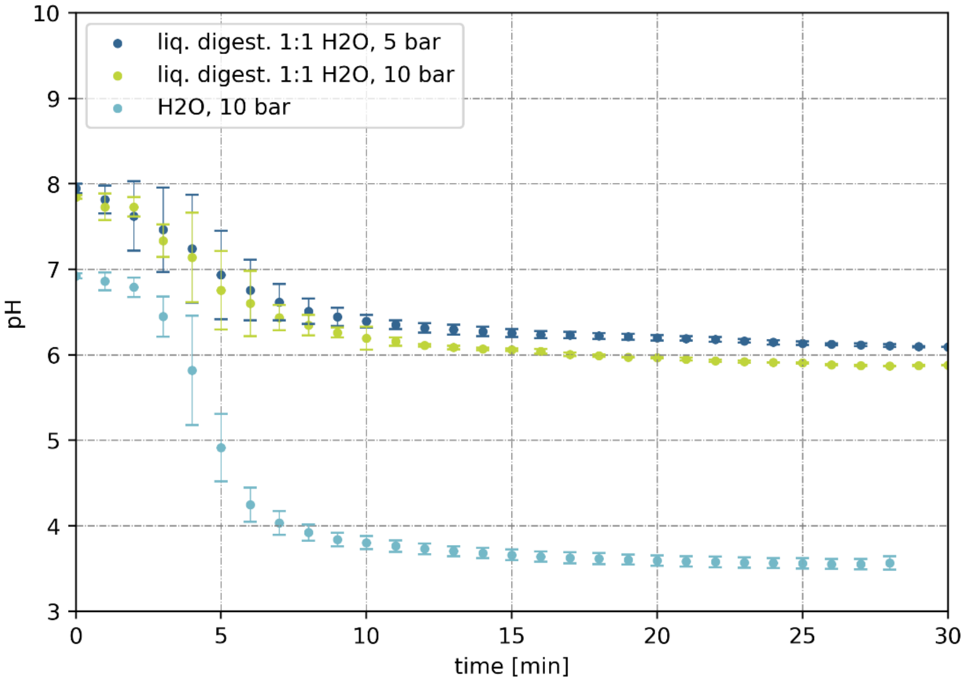

Figure 1: pH curves of CO_2-acidification of dist. water and a 1:1 dilution of liquid digestate with dist. water at 5 and 10 bar. The acidification was carried out in 500 ml batch reactors with a trickle bed and circulation of 35 ml/min.

Moreover, it can be observed that the P content of the centrifugation pellet is considerably lower after CO_2-acidification compared to the non-acidified control (Figure 3). At the same time, the P content of the centrifugation supernatant increases as a result of CO_2-acidification compared to the non-acidified control.

Comparing the CO_2-acidification at 5 bar and 10 bar, shows that CO_2 acidification at 10 bar leads to higher mean P-concentrations in the centrifugation supernatant as well as in the pellet. However, the difference to the P concentrations after acidification at 5 bar does not appear to be significant. One possible explanation for the high error is the necessary depressurization before centrifugation. Although this period was kept as short as possible (less than 10 min), it must be assumed that the pressure release leads to a change in pH value and consequently a change in phosphate solubility shortly before centrifugation cannot be ruled out. This could also be a reason why acidification with H_2SO_4 leads to better results, as titration with H_2SO_4 solution achieves pressure independent stable pH values. In summary, it can therefore only be stated with certainty that acidification with CO_2 leads to a solution of P contained in the fermentation residue.

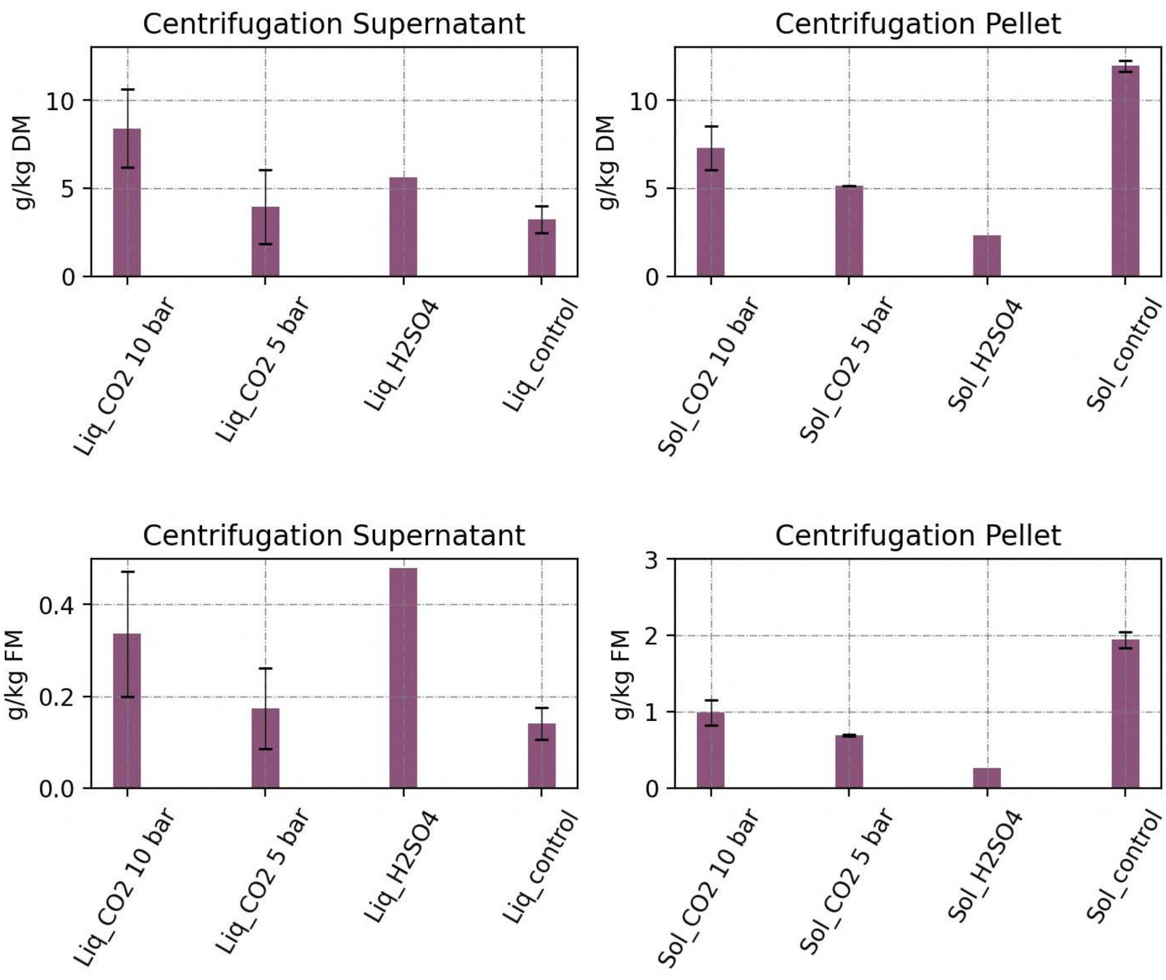

Figure 2: Phosphorus content of the liquid phase and solid phase after acidification with CO_2 for 30 min at 5 bar and without acidification (control). Solid-liquid separation by centrifugation (10 min at 3500 rpm).

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NATURE-BASED SOLUTIONS COUPLED TO IRON SLAG FILTERS FOR SUSTAINABLE PHOSPHORUS RECOVERY FROM AGRICULTURAL RUNOFF WATERS AND CROP PRODUCTION EVALUATION

Fornells, Ll.[1a], Manyosa, R.[1a], Aponte, D.F[1]., Fernandez-Gatell, M[1]., Gouerec, E[1]., and Puigagut, J[1*].

[1]*Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya, Spain.*

[a]*First co-author – equal contribution to the work*

**Corresponding author*

Phosphorus (P) is a key element for agriculture and is mainly obtained from sedimentary rocks mining. However, phosphorus supply for chemical-based fertilizers is currently at risk due to a substantial decrease of economically feasible mining sites available. Therefore, phosphorus recovery and recycle in agriculture is necessary to ensure future sustainable crop production. The results here presented are a summary of a two-year project that aimed at recovering soluble phosphorus from agricultural runnoff waters using constructed wetlands with steel slag as filter media and then, using the phosphorus enriched slag as soil amendment for side-by-side crop production evaluation compared to chemical-based fertilizers. Soluble phosphorus recovery was conducted using a steel slag filter operated after a vertical flow constructed wetland.

The two-stage pilot system treated about 500 L of real runnoff agriculture water and its efficiency evaluated on a weekly basis for two months. The pilot plant was set up within the research park of Agropolis, located within the agricultural park of Baix Llobregat (Catalonia, Spain). After the pilot plant operation, steel slag was used as a P-enriched amendment to evaluate the production of basil (*Ocimum basilicum*) for 9 weeks under laboratory conditions. Experimental conditions during the pot experiment were : ***i)*** negative control (basil growth evaluation under a nutrient deficient soil); ***ii)*** positive control (basil growth evaluation under the administration of a standard Hoagland solution); ***iii)*** experimental condition 1 (amendment with P enriched slag equivalent to the amount of P dosed with the Hoagland solution); ***iv)*** experimental condition 2 (amendment with P enriched slag equivalent to 10 times the amount of P dosed with the Hoagland solution) and, ***v)*** experimental condition 3 (amendment with P enriched slag equivalent to 20 times the amount of P dosed with the Hoagland solution). All experimental conditions above mentioned were carried out in sets of 4 replicates under a random distribution experimental array. During crop production, soil microbial activity, plant height and chlorophyll content of leaves was recorded on a weekly basis, and at the end of the production period, above and below ground biomass was weighted.

Furthermore, water leaching samples were also collected on a weekly basis to assess metal leaching from the pots experiment. According to the results obtained, the main conclusions of this project are: a) Constructed wetlands coupled to steel slag filters are able to successfully remove contaminants form agriculture runoff waters. In case of soluble phosphorus, we are able to recover more than 70% of influent phosphorus; and

b) Iron slag amendment having 10 times higher phosphorus than a conventional chemical fertilizer improves soil microbial activity, and plant height and biomass.

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EVALUATION OF AMMONIA AND PHOSPHORUS REMOVAL EFFICIENCY FROM AGROINDUSTRIAL EFFLUENTS IN BRAZILIAN AMAZONIAN CITIES USING STRUVITE PRECIPITATION

Bianca Kristhine Santos Nascimento
Federal University of Western Pará Master's student in Natural Resources of the Amazon (UFOPA). Santarém, Pará, Brazil. biancakristhine@gmail.com

Rose Caldas de Souza Meira
Professor, PhD in Geology and Geochemistry. Federal University of Pará (UFPA), Institute of Technology, Belém, Pa, Brazil. rosemeira@ufpa.br

Camila Carneiro dos Santos Rodrigues
Oceanographer from the Federal University of Pará - UFPA. Master's and Ph.D. in Environmental Geochemistry (UFPA)

Jolene Rodrigues Lopes
Master's student in Natural Resources of the Amazon (UFOPA)

Ellen Kaline Miranda de Figueiredo
Master's student in Natural Resources of the Amazon (UFOPA)

Erielma Monteiro Ferreira.
Master's student in Natural Resources of the Amazon (UFOPA)

Katiucia Nascimento Adam
Professor, Ph.D. UFPA - Federal University of Pará - UFPA. Institute of Technology, Belém, Pa, Brazil. katiucia@ufpa.br

Effluents from agro-industrial activities can contain significant amounts of nutrients, depending on the source activity. These effluents can be highly impactful to the environment when discharged into water bodies without proper treatment, as required by current legislation and regulations in Brazil. One prominent nutrient removal technique is the recovery of phosphate ions from wastewater through the precipitation of moderately soluble phosphate salts, such as struvite. Struvite is an excellent slow-release fertilizer that can be used directly in horticulture and agriculture. This study evaluated the efficiency of ammonia and phosphorus removal from agro-industrial effluent through struvite precipitation. The effluent was collected in the community of Santa Luzia, in Santarém - Pará, in the Brazilian Amazon. Ammonia and phosphorus analyses were performed using a Hanna Instruments multiparameter bench spectrophotometer. The synthesis and optimization method for struvite used was based

on Meira (2020). Initial characterization of the raw effluent revealed an initial phosphate (PO_4^{-3}) concentration of 760 mg/L and ammonia nitrogen (NH_3) of 192 mg/L. Seventeen experiments were conducted using a central composite factorial design called Design of Experiments (DOE). The results showed excellent performance in the efficiency of the struvite precipitation treatment, with all conditions presenting significantly high results. The experiments 3 (99.94%) and 13 (99.84%) stood out. It was concluded that the removal of ammonia nitrogen and phosphorus through struvite precipitation is suitable for agro-industrial effluents, providing an economically viable destination for the treated waters.

Keywords: Ammonia, Phosphorus, Agro-Industrial Effluent, Struvite Precipitation.

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DEVELOPMENT OF SUSTAINABLE FERTILIZERS FROM PHOSPHORUS RECOVERY OF AGRO-INDUSTRIAL EFFLUENTS IN AMAZONIAN CITIES

Ellen Kaline Miranda de Figueiredo.
Master's student in Natural Resources of the Amazon (UFOPA). Santarém, Pará, Brazil. ellenkfigueiredo@gmail.com

Rose Caldas de Souza Meira.
Professor, PhD in Geology and Geochemistry. Federal University of Pará (UFPA), Institute of Technology, Belém, Pa, Brazil. rosemeira@ufpa.br

Orivan José de Matos Campos Junior.
Master's in Natural Resources of the Amazon. Federal University of Western Pará (UFOPA)

Manoel Roberval Pimentel Santos.
Professor, PhD in Physics. Federal University of Western Pará (UFOPA)

Jolene Rodrigues Lopes
Master's student in Natural Resources of the Amazon (UFOPA)

Bianca Kristhine Santos Nascimento.
Master's student in Natural Resources of the Amazon (UFOPA)

Erielma Monteiro Ferreira.
Master's student in Natural Resources of the Amazon (UFOPA)

The urgent need for more sustainable agricultural practices arises from the rapid depletion of natural resources and ongoing environmental degradation. Phosphorus (P), an essential element for life and a key component of fertilizers, is facing growing demand, highlighting the need for innovative recovery techniques. Brazil heavily relies on fertilizer imports, making it imperative to explore alternatives for phosphorus recovery. Recovering phosphorus from agro-industrial effluents can be a viable solution. This study aims to develop fertilizers from phosphorus recovery of agro-industrial effluents for agronomic tests in Brazilian Amazon cities. The methodology involved collecting and analyzing samples of agro-industrial effluents, utilizing photometry techniques to determine phosphorus and nitrogen concentrations. After characterizing the effluents, struvite synthesis was performed through chemical precipitation. This process involved mixing ammonium chloride and magnesium chloride hexahydrate solutions with the effluents, adjusting the pH to 10 with sodium hydroxide. The bench-

scale experimental test was conducted in a 2000 ml beaker connected to a mechanical stirrer, operating continuously at 250 rpm and at an ambient temperature of 27°C. The process included 10 minutes of stirring followed by 20 minutes of rest for the crystals to nucleate. The struvite fertilizer produced was applied to Amazonian soils in greenhouse conditions, using BRS Gigante Amarelo passion fruit crops. The experiment included treatments of different doses of struvite, as well as controls with conventional mineral fertilization and soil with no added nutrient. Soil fertility analyses were conducted before and after fertilizer application. Results showed that the effluents had significant concentrations of phosphorus and nitrogen, suitable for struvite synthesis, with phosphorus recovery efficiency of over 80%. X-ray Diffraction (XRD) analysis confirmed the formation of pure struvite, and Scanning Electron Microscopy (SEM) revealed a crystalline morphology consistent with the literature. Agronomic experiments demonstrated that the use of struvite fertilizers significantly improved soil fertility and passion fruit crop productivity, with plants showing growth comparable to treatments with conventional mineral fertilization. The discussion of results highlighted the importance of phosphorus recovery for fertilizer production, indicating that struvite precipitation is a viable technique for nutrient recovery from effluents without the formation of unwanted by-products. In conclusion, the application of the produced fertilizers to Amazonian soils resulted in significant improvements in soil fertility and agricultural productivity, highlighting the potential of chemical precipitation of struvite as a sustainable solution for waste management and the promotion of more ecological agricultural practices. Continuing this research could contribute to food security and environmental sustainability in the Amazon and other regions, reducing Brazil's dependence on fertilizer imports and promoting the circular economy and sustainability in agriculture. This study represents an important step towards mitigating the environmental impact of agriculture, promoting an integrated approach that unites technology, sustainability, and efficient waste management, ensuring a more balanced and productive future for Amazonian agriculture.

Keywords: Struvite precipitation, nutrient recovery, ecological agriculture, environmental sustainability.

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SEWAGE SLUDGE UTILIZATION 2.0: NUTRIENT AND CARBON RECOVERY VIA HYDROTHERMAL CARBONIZATION

Gabriel Gerner[1], Jae Wook Chung[1], Luca Meyer[1], Rahel Wanner[1], Simon Heiniger[1], Daniel Seiler[1], Rolf Krebs[1], Alexander Treichler[2], Thomas Keller[2], Roman Kontic[3] and Beatrice Kulli[1]

[1]*Institute of Natural Resource Sciences, Zurich University of Applied Sciences (ZHAW), Campus Grüental, CH-8820 Wädenswil, Switzerland*

[2]*Institute of Chemistry and Biotechnology, Zurich University of Applied Sciences (ZHAW), Campus Reidbach, CH-8820 Wädenswil, Switzerland*

[3]*School of Engineering, Zurich University of Applied Sciences (ZHAW), CH-8401 Winterthur, Switzerland*

To this day, sewage sludge as a resource is mostly disposed of in landfills or incinerated and is thus removed from the circular economy. In recent years, there have been promising developments in the hydrothermal carbonization (HTC) of sewage sludge and the potential to recover phosphorus and nitrogen from such waste streams while preserving the hydrochar as an energy and carbon source. In this study, the HTC of digested sewage sludge (DSS) was investigated for the downstream production of heavy metal (HM)-free fertilizer and the usage of freeze concentration as a novel technology for process water treatment.

Phosphorus was extracted from the hydrochar directly after the HTC treatment by acid leaching. To obtain clean fertilizer, phosphatic acid extracts were first treated with ion-exchange resins to remove dissolved HM, as well as phosphorus precipitating agents (i.e., aluminum and iron). Over 98% of the aluminum (Al) and 97% of the iron (Fe) could be removed in a single treatment step. The purified extract was then used for the precipitation of HM-free struvite crystals, with P-recovery rates exceeding 89%.
Compared to the mono-incineration of sewage sludge with P-recovery from the ash, HTC treatment also enables the recovery of nitrogen and the utilization of the remaining hydrochar as a climate-neutral energy source with similar energy content to the original material. It is therefore a key technology in the utilisation of moist biomass for achieving the global goal of a circular economy.

The HTC process consists of two main products, hydrochar and process water. While hydrochar is the product of interest, process water (PW) makes up the largest share and is very rich in dissolved organic compounds and nitrogen. Compared to evaporation or membrane separation, freeze concentration is a promising technology for concentrating solutes from PW. Separation experiments resulted in the recovery of over 90% of the dissolved compounds in the concentrate. In our study, the concentrate was later utilized as an ammonium source for struvite precipitation, and the subsequent aerobic digestion of the remaining ice water resulted in an 85% reduction in chemical oxygen demand (COD) in 15 days.

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AGRONOMIC EFFICIENCY OF PHOSPHOROUS FROM BBFS DERIVED FROM PIG SLURRY IN RYEGRASS CULTIVATION OF THE FERTIMANURE SPANISH ON-FARM PILOT

B. Singla Just[1*], O. Castaño- Sanchez[1], N. Guerra Gorostegi[1], R. Vilaplana[1], L. Díaz-Guerra[1], A.A. Robles[1], E. Meers[2], L. Llenas[1]

[1] *BETA Technological Centre, University of Vic – Central University of Catalonia, Vic, Spain*
[2] *Department of Green Chemistry and Technology, Ghent University, Belgium*
** Corresponding author, e-mail: berta.singla@uvic.cat*

The FERTIMANURE project aims to develop, evaluate, and validate innovative strategies for nutrient management while recovering mineral nutrients and other agronomically valuable elements from animal manure. The Spanish biorefinery was implemented in a pig farm in Catalonia, where several innovative and conventional technologies were combined to recover nutrients from pig slurry and produce different bio-based fertilizers (BBFs). The study aimed to assess the efficacy and bioavailability of phosphorous (P) in the four BBFs produced in the Spanish pilot.

A pot trial using ryegrass as a tested crop was conducted to compare the P mineralization and P uptake in soils amended with BBFs. The BBFs tested were the biodried solid fraction, and the phosphoric acid that was extracted from the combustion of P-rich ash using sulfuric acid. Also, two different combinations of nutrient-rich concentrate were produced by subjecting the liquid fraction to a combination of various membrane systems and freeze concentration (MFR and MFRO, respectively).
Additionally, two positive references were included (mineral fertilizer TSP and pig slurry). The treatments were applied at three different levels (30%, 60%, and 100%) of the recommended P dosage (48 kg TP/ha), representing 7.2, 14.4, and 24 mg P/pot. The plants were grown for three months in a growth chamber following a randomized block experimental design. Throughout this period, three sequential cuts were done monthly, and various plant parameters (i.e. fresh and dry yield) and nutrient uptake ((i.e., N, P, K, Cu and Zn) were investigated. On the last day of the experiment, a full soil characterization was conducted to provide data on the mineralization of BBFs. The bioassay data was analysed using a general linear model (two-way ANOVA) to study

the impact of three different P doses (7.2, 14.4, and 24 mg P pot^{-1}) and time (day 30, day 60, and day 90) on plant parameters for each type of fertilizer.

Overall, we observed a gradual increase in dry yield across consecutive cuts, with the highest yield occurring in the last cut after 90 days. The results of the two-way ANOVA emphasized the significant impact of the interaction between time (cut) and the fertilizer application rate on dry yield. This increase could support the hypothesis of the slow-release fertilizers from these secondary fertilizers. In addition, certain treatments using BBFs showed better performance compared to mineral fertilizer TSP, highlighting the efficacy of BBFs enhancing plant yield and nutrient availability.

To summarize, the FERTIMANURE Spanish pilot demonstrates the potential benefits of using BBFs for a more sustainable agricultural practices. The BBFs developed during the project have proven to be effective fertilizers that can partially replace mineral fertilizers currently available in the market. By using BBFs, it is possible to optimize the nutrient use while contributing to the circular economy in rural areas.

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EFFECT OF CONTRASTING SOIL PHOSPHOROUS LEVELS AND CARBON AVAILABILITY ON GREENHOUSE EMISSIONS IN A SOIL INCUBATION

B. Singla Just[1,2*], V. Shrivastava[1,2], O. Castaño- Sanchez[1], N. Guerra Gorostegi[1], L. Díaz-Guerra[1], A.A. Robles[1], R. Vilaplana[1] I. Sigurnajak[2], E. Meers[2], L. Llenas[1]

[1] BETA Technological Centre, University of Vic – Central University of Catalonia, Vic, Spain
[2] Department of Green Chemistry and Technology, Ghent University, Belgium
** Corresponding author, e-mail: berta.singla@uvic.cat*

Nitrous oxide (N_2O) and carbon dioxide (CO_2) are two of the main greenhouse gases (GHG) emitted from agricultural soils. In addition, soil management practices such as the use of nitrogen fertilizers, changes in land use, and tillage might impact in the amount of GHG emitted from soils. Yue et al. (2021), estimated that the global emissions from soils are 70% of the total N_2O emissions from human activities.
However, there is still a lack of understanding about the interaction between soil nutrients, such as available phosphorus (P) and carbon availability, and their subsequent impact on greenhouse gas emissions.

For this reason, this research aimed to investigate how different carbon mineralization from different Bio-Based Fertilizers (BBFs) and soil P levels affect GHG emissions and underlying the main mechanisms involved such as soil microbial community and soil respiration.

A soil incubation was conducted with a soil from Belgium with low soil available P. Two different bio-based fertilizers (BBFs) from pig slurry with different carbon mineralization rates were used: Biodried solid fraction and nutrient-rich concentrate. BBFs were applied at a rate of 9000 kg TOC·$ha^{-1}$and were treated with two different of P (0 kg TP·ha^{-1} and 48 kg TP·ha^{-1}) using TSP. In addition, a negative control (without adding C or P source) was included while pig slurry was used as a positive treatment. Since the treatments varied in their N content, mineral fertilizer CAN was used to level up the N levels. The soil water content was adjusted to 60% water-filled pore space.
The gaseous emissions were measured for CO_2, N_2O, CH_4 and NH_3 for 28 days. At the

end of the incubation, hot-water carbon extraction, nitrogen mineralization (nitrate and ammonium), and soil available P were also analysed.

The preliminary results indicate statistical differences between treatments. In general, the addition of P decreased in all the treatments, suggesting that P limitation stimulates N_2O emissions. This is because the limited availability of P can reduce the microbial mineralization of N, which is a key process in preventing N_2O emissions. However, treatments with high labile carbon availability, such as nutrient-rich concentrate and pig slurry, exhibited higher cumulative N_2O emissions as compared Biodried solid fraction. This suggests that available carbon moderates the impact of N_2O emissions, while methane (CH_4) emissions increased in all treatments regardless of P addition. In contrast, cumulative CO_2 emissions were higher in treatments with the addition of P, such as nutrient-rich concentrate and pig slurry, which have higher carbon mineralization rates. This indicates that the addition of P stimulates soil respiration, leading to increased CO_2 emissions.

This is one of the first studies highlighting P and C's key role in the GHG dynamics within terrestrial ecosystems. These findings advance knowledge about effective management strategies underpinning the optimised use of N, C and P inputs to agricultural soils as mitigation measures for food security and reducing GHG emissions.

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NUTRIBUDGET, OPTIMISATION OF NUTRIENT BUDGET IN AGRICULTURE: THE MEDITERRANEAN PILOT

Laura Díaz-Guerra[1*], Yasmina Chourak[1], Natasha Manyenga[1], Sergio Martínez-Campos[1], Meritxell Abril[1], Rosa Vilaplana[1], Laia Llenas[1], Lorenzo Proia[1]

1 BETA Technological Center, University of Vic – Central University of Catalonia, Vic (Barcelona), Spain.

** Corresponding author, E-mail: laura.diaz.guerra@uvic.cat*

Nutrients such as nitrogen (N) and phosphorus (P) play an essential role in agriculture but the rise of the machines and the use of mineral fertilizers in the past decades have negatively affected water, air, and soil quality, as well as its biodiversity also contributing to climate change. To address this, the European Commission's Green Deal aims to reduce nutrient losses and fertilizer use at least 50% and 20%, respectively by 2030.

With the objective of optimizing nutrient flows and reduce pollution without compromising food production in agriculture, the Horizon Europe project NutriBudget will develop and implement an integrated nutrient management platform, called Nutriplatform, as a decision-support tool for farmers, advisors, policy makers and regional authorities. The Nutriplatform will be grounded on knowledge from existing and new field-tested agronomic measures to mitigate nutrient losses from agriculture combined with cutting-edge models on nutrient budgets, data standards and indicators. Thus, a wide range of mitigation measures to shrink nutrient losses from agricultural-farming systems are being tested in 5 pilot regions (4 nutrients hotspots and 1 nutrients-deficient) distributed along 4 different climatic regions: Boreal (Finland), Atlantic (Belgium), Mediterranean (Spain), Continental + nutrient surplus (Italy), and Continental – nutrient deficient (Switzerland).

BETA Technological Center (UVIC-UCC) is the coordinator of the pilot regions and the leader of the Mediterranean pilot located in Catalonia (Spain), where the main challenge is the soil and water pollution (mainly nitrates) due to excessive application of waste from pig farming. In this context, on-farm experimental work is carried out to identify and evaluate novel combinations of the most effective mitigation strategies evaluating its impacts on nutrient budgets, environmental pressures, agronomic production, and climate change mitigation potential. Specifically, 5 mitigation measures are being tested in this pilot, which are:

- Precision fertilization of bio-based fertilizers and/or mineral fertilizer through multilevel data integration
- Advanced NH_3 emissions mitigation using zeolites
- Dual-purpose Lemna cultivation (green manure production and alternative protein)
- Enhanced and optimised fertilisation with upgraded pig manure products to avoid nutrient excess in soils
- Deep-rooted nutrient cycling with Kernza perennial cereal to mitigate nutrient losses to soils and groundwaters

The data set obtained from these mitigation measures, along with those tested in the other 4 pilots, will provide a valuable knowledge from which the Nutriplatform will be developed. Thus, NutriBudget will help agriculture to intensify sustainably by systemically optimizing nutrient flows and budgets across different agricultural production systems and regions in the EU, to limit and reduce pollution provoked by nutrient losses from agriculture without compromising food production.

Acknowledgments: NutriBudget is a Horizon Europe project (ID 101060455) funded by the European Union.

Website: https://www.nutribudget.eu/

A NOVEL TECHNOLOGICAL APPROACH FOR PHOSPHOROUS RECOVERY FROM CHEESES WHEY BY COMBINING ANAEROBIC DIGESTION WITH CONCENTRATION TECHNOLOGIES

Ipan Hidayat, Lidia Paredes, Laia Llenas

BETA Technological Center (TECNIO Network). University of Vic - Central University of Catalonia (UVic-UCC), Carretera de Roda 70, 08500 Vic, Spain.

The ever-increasing demand for phosphorus-based fertilizers to secure global food production, coupled with finite phosphate rock (PR) reserves, is one of the emerging challenges in Europe. PR was listed as a critical raw material in the EU which triggering attention to find alternative sources to potentially replace the use of this limited resource. To address this challenge, the EU has prioritised the recovery and recycling of nutrients such as phosphorus (P) and nitrogen (N) from secondary raw materials to reduce dependence on imported and unsustainable P- and N-based fertilizers and to decrease the agricultural demand for synthetic fertilizers.

The current scenario opens opportunities for the dairy processing industry to innovate in P recovery by adapting technologies and new strategies for the proper management of dairy processing wastewater (DPWW) that minimize P losses while benefiting from emerging market opportunities. In this sense, the composition of cheese whey, characterized by a high content of organic matter (71-119 g COD/L), nitrogen (1.6-2.7 g NKT/L) and phosphorus (0.38-0.46 g TP/L), demonstrates its potential as a fertilizer product. However, its direct use as a fertilizer is limited by government regulations, being necessary to examine suitable processes based on a holistic approach to produce agronomic value products.

In the framework of the REFLOW project [1], BETA Technological Center evaluated the application of an innovative technological solution based on an anaerobic membrane bioreactor (AnMBR) coupled with a freeze concentration system (FC) for the recovery of P from cheese whey and, consequently obtain a nutrient-rich concentrate with agronomic value to be applied directly as a bio-based fertilizer in field crops.

The technical assessment of the innovative technological approach based on AnMBR coupled with FC for the treatment of CW allowed to achieve a complete valorisation scheme considering 3 relevant vectors: energy – biogas production; water – recovery of water with potential for reuse, and nutrients – obtaining a nutrient-rich concentrate. The nutrient-rich concentrate obtained at the optimal operational conditions was characterized by 12% by mass of total N, 2.2% by mass of total P_2O_5 and 2.5% by mass of total K_2O. Taking into account its composition and the quality requirements in terms of nutrients content established in the Regulation (EU) 2019/1009 on EU fertilizing products, the nutrient-rich concentrate was classified as PFC 1 (A) (II) (liquid organic fertilizer). In addition, this product fulfilled with the safety requirements for metals and pathogens established in this regulation for its potential use as a bio-based fertilizer.

Overall, the innovative application of AnMBR coupled with FC for CW valorisation is a promising technological approach for nutrient recovery that could contribute to ensure the long-term availability and accessibility of sustainable fertilizing products.

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A PROTOTYPE OF PRODUCT ENVIRONMENTAL FOOTPRINT CATEGORY RULES FOR ALTERNATIVE FERTILISING PRODUCTS FROM SECONDARY RAW MATERIALS

Karetta Vikki[1], Jorge Senán-Salinas[2], Pasi Korkalo[1], Heusala Hannele[1], Carlos Alberto Torres Guerrero[2], Nancy Peña[2], Joan Colón[2]

[1]*LUKE, Finland Natural Resources Institute Finland, Bioeconomy and environment / Sustainability science and indicators, Latokartanonkaari 9, FI-00790, Helsinki, Finland*

[2]*BETA Technological Center, University of Vic—Central University of Catalonia, Ctra. De Roda, 70, 08500 Vic, Spain*

Promotion of fertilising products from secondary raw materials (e.g. Bio-based fertilisers, BBFs) is a key element in the Farm-to-fork strategy, and European Green Deal to reduce the dependency on mineral and fossil fertilisers. The promotion of the most environmentally effective products in the market will guarantee environmental protection. For that purpose Life Cycle Assessment (LCA) methods had been pointed out as one of the most suitable and complete tools for that purpose. In particular, the European Commission has created the Product Environmental Footprint (PEF) initiative that aims to create a harmonised framework for sectorial Rules summarised in Product Environmental Footprint Category Rules (PEFCR). The present aims to show the first proposal for a PEF-wise Product Category Rules (PCR) for BBFs. For its development, a review of the scientific literature has been done and methodologies were adapted to the normative constraints of PEF. Other normative frameworks such as Environmental Product Declarations and specific category rules were consulted. Some of the decisions covered by the PEF-wise PCR method for BBFs are the definition of the Functional Unit (FU), system boundaries, emission allocation rules and adaptation of the Circular Footprint Formula. The BBFs are intermediate products with very heterogenous product group of the agricultural systems and embedded in other supply chains. Therefore, the first proposal is to create a PEF-wise PCR method from the feedstock and raw material acquisition to the processing of BBF’s and distribution until the farm/retail (Cradle-to Farm gate).As a separate second part of the first proposal is to give guidance how to revise the inclusion of the application stage in other food products PEFCRs. The FU should be the mass of the fertiliser (i.e. 1 kg of BBF). However, this approach seems limited to the final aim of PEF which is the creation of environmental standards for guiding the consumer's decisions. This simplification would omit the differences in the nutrient capacity of the BBFs and their efficiency among others. Therefore, the solution proposed is the use of complementary FUs (such us 1 kg of P2O5-eq) to give some insight on emission and nutrient efficiency related to application stage and to enhance comparability between BBF’s. Nonetheless, there are technical limitations, such as the variability of the application stage and agronomic performance indicators. Finally, a critical assessment of this normative adaptation revealed 7 methodological challenges in the creation of a suitable and useful mechanism for the emerging sector of the alternative fertilising products in PEF framwork.

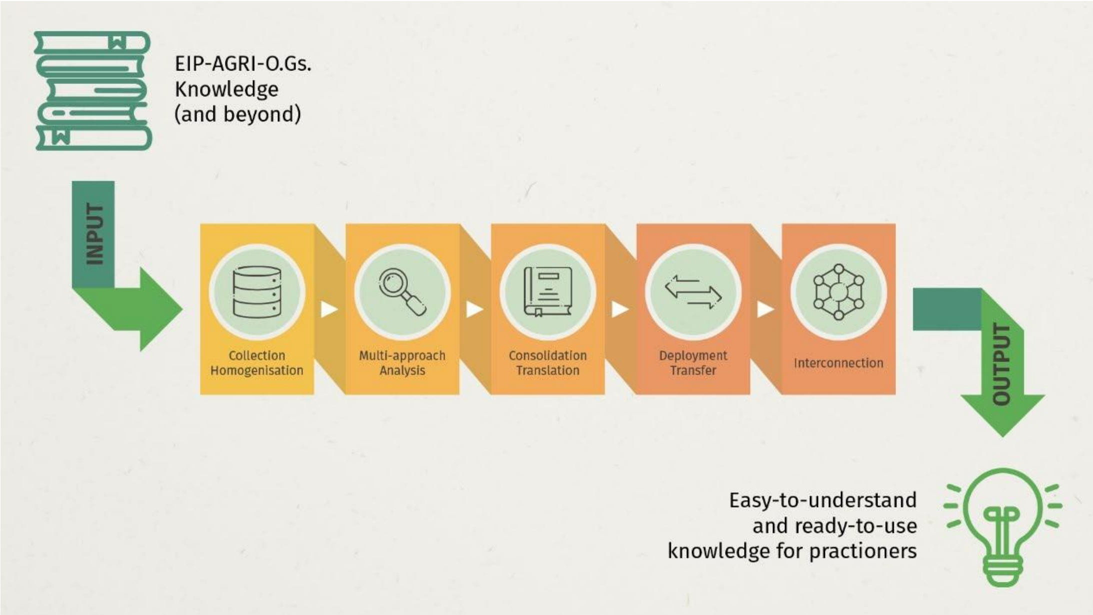
NUTRI-KNOW: EXCHANGING EASY-TO-UNDERSTAND NUTRIENT MANAGEMENT KNOWLEDGE WITH FARMERS

Anna Bagó-Mas[1], Víctor Carbajal Perelló[1]

[1] *BETA Technological Centre, Universitat de Vic-Universitat Central de Catalunya (UVic-UCC), Vic, Spain*

In recent years, several Operational Groups (OGs) have generated a substantial wealth of knowledge on technologies, products, recommendations, and best practices in nutrient management. However, the expected adoption of these new and improved management strategies by practitioners has not materialised. The primary objective of the NUTRI-KNOW project is to increase the impact of OG results on nutrient management to modernise and dynamize the agricultural sector. This will be achieved by collecting, translating, and disseminating practical and easily understandable knowledge. NUTRI-KNOW will ensure the effective adoption of OG results and experiences by farmers, practitioners, and other relevant end-users. To achieve this goal, NUTRI-KNOW strategically involves 12 EIP-AGRI OGs from four Member States (Spain, Italy, Belgium, and Ireland), with at least one consortium partner associated with each OG. These projects span the entire nutrient management value chain, encompassing livestock farming, storage systems, processing technologies, fertiliser production, transport, and application.

The NUTRI-KNOW methodology comprises five key steps: (1) Comprehensive data collection and analysis of outcomes from the engaged OGs, (2) Multi-approach analysis to establish a strong baseline of the current situation, including policies, farming practices, needs, and challenges, (3) Consolidation and translation of knowledge into farmer and practitioner-friendly language, (4) Dissemination and transfer of practice-oriented materials through channels commonly used by farmers and (5) Connecting stakeholders and regions by creating a Community of Practice. Ultimately, NUTRI-KNOW's wealth of knowledge will lead to the development of a Results Amplification Methodology that will serve as a guideline for effectively scaling and broadening project outcomes in any theme of interest. With this approach, NUTRI-KNOW aims to bridge the knowledge-to-application gap, fostering a sustainable and dynamic agricultural sector.


EIP-AGRI-O.Gs.
Knowledge
(and beyond)
INPUT
Collection
Homogenisation
Multi-approach
Analysis
Consolidation
Translation
Deployment
Transfer
Interconnection
OUTPUT
Easy-to-understand
and ready-to-use
knowledge for practioners

USE OF DUCKWEED (*LEMNA SP.)* FOR RECOVERY AND VALORIZATION OF PHOSPHORUS FROM PIG MANURE AND URBAN WASTEWATER

Martínez-Campos Sergio[1], Uroz Meritxell[1], Junca Neus[1], Seguí Cristian[1], Rovira Anna[1], Manyega Natasha[1], Bertrans-Tubau Lluis[1], Proia Lorenzo[1], López-Doval, Julio[1] & Abril Meritxell[1]

1 BETA Technological Centre- University of Vic- Central University of Catalunya (BETA-UVIC- UCC), Carretera de Roda 70, 08500 Vic, Barcelona, Spain

As a consequence of the nutrient imbalances caused by several human activities, which have led to exceeding the planetary boundaries for Nitrogen (N) and Phosphorus (P), over the last few decades, the concept of sustainability and circularity has become increasingly entrenched, especially in nutrients management plans and policies. P is a fundamental chemical element for life that is non-substitutable for food production and is essential for agriculture. On the other hand, there is rising evidence about a growing shortage of phosphorus at the planetary scale. The fertilizer industry is the main consumer of this resource, and the concern is growing because it is estimated that it could be exhausted within this century. It is estimated that at least 17% of P is lost through wastewater, and this percentage increases in the case of pig slurry, where it is estimated that 20% is phosphorus.

This P loss can lead to significant environmental impacts on terrestrial and aquatic ecosystems (i.e. eutrophication) Current tertiary treatments of wastewaters and advanced treatments of pig slurry focus more on nitrogen removal, such as nitrification and denitrification systems (NDN), but rarely seek the recovery and valorization of these nutrients.

Nature-based solutions (NBS) offer a great opportunity to boost the circularity of nutrients currently lost through urban and farming. NBS for wastewater treatment consists of low-cost and sustainable systems that, when properly applied, allow for the recovery and valorization of nutrients. Among these solutions, we tested the efficiency of the floating macrophyte *Lemna sp.*, which has shown a potential P removal rate of about 80-84%, which is directly uptaken by the plants from wastewater and incorporated in its biomass. This allows its reuse as a slow-release green manure or alternative protein, thanks to its high nitrogen removal capacity (90%).

This talk will present results from three projects investigating the potential of *Lemna sp.* for nutrient recovery to reduce P losses from pig slurry and urban wastewaters also focusing on the valorization potential of the nutrient-rich biomass harvested. The Horizon Europe Nutribudget project aims to valorize the liquid fraction of pig slurry previously treated with an NDN technology to harvest duckweed biomass and test its potential as a green manure fertilizer. The Lemna project (funded by the Catalan Government) aims to evaluate the potential of a pilot plant installed in a farm to recover nutrients from the liquid fraction of pig slurry using *Lemna minor* over one year, allowing for the assessment of its efficiency to recover P and the potential application as green-manure or as an alternative protein source for the animal feed industry. Finally, the outcomes of the national funded project Frenawaste will be presented showing results about the potential of Lemna sp. as nature-based tertiary treatment system to recover P from urban wastewater.

In particular, experiments carried out in these projects with *Lemna sp.* under laboratory conditions and at a pilot scale demonstrated *Lemna gibba* can remove up to 70% of P in 7 days. In the same time frame, these trials also confirmed that P is directly taken up by the plants and incorporated into its biomass resulting in an increase of the P content in duckweed biomass of about the 404 % of the initial content in only 7 days.

ENHANCING THE PHOSPHORUS AVAILABILITY IN AQUACULTURE-SLUDGE BASED FERTILIZERS USING CHEMICAL AND BIOLOGICAL STRATEGIES

Miguel Martínez-Quintela1, Dalila Bonanno2; Berta Singla1; Pablo M. Binder1, Joaquin Romero2, Lidia Paredes1, Nagore Guerra-Gorostegui1

1.BETA Technological Center – University of Vic, Carretera de Roda, 50, Vic –Barcelona
2.University of Catania, Department of Civil Engineering and Architecture, Catania
3.Fertinagro Biotech, Pol. Ind. Los Llanos, Utrillas – Teruel

Keywords: aquaculture sludge, bio-based fertiliser, biomass-fuel, biorefinery.
Presenting author email: miguel.martinez@uvic.cat

The fast-growing aquaculture industry, producing 46% of the global fish consumption, generates significant waste, including animal by-products and sludge, such as those coming from recirculating aquaculture systems (RAS). To comply with the New European Circular Economy Plan, this work assessed the production of valuable bio-based fertilisers (BBFs) from a starting biodrying process of RAS-sludge, coupled with different innovative post-processing technologies. The biodried RAS-sludge demonstrated to have a substantial total P-content (4.31% as P2O5), but a low phosphorus bioavailability (15% of soluble phosphorus). Two strategies were proposed to tackle this issue: i) chemical and biological solubilisation of phosphorus; ii) thermal treatment and chemical phosphorus recovery from ash by acidic treatment.

The experimental design of phosphorus solubilisation trials directly with the biodried product were performed via incubation tests. Soil incubations (150 g of low-nutrient soil + 3 g of biodried product) were performed for 30 days in controlled temperature and humidity conditions. Chemical and biological solubilisation of phosphorus was assessed by adding either sulphuric acid (10% addition at 96% m/v) or biological inoculum composed by Pseudomonas putida at different dosing (104-106 CFU/g of soil).

After complete combustion of biodried RAS-sludge product, the acidic phosphorus extraction from ash was performed. First, a screening of optimal operational conditions was performed using different concentrations of sulphuric and citric acid (1 M, 0.75 M, 0.5 M and 0.25 M) at 1 to 20 ash to acid ratio. Concentration of acids was selected after the elemental analysis of ash and following the stoichiometric acid requirement (Donatello et al., 2010). After 2 h extraction at continuous stirring at ambient temperature (25ºC), 80% of phosphorus recovery was achieved with the most concentrated sulphuric acid while over 50% was achieved with sulphuric acid at 0.25M. Over 40% of phosphorus was recovered with the most concentrated citric acid solution (1 M).

To conclude, this work demonstrated the satisfactory enhancement of the quality of RAS-sludge derived biodried product in terms of phosphorus availability.

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DYNAMICS OF PHOSPHORUS SOIL CONTENT IN A LONG-TERM DOUBLE-ANNUAL CROPPING EXPERIMENT FERTILIZED WITH PIG SLURRY

J. Ovejero[a], C. Ortiz[b], E. Arqué[b], X. Serra[a], C. Casas[a].

[a] *BETA Technological Centre. University of Vic – Central University of Catalonia Futurlab - Can Baumann Ctra de Roda, 70. 08500 Vic, Barcelona*

[b] *Soil Service and Environmental Management of Agricultural Production. Department of Climate Action, Food and Rural Agenda. Generalitat of Catalonia. Avda, Alcalde Rovira Roure 191, E-25198 Lleida, Spain.*

Combining a summer crop after a winter crop, both for forage purposes, is a common strategy used to optimize the use of manure in sub-humid regions, although it is strongly conditioned to spring and summer rainfall. This paper aims to assess the effects on phosphorus (P) dynamics after long-term fertilization with pig slurry (PS) following the nitrogen (N) criteria, on a double crop forage strategy. Two crop rotations were combined during an 18-year period: mmaize-triticale (2006-2011) and sorghum-barley (2012-2023). Four N fertilization treatments (T1: 0 kg N ha-1 year-1, T2: 170 kg N ha-1 year-1, T3: 250 kg N ha-1 year-1 and T4: 330 kg N ha-1 year-1) were applied in each rotation. Soil samples at three depths: 0-0.3, 0.3-0.6, and 0.6-0.9 m were collected in 2006, 2011, 2016, 2021, and 2023, in each plot. Soil available P content was analyzed in all of them (Olsen method).

Within the first sampling period (2006-2011), available P increases with the PS rate in the upper layer (0-30 cm). Such an increase is not observed in the layer below (30-60 cm), probably because of the P uptake from crops. In the following sampling period (2011-2016), P content is strongly reduced, even at the higher fertilization rates, which is likely explained with the lower P inputs during this period as well as the higher uptake from the crops. Available P content slightly rises again in the next sampling period (2016-2021) as P inputs increase. Finally, the last sampling period (2021-2023) coincided with a 3-year drought episode, which reduced the crop P uptake and resulted in an increase in available P content in all three fertilization strategies.

The variability of P content and N:P ratio in PS, as well as the wide-ranging rainfall in rainfed conditions, have a deep influence in the soil available P content. In this long-term experiment, the optimal N fertilization rate (170 kg N ha^{-1} yr^{-1}) proved to be also the most sustainable P strategy, as available P soil content remains at the same level after almost two decades of continued PS applications. Phosphorus mining from double cropping systems is about 1.2 mg kg^{-1} yr^{-1}, according to an average yield of 8 t DM ha^{-1}.

PHOSPHORUS USE EFFICIENCY AND GENETICS OF BREAD WHEAT

Degan Francesca[1], Creze Alexia[2], Bogard Matthieu[2], Brandt Yann[3], Helias Regis[3], Cohan Jean-Pierre[4]

[1] Arvalis – Institut du végétal – Villiers-le-Bâcle (France)
[2] Arvalis – Institut du végétal – Baziège (France)
[3] Arvalis – Institut du végétal – Montans (France)
[4] Arvalis – Institut du végétal – La Jallière (France)

Phosphorus (P) is a critical macronutrient for optimal plant growth and yield, yet its availability in soil often constrains crop production (Schoumans et al., 2015). To enhance P utilization efficiency (PUE) in wheat, a key cereal crop, understanding the genetic and environmental factors influencing P acquisition and utilization is essential. This study investigated the relationship between PUE, genotype, and environmental conditions across four field trials conducted in France during 2021 and 2023. A panel of 199 winter wheat genotypes was evaluated for various PUE-related traits, including grain yield, P uptake, and shoot P concentration. To account for spatial variability in soil P availability, soil samples were collected and analyzed for Olsen P. Mixed linear models were employed to analyze the data, considering genotype, environment, and their interaction effects. Our results revealed significant genotypic variation for PUE-related traits, indicating the potential for genetic improvement. Vegetation indices, particularly the red edge chlorophyll index, demonstrated a positive correlation with grain yield, suggesting their utility in identifying P-efficient genotypes (Rose & Wissuwa, 2012). while the commonly used NDVI displayed lower correlation values.
Correlation graphics between the normalized deviations of the Area Under the Curve for each of vegetation indices dynamics illustrated notable disparities in AUC deviations, ranging from 30 to 70% and from -10 to 10% according with different trials. However, the strength of this relationship varied across sites, emphasizing the importance of considering environmental factors. Genome-wide association studies (GWAS) were conducted to identify genetic loci associated with PUE. A total of 120 single nucleotide polymorphisms (SNPs) were significantly associated with PUE-related traits, providing valuable insights into the genetic architecture of PUE in wheat. These findings contribute to our understanding of the complex interplay between genotype, environment, and PUE, and offer opportunities for developing P-efficient wheat

cultivars through marker-assisted selection. By elucidating the genetic basis of PUE and identifying key environmental factors, this research provides a foundation for improving P use efficiency in wheat production systems. This is crucial for sustainable agriculture, as it can help to reduce reliance on P fertilizers, mitigate environmental impacts, and enhance food security.

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EFFECTS OF BORDER CARBON REGULATION ON THE FERTILIZER SECTOR OF TÜRKİYE

Bahri Gündüz, Department Plant Nutrition of General Directorate of Plant Production of Ministry of Agriculture and Forest of Türkiye in Ankara, capital of TÜRKİYE

The Border Carbon Regulation Mechanism (CBAM), which the European Union (EU) has implemented to combat climate change, brings major changes in carbon-intensive production.

In order for fertilizer industry companies to comply with CBAM requirements, it is important to first develop strategies to reduce carbon emissions in their production processes.

The embedded carbon emissions of each chemical input used in production processes will play a critical role in determining the final carbon footprint of the product. Therefore, fertilizer manufacturers will need to update their emissions monitoring and reporting systems to comply with these new requirements.

All in all, the fertilizer sector will play an important role in this transformation process and contributes to the future of sustainable agriculture

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PHOSPHORUS RECOVERY TECHNOLOGY FROM VARIOUS SECONDARY SOURCES

Álvarez Carreño, Carlos

Pinedo González, María Teresa

Técnicas Reunidas S.A

Phosphorus (P) recovery and recycling play a crucial role in improving resource efficiency, sustainable nutrient management and moving toward circular economy[i]. In this context, after successfully developing Phos4life® technology for the recovery of P in the form of technical grade phosphoric acid directly from sewage sludge ashes and anticipating its first industrial implementation in the coming years, Técnicas Reunidas has decided to expand the range of inputs for this technology. Consequently, research and development work is being conducted at the Técnicas Reunidas José Lladó Technological Center in Madrid to adapt our phosphorus recovery technology capabilities in two ways: [i] evaluating the feasibility of using three different types of secondary raw materials, and [ii] producing various phosphorus-based final products for the agricultural and recycling industries.

Currently, research is examining emerging and advanced technological routes for phosphorus recovery from various secondary sources, such as sewage sludge, digestates (from anaerobic digestion of purines, sewage sludge from WWTP and plant material), and biochar (residue from thermal treatment for biogas production). The main objective is to validate and demonstrate the efficiency of recovering P from these routes using variants of the Phos4life® process, with a special focus on the fast-growing biogas market. Proper management of these secondary sources can not only mitigate pollution problems but also convert waste into valuable resources.

Characterization of Sources

Below is the characterization of the secondary sources being studied in terms of (P) content:

Raw Material Source	**P Content (%*)**
Sewage Sludge	2.8 - 3.7%

Digestates	1.7 - 3.1%
Biochar	4.3 – 8.6%

*dried weight

Solubilization Results by Leaching

The solubilization efficiency of P was evaluated and the results show as follows:

Raw Material Source	**P Efficiency (%)**
Sewage Sludge	53-87
Digestates	85-99
Biochar	34-91

Advances in Biochar Utilization

Digestate, a byproduct of anaerobic digestion rich in nutrients (especially N, P, K, and organic matter), can be used as a biofertilizer according to EU regulations and as soil conditioner, as observed by various authors. Despite the growing acceptance of anaerobic digestion, there are obstacles hindering its expansion in Europe. One of them is the heterogeneity of the raw material, which causes biological instability, reduces profitability, and hinders new projects. Moreover, its semiliquid nature, and the costs and time of transport from production to utilization points, limit its value.

In this context, the study has focused on biochar as a promising alternative to overcome these limitations. Biochar, produced from thermal treatment, offers a solution for the valorization of these residues more efficiently and profitably. Additionally, the thermal treatment processes can convert sludge into a more stable, significantly enriched in phosphorous and easy-to-transport material, reducing costs and logistical complexity associated with digestate use[ii].

A key aspect of this research is the comprehensive analysis of the problem, aiming not only to generate biochar under optimal conditions for subsequent P recovery but also to ensure that the thermal treatment processes produces syngas with the highest calorific value possible. Several trials at different thermal conditions and employing different catalysts have been conducted to improve this aspect, which could increase the energy efficiency and economic viability of this Phos4life® technology variant.

Conclusions

While the phosphorus recovery efficiencies obtained to date show promising results, it is still necessary to continue experimentation downstream of the PLS and evaluate the quality of the phosphorus products that could be obtained.

Further developments are needed to make the Phos4life® not only viable from technical point of view but also from economical side in a huge potential market for EU as Biogas.

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IMPROVEMENT OF PHOSPHORUS RELEASE FROM AND DEWATERING PERFORMANCE OF DAIRY CATTLE MANURE WITH PERSULFATE TREATMENT

Tian Zhao, Sidney Omelon

Materials Engineering, McGill University, Canada

Intensification is a modern agricultural practice that efficiently produces food for our increasing population. One of the many consequences of agricultural intensification is the production of large amounts of manure within small land areas. Although manure has a long history of land application as a fertilizer, its management and storage are challenging, as it contains a significant soluble inorganic orthophosphate (o-Pi) fraction that can cause eutrophication. Manure generated by Canadian animal stock in confinement pens is collected and ideally applied on local farmland to recover its nutrient and organic carbon value [1]. In Quebec – and all other Canadian provinces except Saskatchewan - manure application to agricultural land is in surplus [2].
Therefore, manure application density is regulated in some regions. Separation of leachable o-Pi from manure would reduce this eutrophication risk.

The proposed manure processing method was inspired by persulfate treatment, which is commonly used for digestion to quantify total P in municipal wastewater samples [3]. Persulphate activation by heat, UV light, and/or metal ions generates oxidative sulfate radicals that release bound o-Pi and degrade extracellular organic polymers. Organic polymer degradation decreases manure viscosity and improves its solid-liquid separation efficiency. This oxidation process converted viscous manure to an easy-to-manage filter cake of undigested plant solids and an o-Pi and nitrogen-rich solution. The filter cake can be dried and used as bedding. The nutrient solution could be concentrated or further processed to precipitate phosphorus and nitrogen fertilizers.

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OPTIMIZATION OF HEAT-TREATED WASTE CONCRETE POWDER TO REDUCE DISSOLVED PHOSPHATE CONCENTRATION THROUGH ADSORPTION

Tian Zhao, Sidney Omelon

Materials Engineering, McGill University, Canada

Phosphorus (P) release and runoff into natural waters is one of the leading causes of eutrophication, which jeopardizes the local ecological system and leads to greenhouse gas emissions. There has been an increasing trend of applying solid waste to treat environmental pollutants. Concrete-based materials are an economically practical option for water treatment to reduce the dissolved inorganic orthophosphate (o-Pi) concentration [1, 2]. Waste concrete is an abundant, cost-effective material because of its use in urbanization. The cement fraction of waste concrete is rich in calcium and alkalinity and, therefore, has the potential to be an effective o-Pi absorbent. Soluble o-Pi in a water-waste concrete mixture has the potential to form calcium phosphate solids through chemisorption and precipitation.

Heat treatment can improve the adsorption efficiency of waste concrete powder [3]. Limited studies have evaluated the relationship between the degree of waste concrete decarbonization and o-Pi reduction efficiency. Calcium carbonate in waste concrete converts to calcium oxide at temperatures above 760 °C. This heat treatment also increases the alkalinity and leachable Ca2+ ion concentration of decarbonated waste concrete. Design and Experiment (DoE) and response surface methodology (RSM) were applied to evaluate the significance and interaction of the heat treatment factors (initial phosphate concentration, concrete powder addition amount, concrete CaCO3 conversion %) and then optimize the o-Pi concentration reduction with heat-treated waste cement. The optimal decarbonated concrete and o-Pi mixture conditions resulted in an o-Pi adsorption capacity of 6.1 mg P·g-1, reaching 92 % o-Pi concentration reduction within 6 hours at room temperature. The o-Pi concentration reduction and adsorption mechanisms with decarbonated waste concrete powder were investigated using surface characterization techniques. Concrete surface calcium phosphate precipitation (as amorphous calcium phosphate and/or hydroxyapatite) was identified with Raman spectroscopy.

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ENHANCED PHOSPHATE ASSIMILATION BY HOP PLANTS DRIVEN BY PSEUDOMONAS STRAINS

Seyedehtannaz Ghoreshizadeh[1,2], Carla Calvo-Peña[1,2], Marina Ruiz-Muñoz[1], Rebeca Otero-Suárez[1], Juan José R. Coque[1,2] and Rebeca Cobos[1,2]

[1]*Instituto de Investigación de la Viña y el Vino. Universidad de León*

[2]*Área de microbiología, Departamento de Biología Molecular. Universidad de León*

Phosphorus (P), an essential nutrient for plant growth, is often applied to agricultural soils in form of chemical fertilizers. Unfortunately, most of this P precipitates as insoluble salts, rendering it inaccessible to plants.

In this study, phosphate-solubilizing bacteria (PSB) from the rhizosphere of hop plants were isolated and characterized. The rhizosphere is a rich source of microorganisms with potential agronomic benefits. Among the isolated strains, two were selected: *Pseudomonas taetrolens* ULE-PH5 and *Pseudomonas* sp. ULE-PH6. These strains exhibited remarkable phosphate solubilization capabilities in both plate assays and liquid culture.

In addition to phosphate solubilization, these bacterial strains demonstrated other beneficial traits. They produce auxins, hormones that promote plant growth, and siderophores, molecules that facilitate iron absorption by plants. Furthermore, the strains showed the ability to degrade phytate, an organic form of phosphorus, and produce acid and alkaline phosphatases, enzymes involved in phosphate mineralization. These characteristics highlight the potential of these bacteria as effective plant growth-promoting rhizobacteria (PGPR).

To assess the practical implications of these findings, greenhouse pot trials were conducted with hop plants inoculated with the selected bacterial strains. The results were promising, with significant increases observed in phosphate uptake and phosphorus accumulation in the aerial parts of hop plants, including stems, petioles, and leaves. This improvement in P assimilation suggests that the selected bacterial strains have the ability to enhance the nutritional status and overall health of hop plants.

The implications of these findings extend beyond hop cultivation. Given the widespread presence of insoluble phosphorus in agricultural soils, the use of PSBs has the potential to enhance nutrient availability and plant productivity in different crops. Furthermore, by facilitating the utilization of existing phosphorus reserves, these bacteria can contribute to mitigating environmental problems associated with excessive fertilizer application, such as water eutrophication.

Further research is needed to elucidate the mechanisms involved in the interactions between phosphate-solubilizing bacteria and plants. Additionally, field-scale trials are required to validate the efficacy of these bacterial strains under environmental conditions. The use of the identified phosphate-solubilizing bacteria in this study will lead to sustainable and resilient agricultural practices that optimize nutrient use efficiency and minimize environmental impact.

EFFICIENCY OF ALTERNATIVE PHOSPHORUS FERTILIZERS: EVALUATION OF POTENTIAL SYNTHETIC AND RECYCLED PHOSPHORUS ADSORBENTS

Iris Zohar[1], Irina Paluy[2], Guy Pe'er[1] , Hasan E. Ganem[1], Dafna M. DiSegni[3] and Adi Jonas-Levi[4]

[1]Department of Environmental Sciences, Tel-Hai College, Upper Galilee, Israel, [2]Migal – Galilee Scientific Research, Israel, [3]Department of Economics and Management, Tel-Hai College, Upper Galilee 12210, Israel, [4]Department of Food Sciences, Tel-Hai College, Upper Galilee 12210, Israel

Recycling of the essential macronutrient phosphorus (P) is required to ensure global food security. Recycling requires an alternative P source and efficient adsorbents. Ideal adsorbents should exhibit both high P capacity and enhanced P phyto-availability within the soil-plant system. Our goal was to identify a chemical configuration of P adsorbent that enhances P solubilizing activity by both roots and microorganisms, thereby boosting plant growth. We investigated two types of adsorbents: synthetic layered double hydroxides (LDHs) and recycled water treatment residuals (Fe-WTR and Al-WTR). Phosphorus sources were dairy wastewater (WW) and inorganic P (Pi) solutions (about 50 mg P L^{-1}). Physicochemical, biological, agricultural, and sustainability aspects were investigated.

Chemical behavior[1] - LDHs entirely removed P from dairy WW, while WTRs took 50–80%. WW-Fe-WTR had higher P solubility in soil solution-like extract than WW-LDHs, with 14-180 times more total dissolved P (TDP). Chemical and structural alterations occurred when mixing adsorbents with WW. LDHs rapidly adsorbed orthophosphate onto their porous Mg/Al-oxide surfaces, while WTRs contained diverse inorganic and organic P forms associated with heterogeneous entities (oxides, calcite, silicates, and Ca-P minerals). *Soil microorganisms' responses* – In soil incubation (without plants), Pi- and WW- LDH and Fe-WTR yielded the same sequence of soil biological responses, including exudation of malic acid followed by elevation of enzymatic activities (phospho-di- and mono-esterase) and late nitrification. The WW-Fe-WTR had a significantly higher P solubility, likely contributing to enhanced microbial P and stimulating biological activity. Re-wetting probably affected the initial microbial activities, producing labile P and C in microbial cells for continuous growth. *Soil-plant system*[2] - In a lettuce growth experiment, WW-Fe-WTR exhibited comparable performance to commercial fertilizer whereas WW-LDH-lettuce showed poor growth. Yet, the cellular concentrations of P and related elements in WW-LDH were equal to or higher than treatments of higher biomass. Moreover, the high correlation between soil application dose of WW-Fe-WTR and lettuce biomass suggests that soil P phyto-availability better predicted lettuce growth than P cellular concentrations, implying carbon assimilation was connected to root signaling. Metabolic analysis revealed WW-LDH lettuce contained reduced levels across all groups, including the carbohydrates. We deduced that carbohydrates (i.e., sugars), produced during photosynthesis and provide building blocks for other metabolite groups, were translocated to the roots to enhance the microbial activity of P dissolution. The chemical nature of WW-LDH, i.e., strong sorption capacity of organic molecules and P, probably accounts for failure in enhanced P solubility in the treated soil. The results suggest that synthetic adsorbents such as the WW-LDH used in this study are not adjusted for efficient application in the soil-microbiota-plant system in their current form, while P sorbed onto the recycled heterogeneous WW-Fe-WTR was accessible and supported plant growth.

WW-Fe-WTR production costs were 160 times lower than WW-LDH's, while recycling P from waste has direct savings of €935/ton. Dairy WW served as a P-rich source, and its organic content enhanced P lability in the Fe-based adsorbent. WW-Fe-WTR serves as an optimal P adsorbent, contributing to circular economy solutions and sustainable agriculture.

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EFFICIENT AND SUSTAINABLE WASTEWATER TREATMENT: UNVEILING THE POTENTIAL OF SIMULTANEOUS NITRIFICATION, DENITRIFICATION, AND PHOSPHORUS REMOVAL (SNDPR)

Johanna Korte, Dorothee Göttert, Jan Dries

BioWAVE, Biochemical Wastewater Valorization and Engineering, Faculty of Applied Engineering, University of Antwerp

Phosphorus (P) removal from wastewater is crucial for protecting aquatic ecosystems from excess nutrient loads, mitigating eutrophication. Meanwhile, P represents an urgently required resource, emphasizing the need to recover P from wastewater.

Enhanced Biological Phosphorus Removal (EBPR) is an emerging process with the potential to replace the chemical precipitation of P as a state-of-the-art technology, as it eliminates the use of cost-intensive chemicals and increases the potential for P-recovery from wasted sludge. It relies on polyphosphate accumulating organisms (PAOs), a group of bacteria able to enrich polyphosphate in their cells under anaerobic conditions [1].

However, the stability of EBPR is often limited by the availability of organic carbon, which is also required for denitrification, an essential step of biological nitrogen (N) removal. An elegant way to optimize carbon usage is simultaneous nitrification, denitrification, and phosphorus removal (SNDPR). Based on denitrifying PAOs, a fraction of PAOs that can utilize nitrite and nitrate as electron acceptors to take up P under anoxic conditions [2], this process occurs in aerobic granular sludge (AGS), when anoxic conditions are maintained in the centers of dense granules within an aerobic environment [3]. Consequently, dissolved oxygen (DO) concentrations as low as 0.5 mg/L can be sufficient for nutrient removal through SNDPR. With the aeration accounting for 50 – 65 % of the net energy consumption of wastewater treatment plants [4], the significantly reduced oxygen demand represents another major benefit of AGS.

The conducted experiments show that denitrifying PAO activity can be established in an activated sludge system through a suitable environment. An 11 L Sequencing Batch Reactor (SBR) was seeded with flocculent sludge from a municipal wastewater treatment plant containing PAO activity. The treatment cycle was specifically designed for SNDPR, implementing an anaerobic step to create a selective environment for PAOs, followed by an extended aerated reaction period with an average DO of

0.5 mg/L, allowing the required intragranular oxygen gradients. The COD/N and COD/P ratios of the synthetic medium were 15 and 50 respectively, with sodium acetate and sodium propionate making up each 50 % of the COD. AGS developed within 8 weeks (Figure 1), and complete N and P removal were achieved (Figure 2). Batch tests with individual electron acceptors demonstrated that biological P removal took place utilizing nitrite and nitrate. The P uptake rates utilizing DO, nitrite, and nitrate were 7.48, 3.59, and 1.98 $mg_P/(g_{VSS}h)$ respectively. In particular, the utilization of nitrite improved in comparison to the flocculent seed sludge. Moreover, the reactor showed almost no accumulation of the greenhouse gas nitrous oxide (N_2O), often associated with SNDPR [2].

Comparable experiments were performed treating high-strength industrial wastewater with sodium acetate as an external carbon source. While the time required to cultivate AGS was considerably longer, and the P release and uptake rates were lower, an equivalent shift of the preferred electron acceptor from DO to nitrite could be observed. The SBR treating industrial wastewater was further characterized by more distinct emissions of N_2O, which requires further investigation.

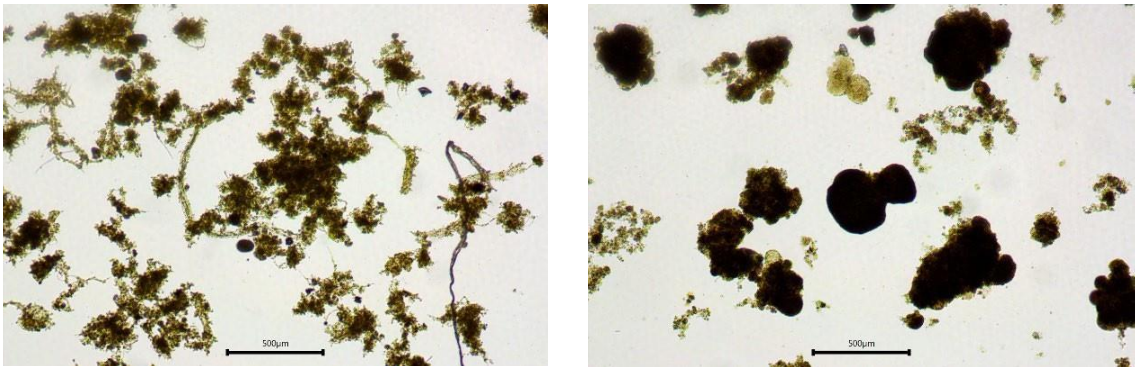

Figure 1. Seed sludge (left) and the sludge in the SBR after 56 days (right), scale bar = 500 µm

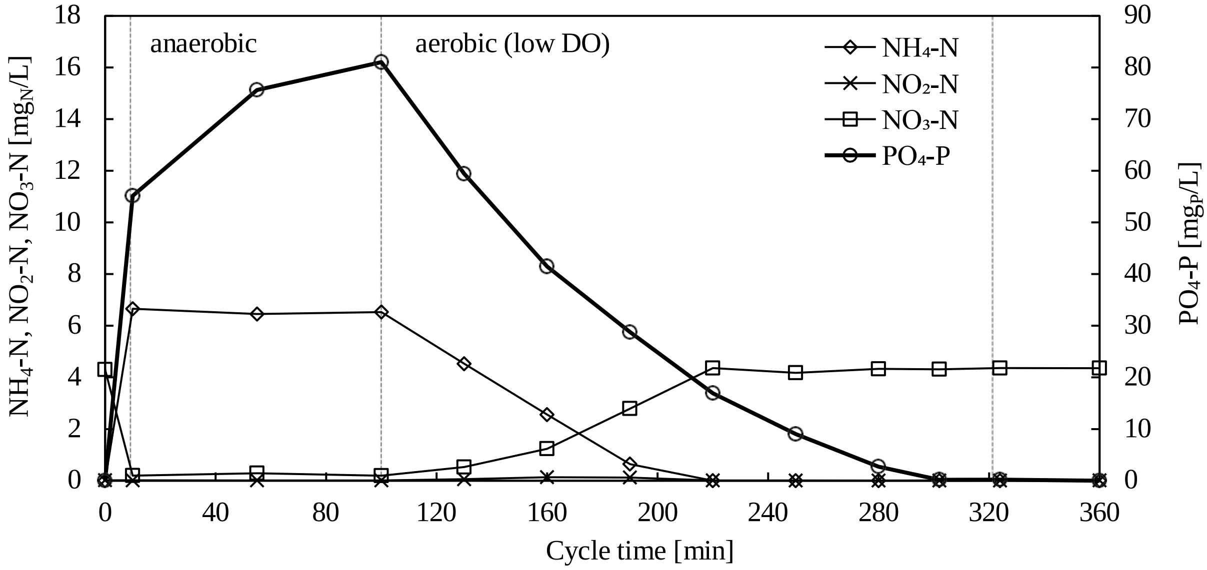

Figure 2. Development of ammonia (NH_4-N), nitrite (NO_2-N), nitrate (NO_3-N), and phosphate (PO_4-P) throughout a 6h reactor cycle

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IMPROVING PHOSPHORUS USE EFFICIENCY ON RAINFED CEREAL IN THE EBRO VALLEY

M. Colomina-Garcia[a] M.R. Teira-Esmatges[b] and C. Ortiz-Gama[c]

[a]*Department of Agricultural and Forest Sciences and Engineering - Agrotecnio-CERCA Center, Universitat de Lleida (UdL), Av. Alcalde Rovira Roure 191, E-25198 Lleida, Spain.*
marc.colomina@udl.cat
[b]*Department of Chemistry, Physics and Environmental and Soil Sciences Department, UdL.*
rosa.teira@udl.cat
[c]*Ministry of Climate Action, Food and Rural Agenda, Government of Catalonia.*
carlos.ortiz@gencat.cat

Improving phosphorus use efficiency (PUE) is necessary to address phosphorus (P) management challenges, especially when using organic biowastes. The aim of this work is to improve P management on rainfed cereal systems in the Ebro Valley (NE Spain).

An on-farm rainfed cropping system (RCS) in Agramunt (Lleida, NE Spain) was studied from 2017-2018 to 2022-2023. The experiment had a completely randomized blocks design with 3 replications. It was established to improve nitrogen management. In this abstract, the evaluated factor is the resulting annual application of different phosphorus rates with organic and mineral fertilisers. The effective applied rates were 0, 50, 86, 104, 168 kg $P \cdot ha^{-1} year^{-1}$. Barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.) and triticale (*Triticosecale Wittm*.), common winter crops in the area, were sown in the sequence barley-barley-barley-wheat-barley-triticale, preceded by a fallow year (2016-17). Straw was exported. Triticale was cut as forage due to drought. Soil was sampled (0-30 cm) to determine P-Olsen in October 2016 and July 2023. PUE was calculated.

A P annual rate around 50 kg $P \cdot ha^{-1}$ is enough to reach the maximum yield (Figure 1), and is significantly the most efficient in P use. The P rate that prevents the accumulation of P-Olsen in soil is 40 kg $P \cdot ha^{-1}$ (Figure 2). Figure 3 shows that P-Olsen must be in the range 20 to 40 mg P-Olsen$\cdot kg^{-1}$ to achieve the highest yield.

On RCS the P fertilization strategy which leads to the highest yield without P-Olsen accumulation is an annual application of 40 kg $P \cdot ha^{-1}$ with a soil P-Olsen of 20 to 40 mg P-Olsen$\cdot kg^{-1}$. More research is needed to assess the P environmental outcome of this nutrient fertilization strategy.

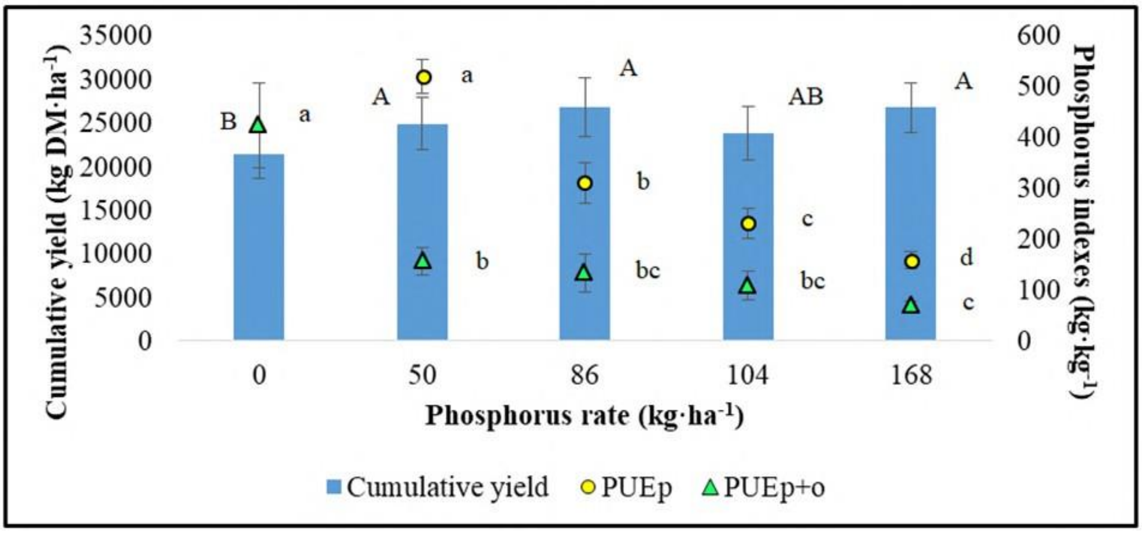

Figure 1. Cumulative dry matter yield (grain yield of 2018-2022 plus forage yield 2022-2023) and P indexes per rate, depending on the average applied P rate. Initial P-Olsen is not represented. PUE is calculated as the ratio between cumulative yield and P applied (PUEp), and P applied plus initial P-Olsen (PUEp+o). Bars indicate the standard deviation of the mean. For a given variable, means with different letters indicate treatment differences at $p<0.05$ (upper-case letters correspond to cumulative yield).

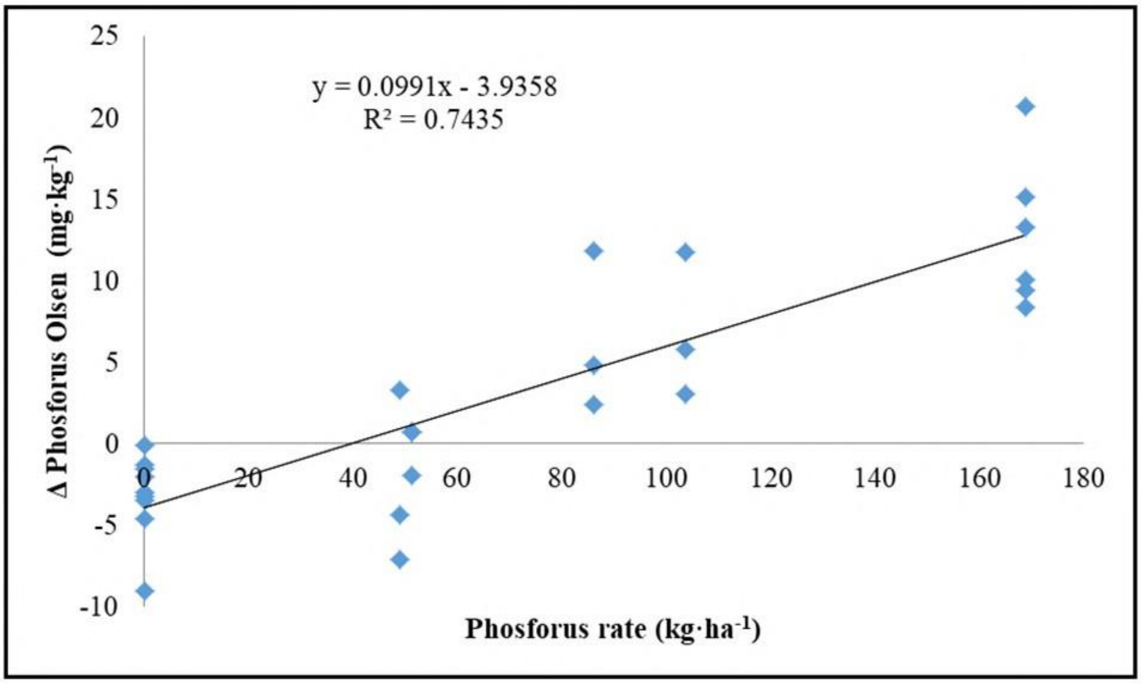

Figure 2. Variation of P-Olsen content for the studied period (2017-2023) per rate. The Δ P-Olsen is between soil P-Olsen content in July 2023 minus that in October 2016.

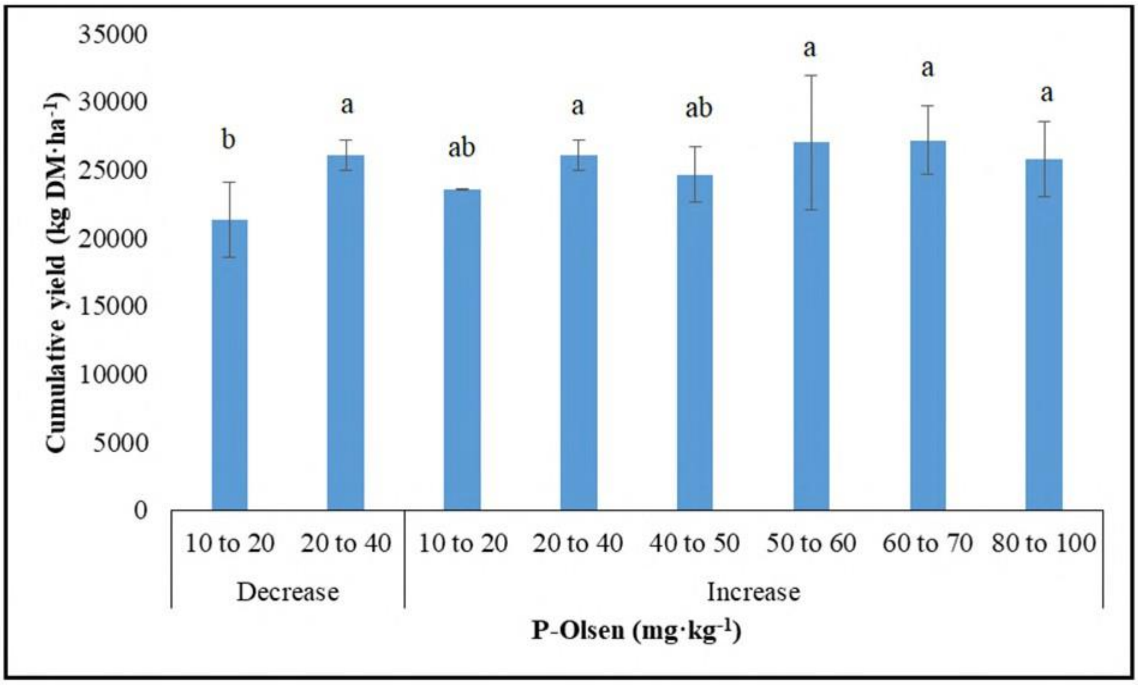

Figure 3. Cumulative yield related to soil P-Olsen content (through the studied period and expressed in ranges). The ranges 10 to 20 and 20 to 40 are repeated because on the left the soils with that content range decreased their P-Olsen in the period 2016-2023, and on the right, they have increased it.

IMPROVING PHOSPHORUS EFFICIENCY AND WHEAT YIELD IN ACIDIC SOILS BY BIOCHAR-BASED CONTROLLED-RELEASE FERTILIZER

Seguel A[1], Montesano de Souza P[2], Palma, R[3], Cea P[4], Rojas N[4], Meier S[2]

[1] *Departamento de Ciencias Agronómicas y Recursos Naturales, Facultad de Ciencias Agropecuarias y Medioambiente, Universidad de La Frontera, Temuco, Chile.*
[2]*Instituto de Investigaciones Agropecuarias. INIA Carillanca, Casilla Postal 929 Temuco, Chile*
[3] *Instituto de Investigaciones Agropecuarias. INIA La Cruz, La Cruz, Región de Valparaiso*
[4] *Vicerrectoría de Investigación y Postgrado, Universidad de La Frontera, Temuco, Chile*

Soil acidity is a significant constraint in agricultural settings, leading to phosphorus (P) deficiencies due to the formation of insoluble or low-solubility compounds. This results in nutrient fixation, necessitating substantial conventional fertilization, which poses environmental risks. Smart fertilizers offer a promising solution for increasing nutrient efficiency in degraded soils. This study aimed to develop and characterize a biochar-based sustained-release fertilizer (BCRF) impregnated with nitrogen (N) and P for degraded soils and evaluate its effect on wheat growth and soil fertility compared to conventional methods. The research spans two cultivation cycles, comparing three treatments: a control, conventional fertilization (CF) with N and P, and BCRF. Each treatment was replicated in four randomized blocks. Soil samples were collected at various wheat growth stages to evaluate chemical and biological properties. The biochar was produced from oat husk, pyrolyzed at 300°C, and impregnated with N and P. The impregnation involved mixing biochar with urea and diammonium phosphate (DAP), followed by heating. Statistical analyses, including ANOVA and post-hoc tests, were used to discern treatment effects. Initial soil analyses revealed typical acidic soil characteristics. Soil incubation experiments measured the reaction to BCRF, emphasizing pH, N availability, Al immobilization, and P availability. Biochar treatments enhanced nitrogen availability and aluminum immobilization. The BCRF treatment increased nitrate levels and reduced aluminum toxicity more effectively than CF. Greenhouse trials with a spring wheat cultivar showed that BCRF and CF treatments significantly improved wheat biomass, spike number, grain yield, and nitrogen uptake compared to the control. BCRF yielded more spikes and seeds and increased grain N content by 38% and P by 33% compared to the control. Enzyme activities indicated increased microbial activity with BCRF, suggesting improved soil

health. The findings suggest that BCRF can replace conventional fertilizers, offering a sustainable alternative by improving nutrient availability and reducing soil acidity and aluminum toxicity, supporting the integration of biochar-based fertilizers in sustainable agricultural practices.

Acknowledgments: Fondecyt project 1211387 and 1220190

Keywords: Biochar, Sustainable agriculture, Nitrogen, Phosphorus, Soil fertility, Acidic soils, Crop productivity, Wheat.

GENOTYPIC RESPONSES TO PHOSPHORUS AND WATER MANAGEMENT IN WHEAT: STRATEGIES TO INCREASE RESOURCE USE EFFICIENCY AND PRODUCTIVITY

Meier S[1], Montesano de Souza P[1], Rojas N[2], Palma R[3], **Seguel A**[4].

[1]*Instituto de Investigaciones Agropecuarias. INIA Carillanca, Casilla Postal 929 Temuco, Chile*
[2] *Vicerrectoría de Investigación y Postgrado, Universidad de La Frontera, Temuco, Chile*
[3] *Instituto de Investigaciones Agropecuarias. INIA La Cruz, La Cruz, Región de Valparaiso*
[4] *Departamento de Ciencias Agronómicas y Recursos Naturales, Facultad de Ciencias Agropecuarias y Medioambiente, Universidad de La Frontera, Temuco, Chile.*

Phosphorus (P) addition can mitigate the adverse effects of water deficit stress, yet the efficiency of wheat in utilizing both components under field conditions has not been thoroughly assessed. This research aims to evaluate the effects of P and water addition on phosphorus use efficiency (PUE) and water productivity (WP) in field conditions for select wheat cultivars co-adapted to climate-induced agronomic challenges. Three wheat cultivars—Chevignon, Fritz, and Tukán—were selected based on their PUE and WP from previous experiments. The trials were conducted over two consecutive years (2020-2022) on an andosol with soil P concentrations of 10 mg P kg^{-1} and 30 mg P kg^{-1}. Two irrigation treatments were imposed: well-watered (+W) and dryland (-W). Plants were sampled at tillering (Z25), anthesis (Z65), and ripening (Z95). At the end of the phenological cycle, grain yield components, grain yield, grain quality, PUE, and WP were evaluated.

Phosphorus addition promoted plant growth, particularly in early vegetative stages, by enhancing tiller development and nutrient and water uptake. These effects were critical during anthesis and ripening, where P and water addition boosted key yield components, such as the number of spikes per square meter and grains per spike, resulting in increased grain yield. Differential responses across cultivars highlighted the genotype-specificity in PUE and WP. Seasonal water deficit stress modulated these effects, revealing a complex genotype-environment-nutrient interaction. Water addition promoted PUE and WP, indicating a synergistic relationship between these components. Among the cultivars, Chevignon consistently outperformed in grain yield, PUE, and WP compared to Fritz and Tukán. However, while P, water, and environmental factors influenced grain quality, the genetic background of the cultivar was the primary determinant of these traits.

This study underscores the importance of implementing nutrient management strategies tailored to specific cultivars and adaptable to environmental conditions under climate change. Given the challenges of water and phosphorus scarcity, such strategies are critical. The results suggest that individual, cultivar-specific nutrient management approaches are essential for optimizing yield and quality under varying environmental conditions. The findings also have significant implications for future research, highlighting the need to understand the genetic mechanisms behind the observed interactions. This knowledge could inform breeding programs aimed at developing wheat cultivars with enhanced PUE and WP, better suited to cope with the challenges posed by climate change.

Acknowledgments: Fondecyt project 1220190 and 1211387

Keywords: Genotypic difference, phosphorus deficit, drought, grain quality

ASSESSING THE INTERACTION BETWEEN PHOSPHORUS AND WATER SCARCITY IN WHEAT GENOTYPES

Meier S[1], Montesano de Souza P[1], Rojas N[2], Palma R[3], **Seguel A**[4].

[1]*Instituto de Investigaciones Agropecuarias. INIA Carillanca, Casilla Postal 929 Temuco, Chile*
[2] *Vicerrectoría de Investigación y Postgrado, Universidad de La Frontera, Temuco, Chile*
[3] *Instituto de Investigaciones Agropecuarias. INIA La Cruz, La Cruz, Región de Valparaiso*
[4] *Departamento de Ciencias Agronómicas y Recursos Naturales, Facultad de Ciencias Agropecuarias y Medioambiente, Universidad de La Frontera, Temuco, Chile.*

Phosphorus (P) is critical in mitigating the adverse effects of water deficit stress in wheat. However, the efficiency of wheat genotypes in using both P and water remains underexplored. This study aimed to investigate the combined effects of P and water-limiting conditions on P utilization efficiency (PUTE) and water use efficiency (WUE) to categorize various wheat genotypes. We screened ten wheat genotypes, including old, current, and advanced lines, for their ability to utilize phosphorus and water. Plants were grown under controlled conditions on an Andisol with an initial soil P concentration of 4 mg P kg-1 (-P), which was enriched to 30 mg P kg-1 (+P). Two irrigation levels were applied: adequate irrigation (+W) and water stress (-W), which received 30% of the water of +W. Wheat was cultivated until the end of its phenological cycle. Our findings indicated that limited P and water conditions result in detrimental changes in wheat genotypes, affecting phenological and growth traits, phosphorus accumulation in shoots, roots, and grains, and yield parameters. Low soil phosphorus concentrations had more pronounced adverse effects than inadequate water conditions. In addition, significant genetic variability was observed among the wheat genotypes concerning their PUTE and WUE. Genotypes such as 'Fritz,' 'Tukán,' and 'Maxwell' exhibited high efficiency in utilizing phosphorus and water, while 'Kirón' was inefficient and unresponsive under most conditions. The high correlation (~85%) between PUTE and WUE underscores the interactive effect between these components.

Therefore, categorizing genotypes based on PUTE and WUE provides a valuable framework for breeders to select and develop new cultivars adapted to diverse agroecological conditions, considering the availability of water and phosphorus. This study is the first to evaluate the combined effects of limiting phosphorus concentration and irrigation on phosphorus utilization and water use efficiency while categorizing

wheat genotypes by both components. It highlights the importance of considering phosphorus and water efficiencies in breeding programs to enhance wheat productivity and sustainability under varying environmental conditions.

Acknowledgments: Fondecyt project 1220190 and 1211387

Keywords: Genotypic difference, phosphorus deficit, drought, water stress.

CHARACTERIZATION OF PHOSPHORUS FORMS IN IRRIGATION RETURN FLOWS OF DIFFERENT IRRIGATED AREAS OF THE MIDDLE EBRO RIVER VALLEY (SPAIN).

Farida Dechmi[1, 2] and Ignacio Clavería[1]

[1]Department of Agricultural and Forest Systems and the Environment, Agrifood Research and Technology Centre of Aragón (EEAD-CSIC Associated Unit), Avenida Montañana 930, 50059-Zaragoza, Spain, fdechmi@cita-aragon.es
[2]AgriFood Institute of Aragon – IA2 (CITA-University of Zaragoza), Zaragoza, Spain.

In the Middle Ebro River Valley (Spain) irrigated systems, there is an increase interest in surface water contamination by phosphorus (P) to determine P losses levels from irrigated areas to water bodies and establish strategies to minimize the impact of P management on the environment. The main objective of this study is to analyse the existing drainage network P concentration data measured in the Alto Aragón Irrigated System (Huesca) and establish future research on P transfer by irrigation return flows (IRF) in arid and semi-arid areas in the attempting of corrective measures to sustain irrigated agricultural productivity and surface water quality. Data of four monitoring points are considered. The drained area of each monitoring point is considered as representative in terms of agricultural water management of Alto Aragón Irrigation System, one of the largest irrigation area of Spain. In the considered area, P was measured in water according to two parameters: dissolved phosphorus (DP), assumed here to be equivalent to soluble reactive P and P total (PT). The concentration of particulate phosphorus (PP) is not directly measured, but had to be estimated by subtracting the value of PD from that of PT. In each considered area, an analysis of P concentration pattern of each P considered parameter, temporal trends and P concentrations and streamflow relationships will be detailed. A comparison between the non-irrigation season (October-March) and the irrigation season (April-September) will be performed and P loaded from each area considered will be calculated. The area-specific P load will be considered as an indicator to compare the P load between the study areas and other non-irrigated agricultural watersheds in Spain and Europe. In addition, the effect of sampling strategy and frequency on P load and average concentration will be studied. The results of this work will provide valuable information on past and present P contamination levels in the IRF and the impact of irrigation practices on P losses in surface water bodies.

BOOSTING PHOSPHORUS RELEASE FROM PHOSPHATE ROCK BY CO-COMPOSTING WITH LEMON PEEL AND CATTLE MANURE

Cecilia Paredes [1,2], Paola Duran [1,2] and María de la Luz Mora [2]

(1) *Universidad de La Frontera, Biocontrol Research Laboratory, Scientific and Technological Bioresource Nucleus, Temuco, Chile.*
(2) *Universidad de La Frontera, Center of Plant, Soil Interaction and Natural Resources Biotechnology; Scientific and Technological Bioresource Nucleus, Temuco, Chile*
E-mail address: cecilia.paredes@ufrontera.cl

The growing global population's need for food has resulted in the unsustainable use of limited resources. The Circular Economy promotes innovative strategies for efficient waste utilization and sustainable resource management to tackle this problem.

Phosphate rock (PR) is a natural source of phosphorus (P) and has the potential to replace chemical fertilizers. However, its direct application to soil is limited by its inability to release sufficient P to support plant growth. One way to improve the solubility of PR is by co-composting it with organic substances. Therefore, this study aimed to determine the solubilized P from PR through composting with lemon peel (LP) and cattle manure (CM). The treatments included PR+LP and PR+LP+CM, with PR used as a control. The composting took place in composting bioreactor for 120 days.

The results indicated that the PR+LP+CM treatment increased available P by 31-fold, while the PR+LP treatment increased available P by 9-fold compared to control.

Additionally, the nutrient content such as Calcium (Ca), Magnesium (Mg), sodium (Na), and Potassium (K) increased at the end of the composting process in all treatments.

There was a noticeable decrease in pH values in the PR + LP treatment. The study's results suggest that co-composting organic wastes with PR improves phosphorus mobilization and provides a viable method for waste management, resulting in P-enriched compost for organic farming systems. The effectiveness of the composting process's final products is being tested through a pot trial using *Lolium perenne* as a model plant. The treatments are as follows: control soil, soil + PR, soil + compost PR + LP, soil + compost PR + LP + CM, and triple superphosphate (TSP) was included as a chemical fertilizer. At the end of the experiment, soil and plant biochemical analyses will be performed.

I3-4-BIOFERTILIZERS: INTERREGIONAL INNOVATIVE INVESTMENTS FOR THE PRODUCTION AND APPLICATION OF BIOFERTILIZERS TO PROMOTE THE BIOECONOMY FOR A SUSTAINABLE AGRICULTURE

Laura Mejias Torrent*, Ricard Carreras Ubach, Sergio Ponsá Salas

BETA Technological Centre, Universitat de Vic-Universitat Central de Catalunya Ctra. de Roda 70, 08500 Vic

** E-mail: laura.mejias@uvic.cat*

The European Green Deal aims to make Europe the first continent to achieve climate neutrality by 2050. As part of this transition, agriculture must adopt more sustainable practices. Chemical fertilizers, dominant in the market, significantly contribute to carbon emissions and environmental degradation. The EU has updated regulations to include biofertilizers, encouraging the shift to more sustainable solutions. Despite their environmental benefits, biofertilizers are underutilized due to legal, technical, or market barriers. Promoting their widespread use requires investment in research and innovation, as well as legislative support, encouraging farmers to adopt sustainable practices.

The I3-4-BIOFERTILIZERS project aims to foster interregional cooperation, focusing on the implementation, demonstration, and commercialization of industrial-scale processes for a series of innovative investments in the production and application of biofertilizers in Europe. During the project execution, a portfolio of 8 investment cases will be implemented for the production of biofertilizers/biostimulants, the development of decision support tools for optimized fertilization, and the preparation of the strategy for the entry of biofertilizers into the market.

Simultaneously, the I3-4-BIOFERTILIZERS project will have a budget to provide financial support to third-party companies (SMEs and startups in the field of biofertilizer/biostimulant production and sustainable agri-food systems) to finance innovation processes, as well as to access technical, financial, and market exit advice for the generated biofertilizer products.

HARVREST PROJECT, GREENER FARMING WITH RES: THE CATALAN USE CASE

Laura Díaz-Guerra[1*], Beatriz Corzo[2], Ignacio García[1], Ana Robles[1], Rosa Vilaplana[1], Laia Llenas[1]

1 BETA Technological Center, University of Vic – Central University of Catalonia, Vic (Barcelona), Spain.

2 ACSA OBRAS E INFRAESTRUCTURAS S.A.U. – Sorigué Group, Barcelona, Spain

** Corresponding author, E-mail: laura.diaz.guerra@uvic.cat*

About 30% of the world's energy is consumed within agri-food systems and about a quarter of the total energy is consumed during the production stage, being responsible for a third of agri-food systems' emissions of greenhouse gases. There is therefore a need to reduce the impact of energy consumption in this sector.

For this purpose, HarvRESt has been launched with the aim of vertically integrating Renewable Energy Sources (RES) into farms by improving the existing knowledge of options for reducing carbon emissions on farms, and by maximising synergies between the integration of RES and sustainable agricultural practices. This will result in a decision support system capable of providing ad-hoc recommendations to both farmers and policy makers that will make it possible to achieve improved production rates on renewable energy as well as food & feed, within agricultural communities.

In order to ensure that the main priority of farmers is preserved, namely the agricultural production rates, while achieving improved environmental impacts and a diversity of incomes for agro communities, i.e. energy exchange and biofuels production, HarvRESt will implement a transdisciplinary and holistic approach based on three main pillars:

1. Social engagement and Innovative business models: This includes not only financial issues but also social sciences and organisational considerations.
2. Agricultural and environmental trade-offs: Addressing the impact of RES technologies on agricultural production, potential trade-offs and synergies of the alternatives to be explored.

3. RES sources and smart energy systems: Addresses the modelling and design of the technological alternatives required to support the uptake and upscaling of RES production.

Supporting these pillars, HarvRESt will address the political and regulatory framework to provide recommendations based on the project outcomes, as well as digital aspects, which will be key to support the early stages of planning and design, implement smart systems at farm level and develop the resulting decision support system of HarvRESt.

To gather valuable information, co-create solutions and validate them, HarvRESt will be fed by real data coming from 4 use cases located in Italy, Denmark, Spain and Norway. Moreover, HarvRESt community will involve 200 Agricultural and energy stakeholders and reach more than 1500 Farms in the project.

The Spanish use case will be conducted in Aragon and Catalunya regions. Focusing on the Catalan use case, the main interest is to collect data from the biorefinery to model the biogas production from agro-residues. Furthermore, the fertilizer potential of the nutrients recovered from the resulting by-product (the digestate), which is currently considered one of the expected trade-offs, will be assessed in order to mitigate RES impacts, increase the circularity in the farm and diversify the farm incomes. The nutrient recovery will improve soil quality, water retention, and conservation. In addition, methane production from recycled CO2 sources to be used as fuel itself or as an H2 energy carrier will be analyzed.

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Website: https://www.harvrest.eu/

NEW GOVERNANCE MODELS TO ENHANCE NUTRIENT POLLUTION HANDLING AND NUTRIENTS RECOVERY.

Carla Febrer, Mercè Boy Roura, Lorenzo Proia i Rosa Vilaplana

BETA Technological Center (UVIC-UCC)

In the context of water resources and soils' rising nutrient pollution and soaring fertilizer prices, recovering nitrogen and phosphorous from waste streams offers a solution, allowing the supply of new fertilisers at a competitive price while enabling cleaner soil, air and water systems. However, to effectively do so, an intensive political, regulatory and governance effort is required to bring all key stakeholders on board. NENUPHAR was conceived to solve this need by developing on one hand, new governance models, understanding barriers and identifying success factors such as capacities and structures relevant for transitioning to a regional or macro-regional circular nutrient management. On the other hand, value chain solutions will be tackled in three waste streams: manure, sewage sludges and dairy wastewaters.

Moreover, NENUPHAR will address four main innovations (i) a methodology for estimating N/P emissions from the application of a fertiliser on soil; (ii) new governance models based on a network governance approach; (iii) innovative economic and financial incentives for public and private entities; and (iv) enabling technologies to treat manure, sludges, and dairy wastewaters to recover the nutrient loads.

Over the next three years, NENUPHAR multi-stakeholder approach will be demonstrated in three different regional clusters from geographically diverse river basins: the Ebro River basin (Spain), the Lielupe river basin (Latvia-Lithuania), and the Danube River basin (Hungary-Slovakia branch) and they will be replicated in two insular systems: Cyprus and Bornholm (Denmark).

NENUPHAR project is a European project funded within the framework of the Horizon Europe and it is coordinated by CIRCE. BETA Technological Center (UVIC-UCC) is a key partner leading two Work Packages on governance and regulatory and economic instruments, apart from supporting the Ebro River basin demo-site.

ARE ALL PHOSPHORUS SOURCES EQUAL? COMPARISON BETWEEN INORGANIC, ORGANIC AND ORGANOMINERAL FERTILIZERS ON RYEGRASS

L. Valverde Vozmediano[1], E. Martínez Sabater[1], S. Sánchez-Méndez[1*], L. Orden[1,2], M.A. Mira Urios[1], J.A. Sáez-Tovar[1], M.D. Pérez-Murcia[1], M.A. Bustamante[1] y R. Moral[1]

[1] *Centro de Investigación e Innovación Agroalimentaria y Agroambiental (CIAGRO-UMH), Universidad Miguel Hernández, Carretera de Beniel Km 3,2, Orihuela, Alicante 03312, España.* [*]*l.valverde@umh.es*

[2] *EEA INTA Ascasubi, 8142, Ruta 3 Km 794, Hilario Ascasubi, Buenos Aires, Argentina.*

Currently, the fertilizer industry relies mainly on phosphate rock for phosphorus (P) fertilizer production but since it is a limited resource it will be exhausted in the near future. This makes the search for alternative P sources essential. A path that is being explored is P recovery from different waste fluxes. A recovered P mineral with great potential is struvite (MgNH4PO4·6H2O), which has proved to be a slow-release fertilizer (Yesigat et al., 2022). In this work, we compared the performance of several P sources on ryegrass plants (*Lolium* perenne var. belida). The P treatments employed can be arranged in 3 groups: inorganic sources (phosphate rock, bone mill, monoammonic phosphate-MAP and struvite-STR), organic sources (vermicompost) and organo-mineral sources consistent of the previously noted inorganic sources mixed with compost in a 50:50 proportion and pelletized. Treatments were evaluated in triplicates (n=30). They were applied at the time of sowing at an equivalent dose of 120 kg P ha^{-}1, with N application of 200 kg ha^{-}1 (provided as KNO_3, 13-0-46). The assay was conducted indoors under controlled production conditions (T 21ºC, moisture 60%, 12h artificial light cycles) in pots with 1500g of clay-loam soil of modified pH 6.5. 3 biomass cuts were performed (Bauer et al., 2007) at days 13, 24 and 36. At the end of the assay, plant yield was calculated as the sum of g biomass fresh matter of the 3 cuts. There were significant differences between the control and all treatments. The best performing treatments were MAP and STR pellets. No significant differences were found between organomineral MAP and STR pellets and the same treatments in inorganic form.

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EVALUATING THE FERTILIZER EFFECTS OF MECHANOCHEMICALLY TREATED CALCIUM-CARBONATE MATERIALS WITH POTASSIUM PHOSPHATE USING A SOIL-PLANT MODEL SYSTEM

Roger Borges[1,2,3*]; Amanda S. Giroto[1,3]; Cristiane S. Farinas[1]; Nicolai D. Jablonowski[3]; Caue Ribeiro[1*]

[1] *Embrapa Instrumentation, 13560970 São Carlos, SP, Brazil.*

[2] *Department of Chemistry, Federal Technological University of Paraná, Medianeira, PR, 85884-000, Brazil.*

[3] *Institute of Bio- and Geosciences, IBG-2: Plant Sciences, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany.*

The formation of calcium and potassium (hydrogen) phosphates from eggshell and KH_2PO_4 through a mechanochemical process was demonstrated successfully in an earlier study [1]. However, this newly developed material has not yet been tested as a potential fertilizer in a soil-plant system, being a prerequisite for validating the products' fertilizer efficiency. The mechanochemical process was conducted using a BM500 Anton Paar ball mill, at 30 Hz, for 100 min. The most conventional sources of phosphorus for agriculture include potassium or calcium phosphate. However, the use of a combined source of calcium and potassium phosphate is still lacking applied studies. Therefore, greenhouse experiments of the final milled samples were conducted to evaluate the Ca, K and P fertilizing behavior under semi-controlled conditions, using 2 kg of sand as a growing substrate and *Brachiaria brizantha* as a model plant. Two sets of experiments were realized using 100 mg and 200 mg of P dm^{-3} [2]. From the harvested above ground dried biomass, it was observed that the milled samples showed an increase in biomass production and phosphorous and potassium uptake throughout each harvest, tending to stabilize in the third harvest. The negative controls, using either Bayovar rock or no fertilization did not show significant biomass production, phosphorous and potassium uptake. However, the obtained results of the positive controls using KH_2PO_4 showed a behavior of increasing biomass production and phosphorous and potassium uptake in the second harvest, mainly when 200 mg P dm^{-3} was applied. In conclusion, the milled sample provide a better nutrient management.

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BIO-BASED and RECOVERED FERTILISERS: 12 years of R&D EU projects

Cassart, Juliette[1]; González, Inmaculada[1]; Estrada, Inés Belén[1]; Gómez, José María[*1]

[1]*BIOMASA PENINSULAR, C/Constancia 38, Bajo, 28002 Madrid. Spain. +34 91 3590181*

** Corresponding author:jmgomez@bpeninsular.com*

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Introduction

Soil fertilisation consists in the supply of the nutrients depleted in the soil. This activity is undoubtedly irreplaceable in the agricultural systems. However, a sustainable fertiliser use and nutrient management is essential to avoid losses and adverse environmental and health effects. Another question is how to improve the sustainability of fertilisers production, through the recovery of nutrients and the development of the bio-based and recovered fertilisers. An important transformation process is undergoing at European level in this direction. The EC, through various initiatives (e.g., F2F Strategy - Farm to Fork, Green Deal, INMAP initiative), aims to reduce nutrient losses by 50% by 2030, as well as a 30% reduction in non-renewable resources in the production of fertilisers. It seeks to implement practices of rational and sustainable nutrition of agricultural soils that preserve and improve their biological properties, while increasing their capacity as carbon sinks, as well as avoiding water pollution and reducing greenhouse gas emissions to mitigate the impacts of climate change. Since the start of its operations in 2001, BIOMASA PENISULAR has been working on the development of experimental bio-based fertilisers, from 2010 through R&D&i EU Projects. Some of these projects are described hereafter and cover bio-based fertilises ranging from soil improvers and compost to organo-mineral fertilisers, humic extracts and biostimulants, from recycled or recovered materials from different sources, such as agriculture and agri-industries, wastewater grown microalgae, garden and park green residues and municipal biowaste from households, markets or commercial premises.

FP7 REFERTIL Project (2011-2014) (RTD FP7-KBBE)

Reducing mineral fertilisers and chemicals use in agriculture by recycling treated organic waste as compost and biochar products

REFERTIL's focus was the improvement of nutrient recovery (in particular P and N) from separately collected biowaste through composting and biochar production and the use of the products (alone and combined) as EU standardized organic fertilisers and soil improvers. Particular attention was paid to crop-specific biotechnological formulations (using selected microbial strains and mycorrhizae with fertilising properties), and the use of wood biochar as compost additive. The latest showed positive agronomical results at biochar/compost additions in the range of 2-4% w/w.

Furthermore, a Pan-European survey covering a total of 21 Composting and 7 Biochar new generation plants in 7 EU countries was performed, to identify the industrial state of the art of these two biowaste processing systems, identifying the technological trends and potential improvements. A deep insight in compost and biochar quality products was also possible through comprehensive sampling, analysis and overall evaluation.

LIFE+ TL- BIOFER Project (2014-2018) (LIFE13 ENV/ES/000800)

Nutrients and regenerated water recycling in WWTPs through twin-layer microalgae culture for biofertilizers production

This project evaluated the feasibility of advanced biofilm microalgae cultivation in a Twin Layer (TL) prototype for nutrients removal (N and P) as tertiary treatment in small wastewater treatment plants (WWTPs) located in sensitive areas. The potential valorisation of microalgae biomass as a component of bio-based fertilisers was also assessed. A *Scenedesmus sp.* strain was chosen, among 33 microalgae strains isolated from El Viso WWTP (Cordoba, Spain), for the inoculation of the TL, due to its high growth rate and its nutrient uptake capacity. Tests carried out in the TL prototype were markedly efficient for total soluble and ammonia N removal (up to 66% and 94%, respectively).

Regarding potential valorisation of the microalgae, their nutrient content was 5.5% N (over 40% protein), 8.8% P_2O_5 and 1.5% K_2O, with high enzymatic activity, very low heavy metals content and without pathogen presence.

Several experiments were performed at laboratory, mesocosm and greenhouse scale on ryegrass and barley, testing various treatment modalities. Among these, the combinations of the following components were tested on ryegrass and barley, in greenhouse:

- vegetable compost (dose adjusted not to exceed 170 $kgN.ha^{-1}$, the maximum level allowed for the application in vulnerable zones contaminated with nitrogen),
- 1 and 4% (w/w) biochar (BC) and,
- 1 and 4% (w/w) solid-state formulated microalgae (µa).

These mixtures showed improved results on both plants yields (on fresh and dry weight basis) compared to the negative control (no treatment) and the positive control (ammonium sulphate), apart from the [compost-biochar4%-microalgae1%] mix in barley. In ryegrass, the best results were obtained with the mixtures containing 1% microalgae, while in barley with 4% microalgae. Another important learning of this projects' experiments was that microalgae concentrations higher than 2% had clear negative effects on the biomass yields.

The lyophilized microalgae themselves could be considered as high value although experimental bio-based fertilizers that met the technical requirements in terms of composition and limits of toxic elements established in the Product Functional Categories (Annex I) and Component Material Categories (Annex II) of the new EU *Fertilising Products Regulation (FPR) 2019/1009*. In this regard, the selected solid-state formulations fitted the definition of the Product Functional Category PFC 6 "*Plant biostimulants"*.

URBIOFIN Project (2017-2022) (H2020-BBI-JTI-2016)

Demonstration of an integrated innovative biorefinery for the transformation of Municipal Solid Waste (MSW) into new Bio-Based products

Over 100 Mt organic fraction of municipal solid waste (OFMSW) are generated every year in EU cities. When properly separated and collected at the source, according to the revised *EU Waste Framework Directive 2018/851*, there is a high potential to convert this biowaste stream into bio-based products. This can take place in so-called Urban Biorefineries.

The URBIOFIN Consortium has built and operated through the Project, an Urban Biorefinery at demo scale, demonstrating the techno-economic viability of transforming 10 t/d of OFMSW into Bioethanol and Organo-Mineral Fertilisers as main outputs, but also biomethane, microalgae-based biostimulants and different kinds of bioplastics and biocomposites (made of PHAs derived from VFAs).

At least two of the final bio-based products are commodities with a steep increasing market demand (i.e., Bioethanol and Organo-mineral fertilisers), contributing to nutrients recycling, sustainable agricultural practices and green chemistry.

In terms of problem solving and business projection, URBIOFIN offers municipalities and waste operators an advanced, enclosed and compact design and layout, to be built *ex novo* or suitable to be integrated in conventional Anaerobic Digestion and Composting Plants as a previous module. It improves digestate quality, increases stabilization and dewaterability of final organic residue and gives the option to directly convert the digestate into granular organo-mineral fertiliser, compliant with *FPR (EU) 2019/100*, skipping the composting phase.

Thanks to its clever design and lean concept, URBIOFIN can save investment resources, space, processing time (from months to days), fossil energy needed for compost production and can reduce environmental impact and costs of air emissions treatment.

Regarding the URBIOFIN agronomical outputs, three different organo-mineral fertilisers were produced after NPK addition to the digestate for the formulation and granulation in a Spouted Bed Dryer pilot line. NPK 8-10-11 and 8-15-8 formulations were tested by CEBAS-CSIC in Murcia (Spain) during agronomic seasons 2021 and 2022, with lettuce and tomato in open field trials. The agronomical yields of the organo-mineral formulations, complemented in N with fertigation along the crop cycle, outperformed the conventional mineral fertiliser treatment with an enhancement of 108% and 109% in the case of tomato. This indicated that the substitution of mineral fertilisers in NPK pre-seedling application is possible with agronomic and environmental advantages and increased yields.

LIFE EBP (2020-2025) (LIFE19 ENV/IT/000004)

Ecofriendly multipurpose Biobased Products from municipal biowaste.

LIFE EBP (still in course) is coordinated by the Italian Company HYSYTECH and has 15 partners from Italy, Spain, France, Greece and Cyprus, including several Companies, Municipalities and Universities. The objective of the Project is to demonstrate at pilot scale (TRL6), the techno-economic and environmental feasibility of an alkaline hydrolysis technology for the transformation of source separated municipal biowaste for its valorisation as high-value bioproducts. In particular, dried humic-fulvic extracts with biostimulant effects are being produced and validated through different lab, greenhouse and open field tomato trials in 4 countries.

The trials performed by CEBAS-CSIC in Yéchar (Murcia, Spain) were the following:

- Agronomic season 2021: N-lixiviation test on lettuce in 1 L pots in cultivation chamber and agronomical crop performance assessment.
- Agronomic season 2023: Agronomic assessment in tomato in open field, determination of the agronomic effect of dried hydrolysates addition to the soil, alone/or combined with mineral fertilisers, on the quality and yield of tomato for the canning industry.

Hydrolysates were applied in pre-seedling at 187 kg/ha rate, combined with 60% and 80% reduced mineral fertilisers dosages. Agronomical results of hydrolysates in tomato open field cultivation were positive, outperforming conventional mineral application in pre-seedling by more than 116%, and presenting similar results to a Vegetable Compost Control and the URBIOFIN organo-mineral formula at 6-9-16 NPK balance.

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THE ATLANTIC CASE IN SEA2LAND PROJECT: PILOT SCALE FRACTIONATION BY TWIN-SCREW EXTRUSION OF FISH BY-PRODUCTS FROM 2 SPECIES FOR THE PRODUCTION OF HIGH P-CONTENT BIO-BASED FERTILISERS

Christine Raynaud[1,2], Clement Chastrette[1,2]; Anne Lung[1,2], William Tapia[1,2]; Laure Candy[1,2]

[1]Centre d'Application et de Traitement des Agroressources (CATAR), INPT, Toulouse, France ; [2]Laboratoire de Chimie Agro-industrielle, LCA, Université de Toulouse, INRAe, Toulouse, France.

The Sea2Land[1] project is a 4-year collaborative Innovation Action (IA) funded by the EU in the frame of the Horizon 2020 programme. Based on the circular economy model, SEA2LAND promotes the production of bio-based fertilizers (BBF) in the EU from its own raw materials in order to reduce the soil nutrient imbalance in Europe. The basis of the project is the regional production of BBF from fishery and aquaculture by-products by developing dedicated demonstration pilots that can be replicated across Europe, boosting local growth. 26 partners from 11 countries are participating in the project. 9 technologies are developed on the basis of 7 demonstration pilots implemented in 6 representative areas of the European fishing and aquaculture sectors. For the Atlantic area case study, the project aimed at producing BBF's from fish by-products[2] using ThermoMechanoChemical (TMC) fractionation by twin-screw extrusion. The process was developed on the fractionation of 50/50 mix of heads/frames of Steelhead trout (ST) and efficiently transferred to the same mix of Sturgeon (S). Both species are interesting sources of nutrients: 7-8% N/DM, 2-4% P/DM and 0.5-1.0% K/DM but also contains between 40% and 50% of lipids. Configured as an extraction process, extrusion represents an industrial continuous process able to provide simultaneously a solid and a liquid fraction [3]. The use of TMC process for fertilizers production is an innovative approach allowing the recovery of not only BBFs with an agronomic value but also fish oil to reach a ZERO-waste process. After process development and optimization at TRL4-5, pilot scale trials at TRL6 were achieved at a feeding rate of 20 kg/h in fish by-products. From 20 kg fish by-products, 2 fertilizing products are obtained for each specie. For ST, 4.2 kg of an organic solid BBF (9.4 N/DM; 19 % Lipids/DM), 6.7 kg of a liquid organic BBF (13.9% N/DM) and 2.0 kg of fish oil. For S, 4.0 kg of solid BBF (9.8% N/DM; 17% Lipids/DM), 6.2 kg of liquid

BBF (10.5% N/DM) and 1.3 kg of fish oil are obtained. Both extracted oils could be highly prized by the human food and animal feed sectors [4]. The efficiency of the process was evaluated in terms of N, P, K recovery in the solid BBF fraction and oil recovery. For ST, nutrients recovery was: N > 90%, P > 97% and K > 80%. More than 50% of oil was also recovered. The solid BBF's from ST was evaluated for pot and field trials. It is conformed in terms of nutrients, heavy metals and pathogens. It is considered as high P-available, medium N-available and good C/N ratio.

Funding programme: The project Sea2Land has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement no. 101000402.

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MITIGATING CLIMATE CHANGE WITH BAMBOO IN CHINA

Biochar Carbon Removal, Terra Preta Sanitation

Chen Xiang Yang

Bamboo is the champion to fight climate change as it grows very fast absorbing carbon dioxide far more than the normal trees. In China, there are over 60 million hectares of bamboos in southern provinces. However, using bamboo as paper and construction materials has becoming unpopular since early 2000 and the farmers have lost motivation to take care of the bamboos which expand wildly and aggressively eliminating the biodiversity and producing more methane and carbon dioxide after its decay.

For practicing Terra Preta Sanitation concepts, we are mixing bamboo biochar with urine collected from the urine diverting dry toilets in Yu Yao City as the fertilizer to grow rice and fruits. The crops have withstood the heaviest drought and coldest weather during last 100 years. The token issued by a carbon versification body claims that one ton of bamboo biochar can sequester 2.88 tons of carbon dioxide in the soil permanently.

The 2nd benefit of our Biochar Carbon Removal and Terra Preta Sanitation efforts is to curb the eutrophication of the lakes and rivers. Quote the Clean Thai Lake Guidelines issued by six ministries on June 22nd of 2022 as saying that even if all the waste water treatment plants meet the strictest emission standard, the amount of phosphorus was still up to 2,150 tons/y to Thai Lake during 2008-2020, which is still four times of the upper limit of the lake with 70 million people living around the shallow lake with a size of 3,690 square kilometers.

Changing the people's mindset is the biggest challenge for us to realize our objective producing 30 million tons bamboo biochar and collect 15 million tons of urine each year. Before 1990, most Chinese lived with waterless toilets such as pit latrines outside the buildings and containers at home. Both animal manures and human waste were used as fertilizers for growing crops and vegetables. All the rivers and lakes were clean. But the ancient circular ecological agriculture has been abandoned since the conventional water and sanitation system was introduced into China in 1990s whereafter most people have become accustomed to the flush and forget living style. As a result, all the rivers and water have become dirty and eutrophic.

Fortunately, in Yu Yao city where the bamboo charcoal factory locates, there are 20 public toilets blocks equipped with urine diverting dry devices and urinals for us to collect urine for biochar inoculation to practice Terra Preta Sanitation concepts as defined in the book compiled by Professor Ralf Otterpohl of TUHH.

With international support, we would be confident to have China to become the Champion to fight climate change with bamboos.

Shen Zhen Blue Waters and Green Hills Eco-Ltd

Baguatian Business Management Ltd

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June 2015, Edition: 1

Publisher: Deutsche Bundesstiftung Umwelt (DBU), Osnabrück, Germany

Editor: Ralf Otterpohl, Torsten Bettendorf, Claudia Wendland

ISBN: 978-3-00-046586-4

WASTEWATER PHOSPHORUS REMOVAL AND RECOVERY THROUGH ION EXCHANGE AND STRUVITE CRYSTALLIZATION

Laura Ruiz-Cosgaya[1], Remedios Martínez-Guijarro[2], Alberto Bouzas[3], Joaquín Serralta[1] and Ramón Barat[1]

[1]CALAGUA, Unidad Mixta UV-UPV, Institut Universitari d'Investigaciò d'Enginyeria de l'Aigua i Medi Ambient, IIAMA, Universitat Politècnica de Valencia, Camí de Vera s/n, 46022 Valencia, Spain

[2]Institut Universitari d'Investigaci´o d'Enginyeria de l'Aigua i Medi Ambient, IIAMA, Universitat Polit`ecnica de Valencia, Camí de Vera s/n, 46022 Valencia, Spain

[3]CALAGUA, Unidad Mixta UV-UPV, Departament d'Enginyeria Química, Universitat de València, Av. de la Universitat s/n, 46100 Burjassot, Valencia, Spain

Traditionally, wastewater treatments have focused on the removal of pollutants in order to meet discharge limits. However, increased interest in the recovery of resources contained in wastewater is giving rise to a new concept, transforming existing wastewater treatment plants into so-called resource recovery facilities. In this scenario, anaerobic treatments (i.e Anaerobic membrane bioreactors) are key processes because they allow the transformation of organic pollutants into biogas, without the need for energy consumption (Robles et al., 2020). Furthermore, the permeate obtained with nitrogen and phosphorus concentrations similar to those existing in raw wastewater, could be reused for fertigation (Jiménez-Benitez et al., 2023). However, when nutrient removal is required, a post treatment is needed. In this work, a combination of physico-chemical treatments such as adsorption and struvite crystallization is proposed to treat this permeate. In the adsorption column we obtained a free nutrient effluent and, after the adsorption column regeneration, a stream with high concentrations of phosphorus, which could be recovered as commercial fertilizer by crystallization process (Martí et al., 2017).

Ferrix AE33 supplied by Purolite was used for phosphorus concentration. Permeate from an AnMBR pilot plant located in Carraixet WWTP and fed with municipal wastewater (Valencia) was used for the tests. Phosphate concentration of this effluent was 6 ± 1,5 P-PO_4/L.

Concentration of the effluent of the resin column was monitored until the stream exceeded a concentration of 1 mg $P\text{-}PO_4$/L. At this point, permeate feed was stopped to continue with the regeneration process. Regeneration was performed with 10 BV of a solution of 2%NaCl and 2%NaOH (Guida et al., 2021), allowing the regeneration of all the resin matrix. After each regeneration, pH was reduced to 7 by stripping CO_2, and a new cycle was started.

During operation, discharge limits were met within 500 Bed Volumes, reaching a maximum adsorption capacity (q_{max}) of 2,1 mg $P\text{-}PO_4$/g resin. Over 95% of the adsorbed P-PO4 was recovered in the regeneration stage, reaching a concentration of 316,7 mg P-PO4/L and a regeneration capacity (q_{reg}) of 2 mg P-PO4/g resin. No reduction of the adsorption capacity was observed in the 16 cycles carried out.

Results from this work confirmed that Purolite resin can meet discharge limits within 500 BV in each cycle, retaining over 95% of the phosphorus presented in the AnMBR permeate. The final phosphate concentration in the regeneration makes feasible P recovery by means of struvite crystallization. Long-term study must be continued to determine when there is a significant loss efficiency and resin needs to be renewed. Additionally, the economic feasibility of the full-scale application must be evaluated.

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RUBIPHOS TECHNOLOGY APPLIED TO THE P-RECOVERY FROM FLY ASHES

Eng. Mohamed Takhim

TTBS (Takhim for Technology and Business Services).

TTBS is a Belgian company whose the objective is to supply the phosphate market with efficient technical and business solution for its faced challenges. As main achievement, TTBS has developped and patented a new cost-effective chemical process named RubiPhos® to recover P from sewage sludge ashes or low-grade phosphate rock.

This process technology can also be applied for other applications such as purification of fertilizer grade phosphoric acid, P-recovery from other phosphate materials and lithium recovery from black mass/LFP.

In its speech, TTBS will address and present the pathway of its RubiPhos technology. After that, the presentation will be focused on the pilot test campaign that was carried out last year during 3 weeks (200 hours of operation) in continuous mode @12,5 kg/h of fly ashes as input on the site of our client HVC at Dordrecht in the Netherlands to recover P from their mono-incinerated fly ashes and to produce as end products fertilizer grade SSP compliant with the EU regulations and magnesium/potassium liquid solution used in greenhouses for horticulture. The positive results will be shown and described.

Some words about Eng. Mohamed Takhim.

Engineer Mohamed Takhim has over 25 years experience as process developer and industrial project manager. He is a process chemical Engineer holding a Master Degree in Project Management from ESC Lille and a MBA from the French Business School SKEMA.

He has more than 10 granted patents on his name called EcoPhos Technology which has been acquired recently by Prayon when EcoPhos group closed its activities in 2020.

He was nominated two times Manager of the year in Belgium and he was awarded by The famous Pierre Becker Memorial Award by IFA DG Charlotte Hebrebrandin in IFA 2018 conferences in Madrid.

He has leaded the conception and construction of several factories based on his technologies overall the world (Peru : Quimpac, Russia : Eurochem, India : Egil, China : Chanhen, Egypt : Evergrow, Namibia : Namphos) for a project amount exceeding 150 millions euro of engineering and equipment supply.

QTL IDENTIFICATION FOR PHOSPHORUS DEFICIENCY TOLERANCE IN BREAD WHEAT

Creze Alexia1, Degan Francesca2, Bogard Matthieu1, Brandt Yann3, Helias Regis3, Cohan Jean-Pierre4

[1] *Arvalis – Institut du végétal – Baziège (France)*
[2] *Arvalis – Institut du végétal – Villiers-le-Bâcle (France)*
[3] *Arvalis – Institut du végétal – Montans (France)*
[4] *Arvalis – Institut du végétal – La Jallière (France)*

Phosphorus (P) is an essential macronutrient vital for various metabolic processes in plants, crucial for achieving optimal crop yields. As plants rely predominantly on soil phosphate (Pi) as their source of phosphorus, its availability significantly influences plant growth and productivity, making it a limiting factor in most soils worldwide.
However, due to economic and environmental concerns, the use of Pi fertilizers faces increasing restrictions. Despite the importance of evaluating Pi bioavailability and traits related to Pi starvation, current methods often fall short in accurately assessing plant Pi status, necessitating the development of phosphorus-efficient crop varieties, especially in wheat.

In a recent study conducted across three trials in France in 2021 and 2023, involving 199 winter bread wheat genotypes, researchers explored various indicators of phosphorus efficiency and their correlation with grain yield. Through a genome-wide association study (GWAS), we identified 18 quantitative trait loci (QTL) associated with phosphorus use efficiency (PUE) across ten chromosomes. The wheat panel, predominantly comprising recent breeding lines cultivated between 1988 and 2022 in France and the United Kingdom, underwent phenotyping and genotyping using high-throughput SNP arrays. The trials encompassed parcels with varying soil phosphorus concentrations, with conditions including both untreated and phosphorus-amended plots. Agronomic characterization involved measuring conventional traits such as grain yield (GY) and earliness, supplemented by drone flights to monitor temporal changes in several vegetation indexes. Additionally, phosphorus content in grains (Pgrain) was quantified, and traits linked with PUE were calculated.

The heritability of P use efficiency (Pue_eff) ranged from 0.23 to 0.59, with noticeable genotype-environment interactions observed. Out of 201,557 SNPs employed in

GWAS, 120 were significantly associated with PUE-related traits above the LOD threshold of 6.05, with Pue_eff, GY, and Pgrain exhibiting the strongest associations. Notably, several QTL identified in this study co-localized with known genes implicated in phosphorus metabolism. Furthermore, the development of genomic prediction models holds promise in enhancing breeding efforts for phosphorus deficiency tolerance, offering potential utility in the early-stage selection of wheat varieties.

In conclusion, this comprehensive study elucidates the genetic underpinnings of phosphorus efficiency in wheat, furnishing valuable insights for refining phosphorus management strategies in agriculture to ensure sustainable crop production amidst evolving environmental and economic challenges.

WASTEWATER PHOSPHORUS REMOVAL AND RECOVERY THROUGH ION EXCHANGE AND STRUVITE CRYSTALLIZATION

Laura Ruiz-Cosgaya[1], Remedios Martínez-Guijarro[2], Joaquín Serralta[1] and Ramón Barat[1]

[1] CALAGUA-UPV: CALAGUA – Unidad Mixta UV-UPV, Universitat Politècnica de València, 46022, Valencia, Spain

[2] Instituto de Ingeniería del Agua y Medioambiente, IIAMA, Universitat Politècnica de València, 46022 Valencia, Spain

Introduction

Traditionally, wastewater treatments have focused on the removal of pollutants in order to meet discharge limits. However, increased interest in the recovery of resources contained in wastewater is giving rise to a new concept, transforming existing wastewater treatment plants into so-called resource recovery facilities. In this scenario, anaerobic treatments (i.e Anaerobic membrane bioreactors) are key processes because they allow the transformation of organic pollutants into biogas, without the need for energy consumption. Furthermore, the permeate obtained with nitrogen and phosphorus concentrations similar to those existing in raw wastewater, could be reused for fertigation. However, when nutrient removal is required, a post treatment is needed. In this work, a combination of physico-chemical treatments such as adsorption and struvite crystallization is proposed to treat this permeate. In the adsorption column we obtained a free nutrient effluent and, after the adsorption column regeneration, a stream with high concentrations of phosphorus, which could be recovered as commercial fertilizer by crystallization process.

Materials and Methods

Ferrix AE33 supplied by Purolite was used for phosphorus concentration. Permeate from an AnMBR pilot plant located in Carraixet WWTP and fed with municipal wastewater (Valencia) was used for the tests. Phosphate concentration of this effluent was between 6 and 8 mg $P\text{-}PO_4$/L.

Concentration of the effluent of the resin column was monitored until the stream exceeded a concentration of 2 mg $P\text{-}PO_4$/L. At this point, permeate feed was stopped to continue with the regeneration process. Regeneration was performed with 10 BV of a solution of

2%NaCl and 2%NaOH, allowing the regeneration of all the resin matrix. After each regeneration, pH was reduced to 7 by stripping CO_2, and a new cycle was started.

Results and Discussion

Discharge limits were met for 500 Bed Volumes. Results shown in Figure 1 show that except for the first cycle, the retention capacity tends to remain constant between 1,7 and 2 mg $P\text{-}PO_4$ retained/g resin. About 99% of the adsorbed phosphorus was recovered in the regenerant solution, reaching an average phosphate concentration of 300 mg $P\text{-}PO_4$/L.

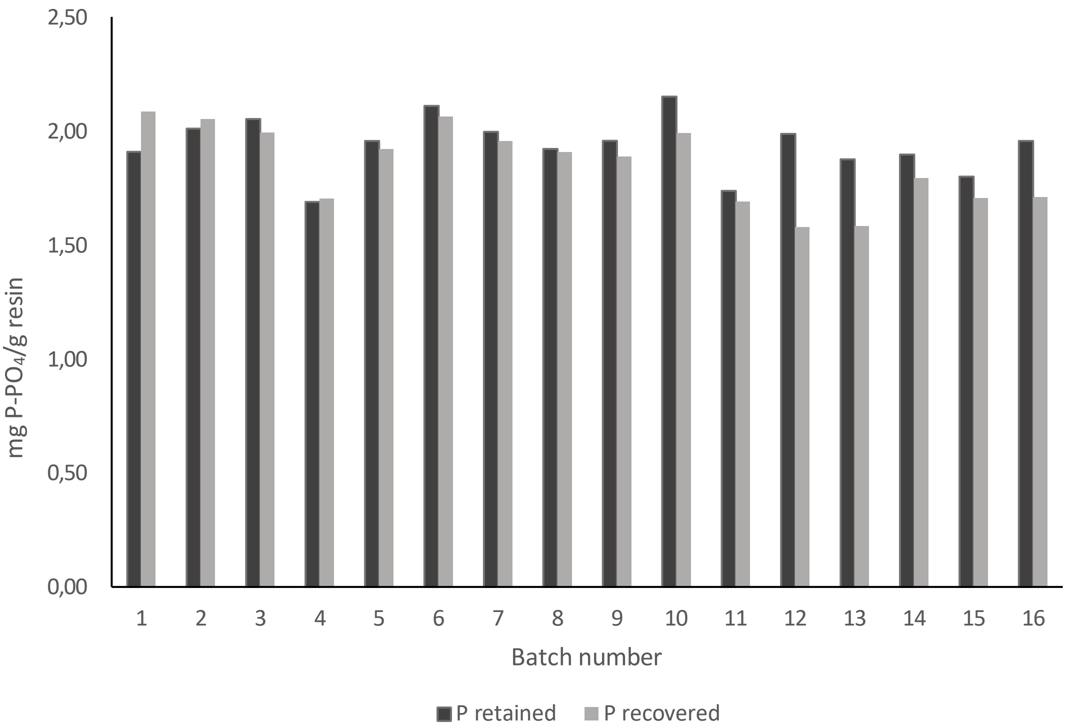


Figure 1. Adsorption capacity after 16 saturation-regeneration tests

Conclusions

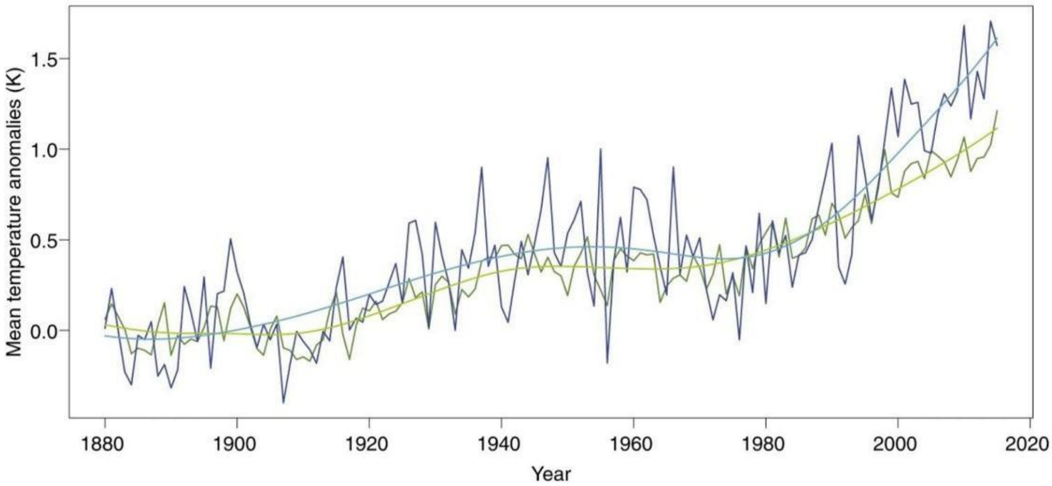
Results from this work confirmed that Purolite resin can meet discharge limits within 500 BV in each cycle. Over 97% of the P retained was recovered during regeneration, increasing phosphorus concentration about 50 times, and reaching a concentration of 300 mg $P\text{-}PO_4$/L, which makes feasible P recovery in crystallization through struvite precipitation. During the 16 completed cycles, adsorption capacity remained constant. Long-term study must be continued to determine when there is a significant loss efficiency and resin needs to be renewed. Additionally, the economic feasibility of the full-scale application must be evaluated.

CRUCIAL ASPECTS OF PHOSPHORUS RECOVERY FROM SEWAGE SLUDGE IN CONTEXT OF CLIMATE CHANGE

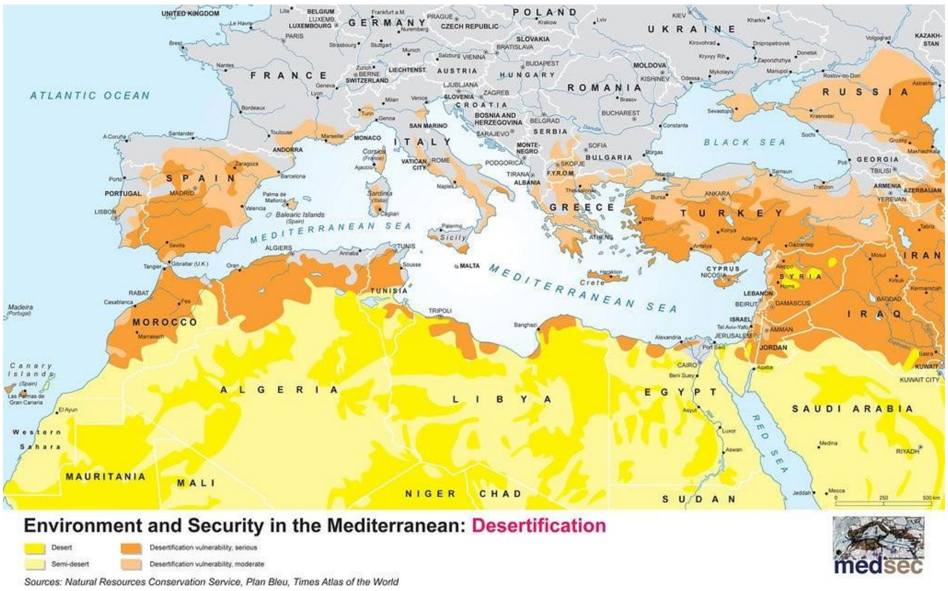
Helmut Gerber

PYREG GmbH

Recent accelerated climate change and rising temperatures are excelling existing environmental problems in the Mediterranean Basin that are caused by the combination of changes in land use, increasing pollution and declining biodiversity. In most impact domains (such as water, ecosystems, food, health and security), current changes and future scenarios consistently point to significant and increasing risks during the coming decades. In the Mediterranean region, average annual temperatures are now approximately 1.5°C higher than during the period 1880-2019, well above current global warming trends [1]

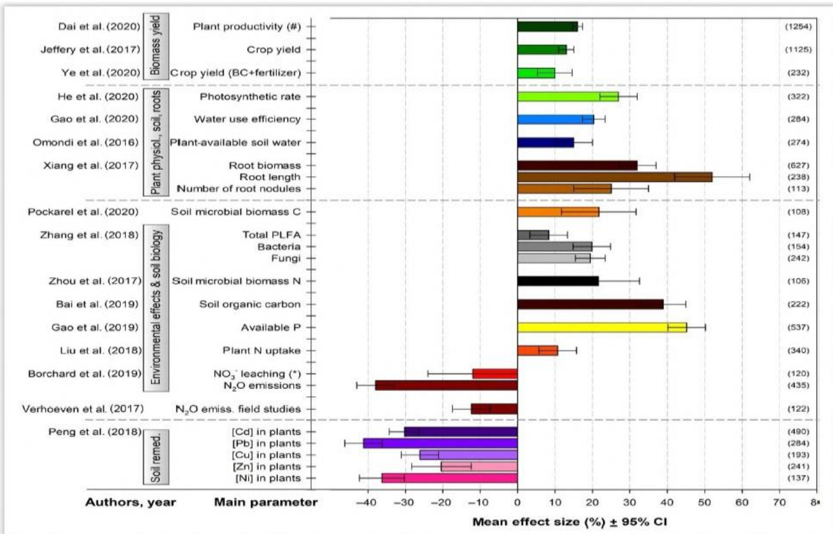


Warming of the atmosphere (annual mean temperature anomalies with respect to the period 1880-2019), in the Mediterranean Basin (blue lines, with and without smoothing) and for the globe (green line). Policies for the sustainable development of Mediterranean countries need to mitigate these risks. Studies suggest that 30% of semiarid Mediterranean drylands are affected by desertification and that 47% of the region's people suffer these effects [2]

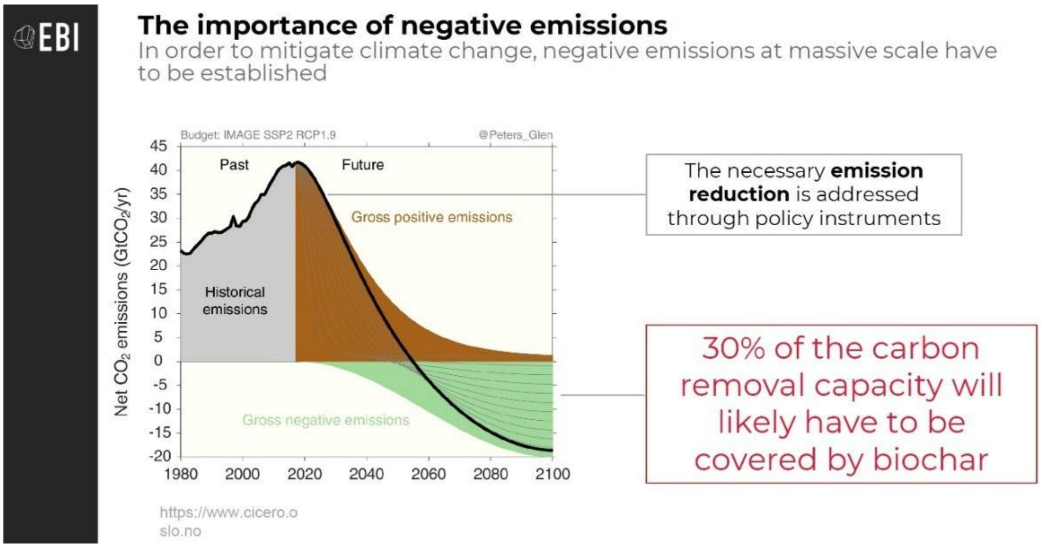


Soil degradation affects more than one billion people worldwide, particularly in dry regions, where around 40% of the world population live. Soil degradation is indicated mainly by a loss of soil functions, a large portion of which depends on soil aggregation and soil organic matter (SOM) storage within aggregates. The provision of microbial substrate by compost and of habitat by biochar are central in sustainable soil amelioration. A new field of biochar and compost application is the large-scale rehabilitation of degraded soils to restore their functions and to enable sustainable use over the long term. [3]

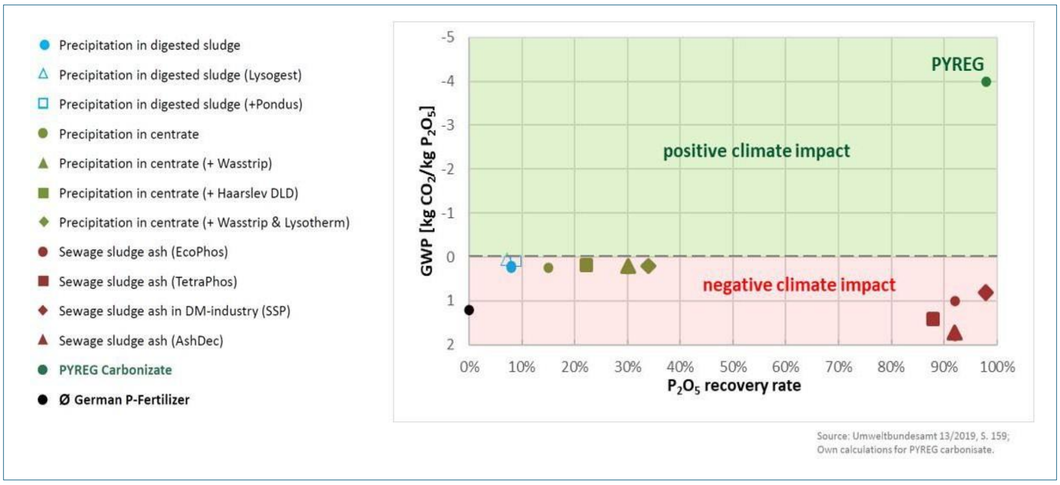
Biochar addition in soils increases besides other eligible effects water use efficiency and plant available soil water [4]



Emissions reduction alone is no longer sufficient to contain the climate crisis. In parallel with the reduction of emissions, a start must now be made on expanding and further developing the existing options for creating carbon sinks. The magnitude of the task is enormous: In order to achieve climate neutrality in the European Union, the volume of sinks to be created annually must increase to at least 850 million tonnes of CO_2 by the year 2050. [5]



Biomass pyrolysis and agricultural use of the biochar is thus a key technology for saving the climate. Biochar has been intensively researched in recent years. A wealth of experience with its applications and innumerable scientific publications prove today that in addition to its direct climate benefit as a carbon sink, biochar can be used in agriculture in many profitable and beneficial ways. Besides the carbon sink effect, sewage sludge biochar delivers a highly valuable phosphorus source with a high P recovery rate. [6]



Global warming potential (GWP) of different fertilizers

The 2019 study by the German Federal Environmental Agency [6] showed that conventional fertilizer production in Germany emits about **+1.2 kg CO_2 eq /kg P_2O_5**. Furthermore, phosphate recovery processes like precipitation (in digested sludge or centrate) or sewage sludge ash also demonstrably cause CO_2 emissions.

Using the same calculation methodology in comparison to the global warming potential (GWP) of these processes, PYREG biochar from sewage sludge has a negative GWP of **-4,01 kg CO_2 eq /kg P_2O_5**.

Consequently, the recovery of phosphate within the PYREG process and the final application of the biochar contributes to fight global warming, increase water use efficiency and reaching net zero.

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PHOSPHATE REMOVAL AND RECOVERY FROM MUNICIPAL WASTEWATER BY ADSORPTION ON HYDROTALCITE-RELATED MATERIALS

Dario Frascari[a], Davide Pinelli[a], Carla Maggetti[a], Enrico Temellini[a], Laura Sisti[a], Walter Felix Cossio Guzman[a], Tommaso Tabanelli[b], Valentina Medri[c], Elettra Papa[c], Elena Landi[c]

[a] Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), Alma Mater Studiorum – University of Bologna, via Terracini 28, 40131 Bologna, Italy.
[b] Dipartimento di Chimica Industriale "Toso Montanari", Alma Mater Studiorum – University of Bologna, Viale Risorgimento 4, 40136, Bologna, Italy. [c] National Research Council of Italy, Institute of Science, Technology and Sustainability for Ceramics (CNR-ISSMC), Via Granarolo 64, 48018 Faenza, RA, Italy.

In the current international context characterized by the tendency to stricter limits for P concentration in treated wastewater and a strong drive towards phosphate recovery, it is crucial to develop cost-effective technologies to remove and recover phosphate from municipal wastewater (MWW).

In this study, an initial screening of the phosphate adsorption performances of 9 sorbents led to the selection of 3 materials that were subject to further investigation: i) calcined pyroaurite - an innovative material composed of mixed Mg/Fe oxides (Maggetti et al., 2024); ii) Sorbacid 911, a commercial hydrotalcite consisting in an Al – Mg- Carbonate Hydroxide; and iii) a composite material composed by a metakaolin geopolymer named G13 and P70, a commercial hydrotalcite featuring a $MgO:Al_2O_3$ 70:30 ratio. The selected materials were further investigated by means of both isotherms and continuous-flow tests, conducted with a P-spiked effluent of a wastewater treatment plant (WWTP) and a floating stream obtained from the municipal sludge centrifugation.

Calcined pyroaurite resulted in a high P sorption capacity of 12 $mg_P\ g_{sorbent}^{-1}$ at the typical phosphate concentration in MWW, the capacity to treat 600-700 bed volumes at the 1 $mg_P\ L^{-1}$ breakpoint imposed by the current EU legislation for large WWTPs, and a 90-95% phosphate recovery. In the continuous-flow tests conducted with calcined pyroaurite, phosphate and the other sorbed anions were effectively desorbed with 20 bed volumes of NaOH 0.5 M. In order to recover a marketable P-rich product, $Ca(OH)_2$ was added to the desorbed product. The final product resulted composed of $Ca_3(PO_4)_2$ -

typically used for the production of P-based fertilizers - and $CaCO_3$, whereas no traces of chloride, sulfur, iron, magnesium, aluminum or heavy metals were detected.

Sorbacid 911 resulted in a very high P sorption capacity (120-140 $mg_P\ g_{sorbent}^{-1}$ at the typical phosphate concentration in MWW), with the possibility to treat 300-350 bed volumes at the 1 $mg_P\ L^{-1}$ breakpoint. P desorption from Sorbacid resulted more challenging, as a 95% P recovery required the supply of 60 bed volumes of Na_2CO_3 at pH 14 and 60°C.

The G13-P70 composite sorbent resulted in the isotherm tests in a P sorption capacity of 27 $mg_P\ g_{P70}^{-1}$ at the typical phosphate concentration in MWW, whereas the continuous flow adsorption/desorption tests are in progress. The interesting feature of this composite is that it allows the contemporary removal of ammonium (on the geopolymer) and phosphate (on the hydrotalcite). The isotherms indeed resulted in an N sorption capacity of 13 $mg_N\ g_{G13}^{-1}$ at the typical ammonium concentration in MWW.

These results point to the tested sorbents as very promising material for phosphate removal and recovery from MWW and other P-rich effluents, in a circular economy perspective.

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Acknowledgment

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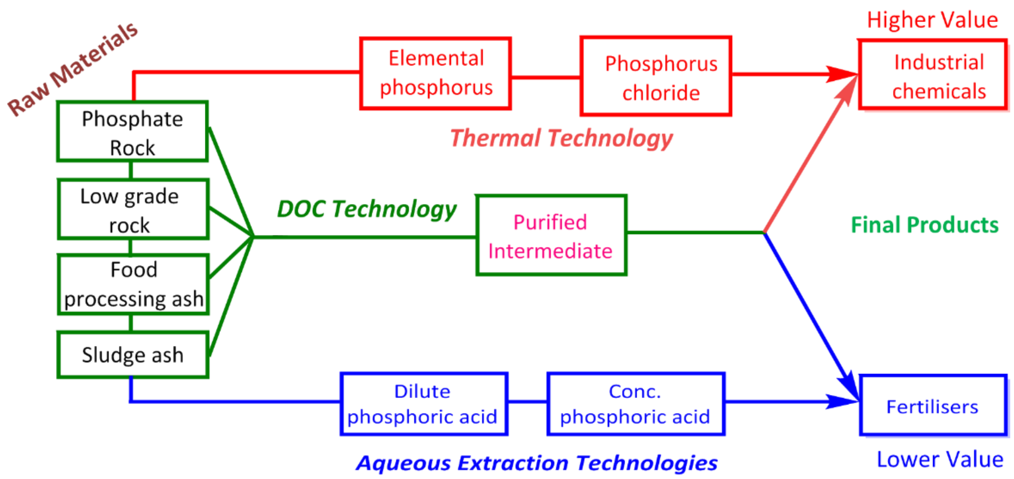
SINFERT: A NOVEL APPROACH TO PHOSPHORUS RECOVERY

Kirill Nikitin, Simon Hodge, Declan Gilheany, Rajan Choudhary

School of Chemistry and School of Agriculture, UCD Dublin, Ireland

Our interdisciplinary project SINFERT is focussed on a novel non-aqueous liquid-phase extraction of phosphorus. Our aim is to address a number of phosphorus challenges by creating efficient and commercially viable recovery of phosphorus from a range of waste streams and bypassing white phosphorus.



The technology comprises of a solid/liquid process leading to a range of pure phosphorus compounds. The effectiveness of industry equivalent DAP and MAP phosphate fertiliser synthesized in our lab has been evaluated in greenhouse trials.

The value of DOC process for the chemical industry is the possibility to bypass white phosphorus *en route* to most industrially relevant phosphorus compounds including trialkyl- and triarylphosphate esters, plasticizers, flame retardants and phosphines.
SINFERT is an ESPP member seeking effective collaboration with industry, policy makers and academic stakeholders.

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PHOSPHORUS RELOADED: TURNING WASTE INTO RESOURCES

Felix Bein

Wien Energie GmbH

Wien Energie is the largest regional energy provider in Austria and a subsidiary of the municipal utility company Wiener Stadtwerke. We reliably supply two million people with environmentally friendly power, cooling, heating, electromobility and telecommunications. In order to promote climate protection, we plan to invest 2.6 billion euros in the next five years to expand the use of renewables such as solar-, wind- and hydropower as well as electromobility. With that we want to decarbonize our portfolio and extend the renewable energy production - all for the goal of a climate neutral Vienna by 2040.

Wien Energie is making significant strides in advancing in the field of circular economy. A initiative focuses on our incineration plant, where we process sewage sludge from Vienna's water treatment facility - one of the largest in Europe. As pioneers in this sector, we are now planning to implement a comprehensive circular economy system by recovering phosphorus from sewage sludge ash. This phosphorus recovery effort is closely aligned with the new Waste Incineration Regulation, which requires the recycling of 80% of phosphorus from sewage sludge by 2033. Our goal is to reduce the import of raw phosphate to Austria by recovering phosphorus, but furthermore we also want to contribute to the circular economy and reduce environmental impact.

In this area we have two initiatives:

- Initiative 1: This initiative is a collaboration between the City of Vienna, a fertilizer producer, and Wien Energie GmbH. The project focuses on using ash itself from sewage sludge mono-incineration for converting it into fertilizer.
- Initiative 2: Currently in planning and preparation phase, this initiative aims to find and establish a collaboration in the field of phosphorus recovery. The aim would be a successful project development and possible phosphorus recovery at least for the city of Vienna starting in 2033.

The role of advanced technologies towards a sustainable phosphorus value chain

Andrea Salimbeni

RE-CORD, Renewable Energy Consortium for Research and Demonstration.

Wastewater discharges about 3 million tonnes of phosphorus into the environment every year globally (1). Excessive release of phosphorus and other substances such as nitrogen form wastewater is not only an environmental issue, but a huge economic loss (2). In fact, phosphorus is an indispensable nutrient used to produce fertilisers, but also added value products. To date, phosphorus is obtained from phosphate rock, a mineral available in only specific regions worldwide. Phosphorus is expensive, and finite. For this reason, both phosphate rocks and phosphorus were included in the EU list of critical raw materials. Reducing nutrient pollution and recovering phosphorus from waste streams can be a win-win solution both for the environment and human health. With the critical raw materials act and the new EU wastewater treatment directive, the EU commission is pushing towards this direction (2).

However, phosphorus losses happen not only when wastewater is discharged, but also when P-fertilisers are applied. According to W.J. Brownlie et al, 2022 (3), phosphorus losses from land to fresh waters have doubled in the last century and continue to increase. It was estimated that about 80% of P is lost or wasted during fertilisers use. Along with the environmental damage, this represents a additional cost for farmers. For this reason, the recovery of phosphorus and nitrogen from waste streams is crucial, but not enough. Advanced fertilising products must be obtained, containing minerals with the target solubility, and in a suitable amount, facilitating precision farming practices.

Despite phosphorus is contained in animal manure, and sewage sludge, its use should be improved. Farmers and wastewater industries, with scientists, must explore ways of recovering phosphorus from manure and sewage sludge to obtain clean phosphate salts. The Global Biodiversity Framework calls for a 50 % reduction in excess nutrients lost by 2030 (4). To create a sustainable phosphorus value chain, scientists and policy makers must set new research targets. Today, further economic and policy support is needed to make recycled phosphates competitive, but P-recovery technologies demonstrated to be ready for the market. To make a further step, research should now target a sustainable, carbon neutral P4 production. To obtain P4, submerged arc furnaces are usually adopted, where SiO_2, apatite, and coke undergo to melting and chemical reactions (5). This process, similar to EAF steelmaking, is a strong consumer of electricity, and fossil coal. But like the steel sector is replacing fossil coal with biogenic alternatives, P4 furnaces could be operated sustainably, replacing coke with biocoal, and phosphate rock with recycled phosphate salts. Both the biogenic carbon, and the recycled phosphorus, they are largely available in sewage sludge, of which Europe is a massive producer.

References

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Go to the website for more details of the conference:
https://www.phosphorusplatform.eu/espc5

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