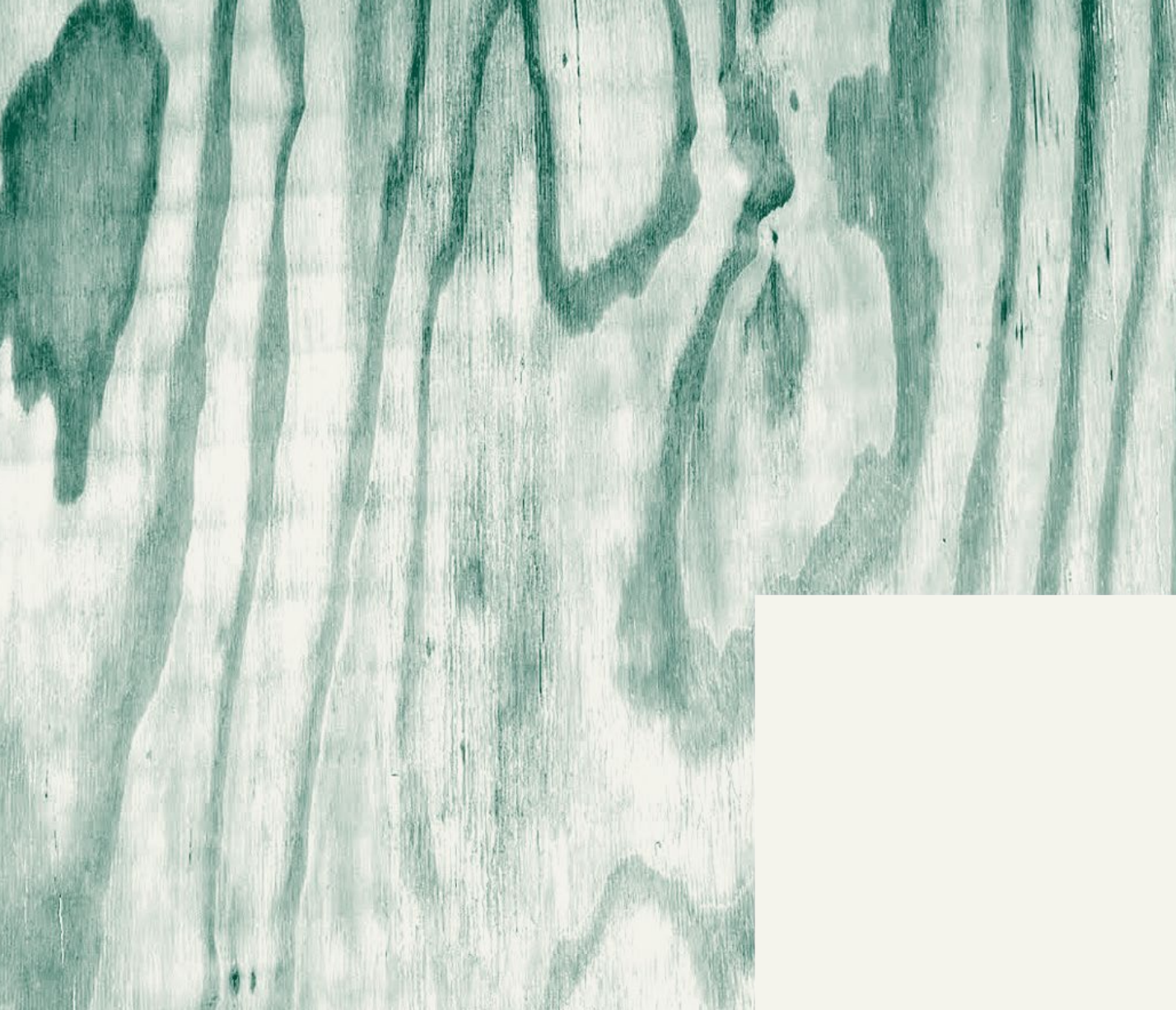




SLUTRAPPORT

Water treatment plants as resource hubs: enabling circularity by maximizing recovery of iron coagulants, phosphorus, silicate materials and others with the Sahara process

EasyMining Services Sweden AB

**RE:
SOURCE**

Slutrapport för projekt:

Vattenreningsverk som resurshub: Sahara-processen möjliggör cirkularitet genom att maximera återvinningen av järnbaserade fällningskemikalier, fosfor och silikatsand

Engelsk titel: Water treatment plants as resource hubs: enabling circularity by maximizing recovery of iron coagulants, phosphorus, silicate materials and others with the Sahara process

Projektperiod: 220815-240815

Datum: 241015

Projektnummer: P2022-00339

Diarienummer: 2022-200507

Projektledare: Hanna Landbring

Organisation: EasyMining Services Sweden AB

Adress: Box 952, 191 29 Sollentuna

Nyckelord: circular economy, sewage sludge, recycling, coagulant, ferric chloride, water treatment, sludge ash treatment

RE:Source är ett strategiskt innovationsprogram och finansieras av

VINNOVA

 **Energimyndigheten**

FORMAS ::

Foreword

This project has been made possible by the funding from Energimyndigheten, Vinnova and Formas within the strategic innovation program Re:Source. We would like to express our gratitude to our project partners Feralco, Sydvatten, Thomas Concrete and Ragn-Sells Treatment & Detox for their expertise and valuable insights that made this project a success. We thank Imperial College London, Svenskt Vatten, Käppala and Stockholm Avfall och Vatten who participated in the workshops and were consulted in the project. Thank you also to IVL Svenska Miljöinstitutet for contributing to the LCA analysis.

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1. Sammanfattning

Projektet undersökte ett nyskapande och cirkulärt förhållningssätt till att producera järnkloridflockningsmedel och silikatprodukter. Ett vattenreningsverk med slamförbränning producerar tiotusentals ton slamaska årligen som ofta läggs på deponi på grund av förekomsten av föroreningar som tungmetaller. Askan innehåller betydande mängder järn, aluminium, fosfor, kalcium, magnesium och silikatföreningar. Återvinning av fosfor från slamaska har de senaste åren fått ökad uppmärksamhet. Medan detta kan göras med högt utbyte är återvinning av järnklorid, som ofta används som flockningsmedel för att producera slammet, inte lika utforskat och därför inte lika effektivt. Den största delen av järnet går förlorat i silikatfraktionen vilket i sin tur begränsar dennas användbarhet. Omkring 15 % av järnet och 90 % av fosfor kan återvinnas med EasyMinings Ash2Phos-process, en teknologi för återvinning av slamaska som snart lanseras i Sverige och Tyskland. Projektet syftade till att avsevärt öka utvinningen av järnklorid och samtidigt öka återvinningseffektiviteten av andra grundämnen genom implementeringen av en tilläggsprocess kallad 'Sahara'. I projektet genomfördes vidareutveckling och optimering av Sahara samt testning med relevant utrustning för att lägga grunden för implementering i Europa. I kombination med Ash2Phos möjliggör Sahara nästintill fullständig återvinning av fosfor och järn ur slamaskan i form av rena, kommersiella produkter som kalciumfosfat och järnklorid. Eftersom järnet i askan effektivt återvinns produceras ett järnfattigt silikatmaterial. Utvärderingen av denna järnfattiga silikatprodukt av Thomas Concrete visade att materialet uppvisar en puzzolaneffekt och kan ersätta cement i betong, vilket leder till märkbara koldioxidbesparingar. EasyMining håller just nu på att utvärdera en standardisering av det återvunna silikatmaterialet genom att göra en Europeisk Teknisk Bedömning (ETA).

Den återvunna järnkloriden utvärderades i samarbete med Feralco och Sydvatten, två av parterna i projektet. Tester bekräftade att produkten är likvärdig sina kommersiella motparter producerade från jungfruliga råvaror och kan användas i vattenrening. En livscykelanalys (LCA) av den återvunna järnkloriden jämfördes med den senaste INCOPA LCA för jungfrulig järnklorid. För implementering i Sverige var koldioxidavtrycket associerat med den återvunna järnkloriden från Sahara lägre jämfört med järnklorid producerad från magnetit utvunnen från bruten malm (ca 75 kg CO₂-ekv. jämfört med 140 kg CO₂-ekv. per ton 40 % järnklorid).

Två workshops sammanförde intressenter från avloppsvattenreningssektorn för att diskutera nya affärskoncept i vilka vattenreningsverk kan bli resursnav och leverera råvaror för cirkulär användning eller andra applikationer. Konceptet "chemicals as a service" utforskades vidare med input från Imperial College London och Ragn-Sells. Workshopparna undersökte hur den återvunna järnkloridens funktion kan erbjudas som en tjänst till användaren i stället för att säljas som en bulkkemikalie, och därigenom skapa ett materialservicesystem med en affärsmodell baserad på "chemicals as a service".

En förstudie av integrering av Sahara i Ash2Phos-anläggningen som planeras i Sverige (Helsingborg) genomfördes. Reningssteg från Sahara infördes i Ash2Phos vilket resulterade i ökad renhet på den återvunna järnkloriden. Således kunde Ash2Phos-processen, även utan Sahara-tillägget, effektiviseras och därigenom kunna producera järnkloridkoaguleringsmedel med hög renhet.

Projektet gjorde det möjligt att titta närmare på processens lönsamhet och utvärdera de återvunna produkterna tillsammans med stora svenska industriaktörer. Stora vinster var ett starkare samarbete mellan intressenter i vattenreningssektorn samt främjandet av innovation genom att erbjuda en cirkulär lösning för järnbaserade flockningsmedel. Sahara kan omdefiniera vattenreningssektorn genom att möjliggöra att reningsverk blir verkligt cirkulära resursnav.

2. Summary

The project investigated a novel and circular approach to producing ferric chloride coagulant and silicate products. A water treatment plant with incineration of sludge produces tens of thousands of tons sludge ash yearly. This is often landfilled due to the presence of contaminants like heavy metals. The ash contains significant amounts of iron, aluminium, phosphorus, calcium, magnesium and silicate compounds. In recent years, recovery of phosphorus from sludge ashes received increased attention. While this can be done with high yield, recovery of iron chloride, widely used as coagulant to produce the sludge, is not as explored and therefore not as effective. Most of the iron is lost in the silicate fraction, limiting its use. About 15 % of the iron and 90 % of the phosphorus can be recovered with EasyMining's Ash2Phos process, a sludge ash recycling technology soon to be deployed in Sweden and Germany. This project aimed at significantly boosting the iron chloride recovery yield while also increasing the recovery efficiency of all other elements through implementation of an add-on named 'Sahara'. In this project, Sahara was further developed, optimized and tested with the relevant equipment, preparing the ground for implementation in Europe. When combined with Ash2Phos, Sahara enables almost complete recovery of the phosphorus and iron in sludge ash as clean, commercial compounds like precipitated calcium phosphate and ferric chloride. Since the iron in the ash is effectively recovered, an iron-depleted silicate material is produced. The assessment of this iron-depleted silicate product by Thomas Concrete showed the material has pozzolanic effect and can replace cement in concrete, leading to considerable savings of carbon dioxide. Currently, EasyMining is evaluating a standardization of the recycled silicate material by pursuing a European Technical Assessment (ETA).

The recycled ferric chloride was assessed in cooperation with Feralco and Sydvatten, two of the partners in the project. Testing confirmed the product is equivalent to its commercial counterpart produced from virgin raw materials and can be used in water treatment. A life cycle assessment (LCA) of the recycled ferric chloride was compared with the latest INCOPA LCA for virgin ferric chloride. For implementation in Sweden, the carbon footprint associated with the recycled Sahara ferric chloride would be lower vs. the ferric chloride produced from mined magnetite (ca. 75 kg CO₂ equivalent vs. 140 kg CO₂ equivalent per tonne 40 % ferric chloride).

Two workshops brought together stakeholders from the wastewater treatment sector to discuss novel business concepts where water treatment plants can become resource hubs and supply raw materials for circular use or use in other applications. The chemicals as a service concept was further explored, with input from Imperial College London and Ragn-Sells. The workshops explored how the function of the recycled iron chloride can be offered as a service to the iron chloride user instead of selling it as a bulk chemical, effectively creating a material service systems with a business model based on chemicals as a service.

Integration of Sahara in the Ash2Phos plant planned in Sweden (Helsingborg) was investigated, concluding a feasibility study. Purification steps from Sahara were adopted into Ash2Phos, resulting in increased purity of the recovered ferric chloride. Thus, even without the Sahara add-on, the Ash2Phos process became better and more efficient, being able to produce high purity ferric chloride coagulant.

The project allowed to look closely at the viability of the process and assess the recycled products together with large Swedish industrial players. Major gains were a stronger collaboration between and with stakeholders in the water treatment sector and promoting innovation by offering a circular solution for iron coagulants. Sahara can redefine the water treatment sector, enabling treatment plants to become real circular resource hubs.

3. Introduction and background

The geo-political and economic events of the last decade confirmed the risks associated with the dependency on imported resources and global industrial material flows. Sweden, alongside many countries, was affected by recent events and has identified potential long-term shortages of phosphorus fertilizers and coagulants for water treatment and drinking water production. Just before the start of this project, Svenskt Vatten had already advised water and sewerage organizations to plan for a 50 % reduced availability of coagulants for the next 6 months (ref. 1).

With pressure to move to a circular economy and decrease greenhouse gas emissions, maximizing the use of secondary materials (wastes) is inevitable. Phosphorus is an essential nutrient for living organisms. The raw material for production of phosphorus fertilizers and animal feed is phosphate rock, a limited resource. In the EU, phosphate rock and phosphorus are critical raw materials (ref. 2). Many countries lack natural deposits and are entirely dependent on imports, making them vulnerable to market fluctuations and geo-political factors. One measure proposed to reduce the import dependency of phosphorus and over-exploitation of natural deposits is its recovery from wastewater and sewage sludge. Governments and industries have recognised this potential and countries like Germany have already adopted legislation which mandates recovery of phosphorus (ref. 3). Alongside phosphorus, significant amounts of iron end up in the sewage sludge. This originates from the iron chloride coagulants used in water treatment plants. In Sweden, iron chloride is produced almost exclusively from virgin magnetite. Sludge oxidation (e.g., incineration) is a key treatment method for biological detoxification, creating ash with concentrated valuable substances (phosphorus, iron, aluminium etc.). However, heavy metals are also concentrated in the ash. For this reason, the ash is often landfilled as technologies to recycle it are not widely available at industrial scale.

EasyMining has developed Ash2Phos, a wet-chemical process that recovers elements from sludge ash and plans to introduce this to the German and Swedish markets in the coming years. Ash2Phos is one of the few solutions that targets individual recovery of all sludge ash constituents, including heavy metals. The process is optimized for recovery of phosphorus (about 90 % yield), but also recovers, among others, 15 % of iron as ferric chloride coagulant. An insoluble silicate sand with the undissolved iron and phosphorus is produced. The leftover phosphorus and the red color (given by the residual iron oxide) in this sand limits its applicability. Cleaning the silicate fraction (further recovery of phosphorus and iron) opens up other applications and prevents insertion of iron into applications where it is not needed. This can be achieved with 'Sahara', an Ash2Phos add-on that enables very high recovery yields for the iron and phosphorus in sludge ash. Iron is recovered as ferric chloride of drinking water quality, making the Ash2Phos-Sahara process a truly circular solution for coagulants. At the same time, this enables production

of iron and phosphorus-free silicate material with pozzolanic effect. This project focused on improving the Sahara process, integrating it into Ash2Phos and preparing for the deployment in Europe.

Sahara offers huge potential for circularity in water treatment and has potential to:

- Change production of iron coagulants and concrete using a secondary source and a process with lower carbon footprint.
- Use other iron sands, e.g., mining waste, reducing the amounts disposed in landfills.
- Save greenhouse gas emissions in construction by replacing cement in concrete with clean silicate fractions.
- Produce clean silicate materials for other applications where the requirements for composition and purity are higher.

An Ash2Phos plant in Helsingborg processing 30 000 t ash/y; will produce 18000 t/y silicate material (dry equivalent) with 15 % wt. iron. An integration of Sahara in the plant to process this could produce 20000 t/y ferric chloride coagulant (40 % solution) and 13 000 t/y iron-free silicate suitable for cement replacement. Sahara would consume mainly hydrochloric acid (still needed to produce ferric chloride from virgin material; available as byproduct on-site), with no waste generation. This is possible due to clever internal circulation of process streams and selective extraction to produce high purity iron chloride. The technology further purifies the ferric chloride stream recovered in Ash2Phos, upgrading this to drinking water quality. The plant could produce most of Sweden's iron chloride needs (estimated at 30000 t of 40% iron chloride per year). In the same thought experiment, a full implementation in Europe will replace hundreds of thousands of tons of sand and recycle hundreds of thousands of tons of iron, so the potential is that a large part of the iron chloride production in Europe will be able to be based on recycled raw materials instead of virgin iron ore (magnetite).

4. Method

The work was structured into several work packages (WPs) (Table 1). The actors involved are presented in Table 2.

Work package	Name	Actors involved
WP0	Project management	All partners
WP1	Planning and preparation	All partners
WP2	Process scale-up and integration in Ash2Phos	EasyMining
WP3	Assessment and validation of products	All partners
WP4	Market analysis and implementation plan	EasyMining with input from partners and stakeholders
WP5	Circular Business Model Development	All partners, Imperial College London, stakeholders from water treatment sectors
WP6	Communication and dissemination	All partners

Table 1. Organization of the project

Actor	Main roles
EasyMining	Coordinator, running the pilot and production of samples, market study and business case
Feralco	Validation of the recycled ferric chloride
Sydvatten	Validation of the recycled ferric chloride
Thomas Concrete	Validation of the recycled silicate fraction
Ragn-Sells Treatment and Detox + Imperial Collage London	Chemicals as a service concept for ferric chloride, workshops with stakeholders
IVL	Life cycle asesement

Table 2. Main roles of the participants

The actions in WP0 (Project management) were carried out throughout the whole project. The goal of this WP was to coordinate and monitor the project to ensure efficient and successful piloting, product validation and establishing the basis for industrial implementation. EasyMining acted as coordinator. The efforts were led by Hanna Landbring, an experienced project manager and process engineer. The project manager reported to EasyMining's internal Steering Committee. The presence of experts from all the different disciplines in EasyMining (R&D, market, engineering) in this Committee ensured a good balance for implementing the activities. Relevant actions in this WP were: update meetings and communication between the partners, monitoring the progress, monitoring risks and implementing contingency methods, documentation, reporting and quality control.

The work in WP1 (Planning and preparation) was carried out in the beginning of the project and before the start of major actions in other WPs. The goal was to make all the necessary planning and preparations for the actions and have a clear overview of the activities and division of tasks. WP1 ensured that the responsibilities between the participants were clear and agreed on. Relevant actions included a kick-off meeting with all partners at the start of the project; detailed planning of the lab and pilot activities; work protocols; purchases (chemicals, equipment, booking of external services); risk assessments; setting up equipment and preparing the facilities for upcoming tasks.

WP2 (Process scale-up and integration in Ash2Phos) consisted of two parts:

- R&D activities to optimize the integration of Sahara in Ash2Phos. Experiments were conducted to optimize the operating parameters, maximize the concentration of the iron chloride product, and ensure a good water balance and reduced chemical consumption.
- Piloting activities, where the optimized process was scaled up and tested with relevant equipment. Dedicated leaching reactors, a filter press and a belt filter were used for the leaching and solid-liquid separation steps. Separation and purification of ferric chloride was investigated using mixer-settlers and an extraction column. The technical limitations, the impact of recirculation and the concentrations of elements in all steps were assessed. Upgrades, modifications to the process and equipment changes were evaluated (also part of WP4).

In WP3 (Assessment and validation of products), the efforts focused on producing and testing the Sahara products together with the partners and stakeholders. Feralco and Sydsvatten assessed the iron chloride product. This included screening of constituents (including potential impurities), coagulation tests and comparisons with commercially available coagulants. Thomas Concrete investigated the silicate product by performing tests according to different standards like SS-EN 196, SS-EN 12390, SS 137244 / CEN TS 12390-9, SS-EN 12617 (pozzolanic effect, compressive strength, activity index studies etc.). The impact of Sahara on the quality of Ash2Phos streams and products was evaluated.

The work carried out in WP4 (Market analysis and implementation plan) looked at commercialization of Sahara and integration of Sahara in the first Ash2Phos plant planned in Sweden. The activities involved:

- Market analysis and future market development for the products (silicate fraction and ferric chloride) and feedstock (additional hydrochloric acid and specific chemicals used in Sahara).
- Performing a feasibility study for the Helsingborg case. This included CAPEX calculations, limitations for implementation of Sahara, and plant layout and design.
- A life cycle assessment (LCA) done by the Swedish Environmental Institute (IVL) based on piloting and feasibility study data supplied by EasyMining. The aim was to compare the environmental impact of the ferric chloride recycled with Sahara in Helsingborg with the virgin product equivalent.
- Updated data sheets for the products.

WP5 (Circular Business Model Development) looked at a novel circular business model concept of chemical-as-a-service (CaaS). The closest comparison is the concept of chemical leasing, which is often described as the performance business model for chemical management. The actions of this WP explored how the function of the iron chloride, as recovered through the Ash2Phos and Sahara processes, can be offered as a service to the

iron chloride user instead of selling it as a bulk chemical, effectively creating a Material-Service Systems (MSS) with a business model based on CaaS. This was studied together with Imperial College London (ICL) and stakeholders from the water treatment sector, including Svenskt Vatten, Sydvatten and Feralco. Two Material-Service System workshops were organized based on ICL's framework.

Communication and dissemination activities were carried out in WP6. The goal was to create awareness about the project, its importance and progress. The participants' communication offices engaged in activities to disseminate results from the projects and reach relevant target audiences. For additional information, refer to sections 7 and 8.

5. Results and discussion

The implementation of the actions was successful, and the tasks set up in the work packages described above were effectively carried out. The Sahara process was further optimized and tested in a suitable pilot environment with relevant equipment. Notable optimizations include:

- Tailoring the composition of the ferric chloride extractant (which is regenerated and reused continuously in the process) to allow improved rejection of elements undesired in the product (calcium, phosphoric acid, heavy metals) and improve the purity of the recovered ferric chloride.
- Reduction in the number of separation and purification steps used.
- Lowering the energy consumption in the process by reducing the dissolution time and changing the equipment used for extraction (for example, lowering the number of electrically powered agitators).

The purification steps from Sahara were adopted into Ash2Phos, where ferric chloride is also produced (but a significantly lower volume vs. Ash2Phos + Sahara). These steps allow further purification of the Ash2Phos ferric chloride stream, resulting in a higher purity for this product. Thus, even without the Sahara add-on, the Ash2Phos process became better and more efficient. When it comes to product quality, the recycled product can be upconcentrated to a stable 40 % ferric chloride coagulant of high purity, in line with the specifications outlines in standard SS-EN 888 (ref 4).

The recycled ferric chloride produced with the Sahara technology was supplied to Feralco and Sydvatten for assessment and testing. The experiments confirmed the recovered ferric chloride is equivalent to its commercial counterpart produced from virgin raw materials and is a suitable replacement for water treatment.

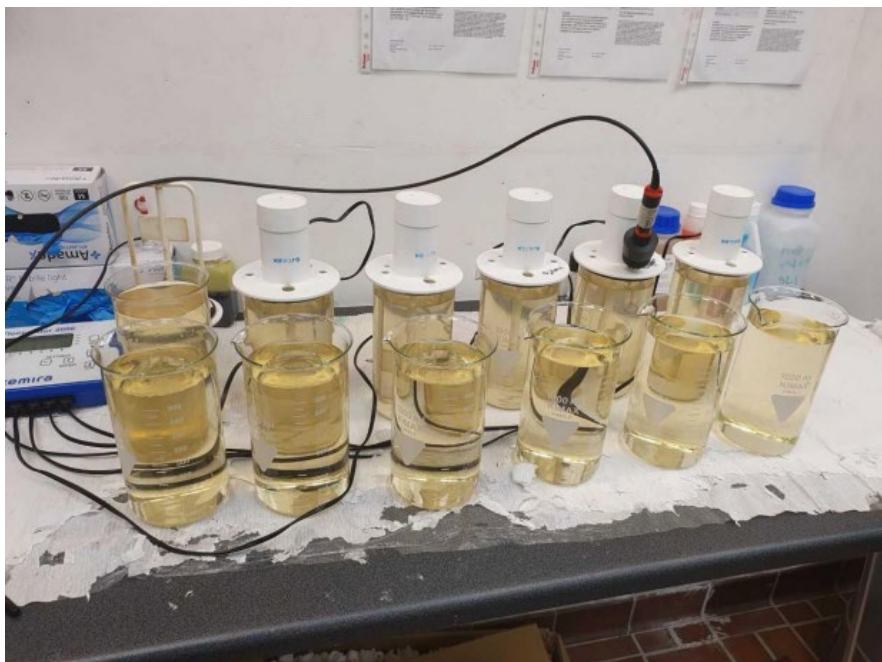


Figure 1. pH test with the recycled coagulant at Sydsvatten

A life cycle assessment (LCA) of the ferric chloride coagulants recovered by Sahara was compared with the latest INCOPA LCA for ferric chloride. For implementation in Sweden (Helsingborg), the carbon footprint associated with the recycled Sahara ferric chloride would be lower vs. ferric chloride produced from magnetite (ca. 75 kg CO₂ eq vs. 140 kg CO₂ eq. per tonne 40 % ferric chloride).

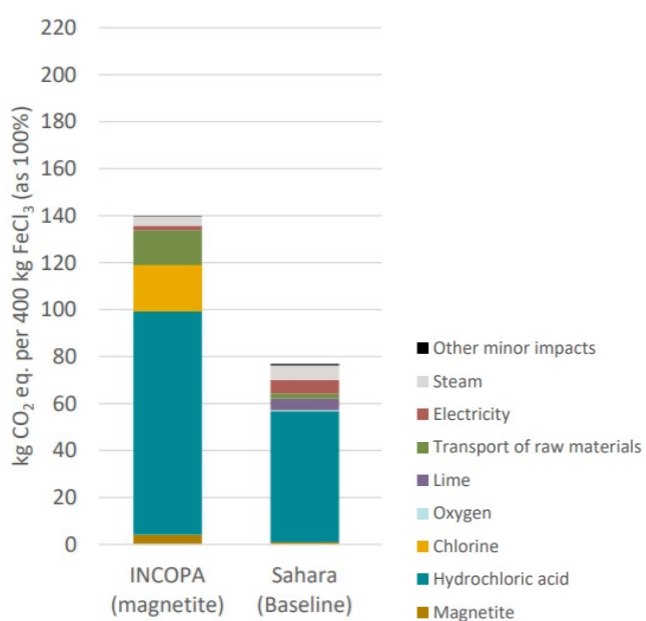


Figure 2. LCA for the recycled ferric chloride coagulant compared to coagulant produced from virgin mining of magnetite (Helsingborg case).

The assessment of the iron-depleted silicate material by Thomas Concrete showed this fraction has pozzolanic effect and can replace parts of the cement in concrete, leading to considerable savings of CO₂. Currently, EasyMining is evaluating a standardization of these recycled silicate materials by pursuing a European Technical Assessment (ETA). Chemical analysis has shown the material is rich in silicates (40 % silicon content), mainly of silicone dioxide. The material is stable when subjected to water leaching tests, showing no dissolution of heavy metals or other constituents.

The feasibility study showed that the implementation of Sahara in Ash2Phos in Helsingborg is both technically and economically feasible. The addition of Sahara introduces several large and expensive pieces of equipment to the process. A layout of the process was created which made it possible to fit Sahara in the already allotted space for the plant in Helsingborg. An analysis of the business case showed that the projected revenue from the increased production of mainly ferric chloride, but also aluminium and phosphorus products, could motivate the higher CAPEX cost when including Sahara, potentially improving the business case. Key limitations of the feasibility of implementing Sahara are available space in the process building, the availability and price of hydrochloric acid as well as the price and available market for the ferric chloride.

The workshops organized by Ragn-Sells together with Imperial College London brought together stakeholders from Svenskt Vatten, EasyMining Sweden and Germany, coagulant producers (Feralco) and coagulant users (water treatment plants, Sydsvatten, Stockholm Vatten och Avfall, Käppala). The discussions focused on:

- the Material-Service Systems and Chemicals as a Service (CaaS)
- aspects of CaaS (the business model & benefits and risks for business, the planet and society; business model discussion)
- the collective ambition of the participants.

The Ash2Phos and Sahara technologies and recycling of coagulants were discussed. Modelling the flow of ferric chloride with online tools (Flow Mapper, Mural) was done.

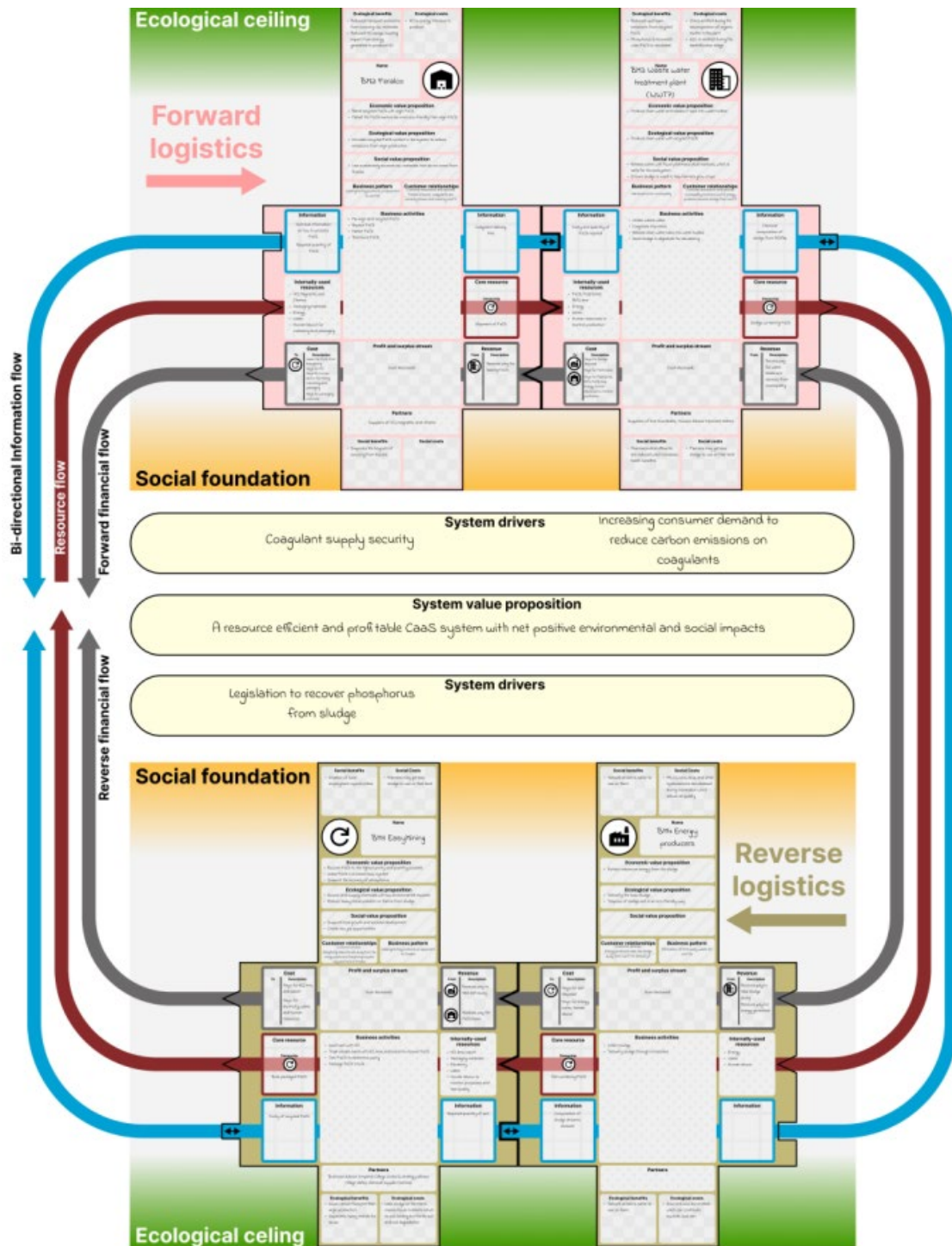


Figure 3. Modelling the flow of ferric chloride chloride and the CaaS Circular Business Ecosystems Model Canvas

The project strengthened the collaboration between stakeholders in the water treatment sector and promoted innovation by offering a circular solution for iron coagulants.

6. Conclusions, utilisation and next step

The Ash2Phos + Sahara combination offers a sustainable solution that transforms wastewater treatment plants with sludge incinerators into circular resource hubs. The technology enables circularity of iron coagulants and minimizes exploitation of natural resource. Iron chloride is often produced from mined magnetite and hydrochloric acid, and is widely used in water treatment plants to precipitate phosphorus. However, this is presently a one-time use. Complete recycling of iron as high purity iron chloride, made possible by Sahara, makes the water sector more sustainable and circular. Combined with Ash2Phos, Sahara can transform the water treatment sector into hubs that fully converts waste (sludge ash) into phosphorus fertilizers, iron and aluminum coagulants, silicate product with various industrial applications (including cement replacement) and other valuable compounds. At the same time, heavy metals in the waste are recovered as separate fraction for safe disposal.

A circular solution like Sahara is attractive for major consumers of iron chloride (water treatment plants, the pulp and paper industry) and silicates (cement and metal industries, glass producers), which desire more sustainable and climate smart materials. Since sludge ash and iron sands are generated globally, Sahara is applicable in many regions. Therefore, there is great opportunities to export the technology and contribute towards global climate savings and sustainability.

Implementation of Sahara in an Ash2Phos plant with a capacity of 30 000 tonnes ash/year can generate ca. 20000 tonnes of 40 % ferric chloride coagulant/year. In Sweden, this could cover a large percentage of the ferric chloride demands.

7. Publication list

Avyay J. et al., 2024. Modelling an Ecosystem of Business Models in a Circular Value Chain: the Circular Business Ecosystem Model Canvas. Proceedings of the Design Society , Volume 4: DESIGN 2024 , May 2024 , pp. 1309 - 1318. Available at: [Modelling an ecosystem of business models in a circular value chain: the circular business ecosystem model canvas | Proceedings of the Design Society | Cambridge Core](#)

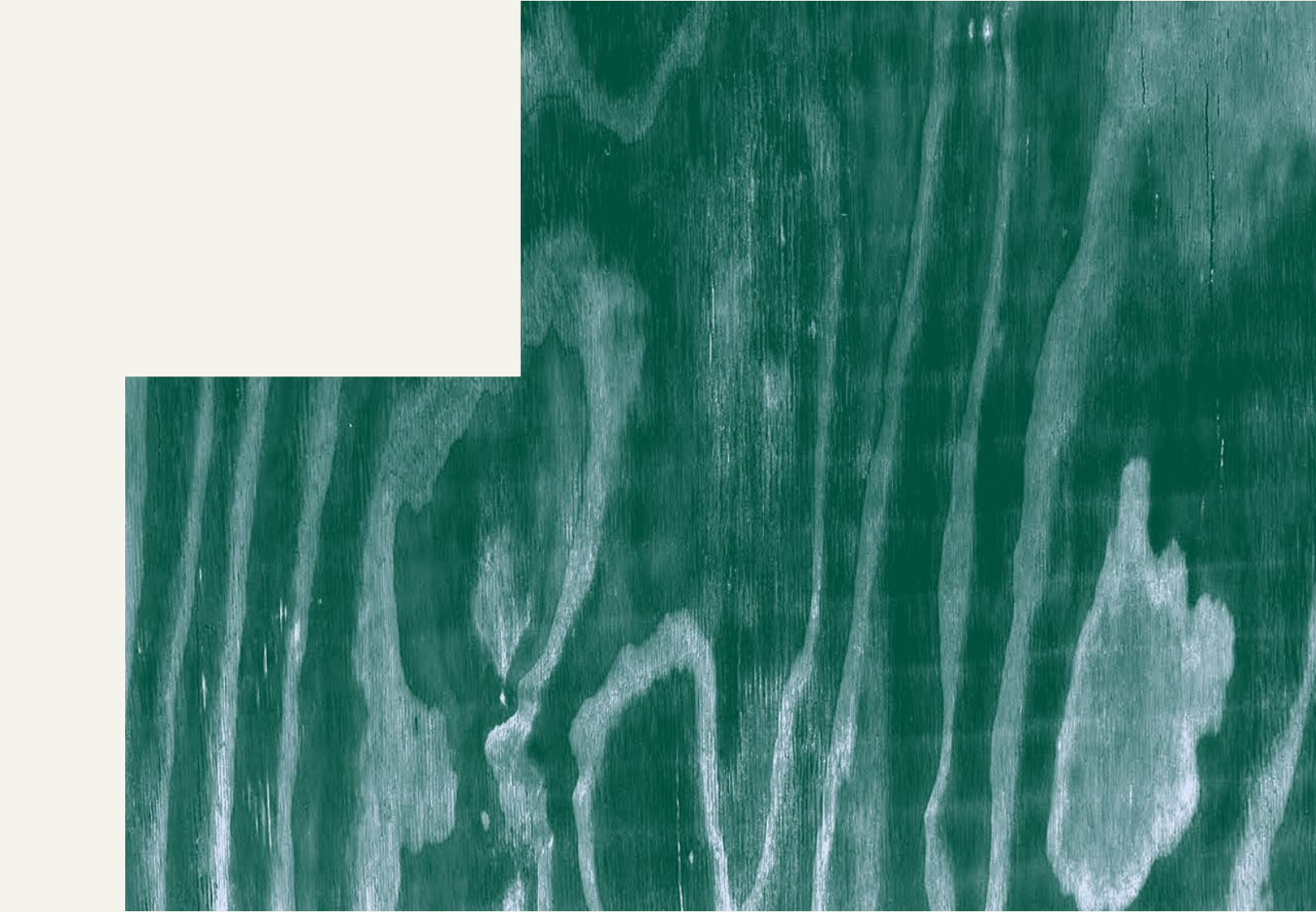
8. Project communication

Communication activity	Target audience	Additional information/ link
Dedicated project webpage on the EasyMining website	Scientific, general public, policy makers, industry	
Dedicated project webpage on the Re:Source website	Scientific, general public, policy makers, industry	<u>Vattenreningsverk som resurshub: Sahara-processen möjliggör cirkularitet genom att maximera återvinningen av järnbaserade fällningskemikalier, fosfor och silkatsand - RE:Source (resource-sip.se)</u>
EasyMining receives grant to expand its resource recovery tech	Scientific, general public, policy makers, industry	<u>EasyMining receives grant to expand its resource recovery tech</u>
How a new add-on makes phosphorus recovery more circular	Scientific, general public, policy makers, industry	<u>New process makes phosphorus recovery more circular (easymining.com)</u>
New process maximises material recovery in water treatment plants	Scientific, general public, policy makers, industry	Press release
Chemicals as a service Workshop 1	Policy makers, industry	Jan 19 2023, Stockholm
Chemicals as a service Workshop 2	Policy makers, industry	Nov 29 2023, Göteborg
Conference presentation CRU phosphates 2013	Scientific, policy makers, industry	27 Feb – 1 Mar 2023, Vienna

Conference presentation CRU, Istanbul	Scientific, policy makers, industry	Feb 2023
Conference presentation IWAT, Toronto	Scientific, policy makers, industry	11-15 August 2024
Berlin Sewage Sludge Conference 2023	Scientific, policy makers, industry	13-14 Nov 2023

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