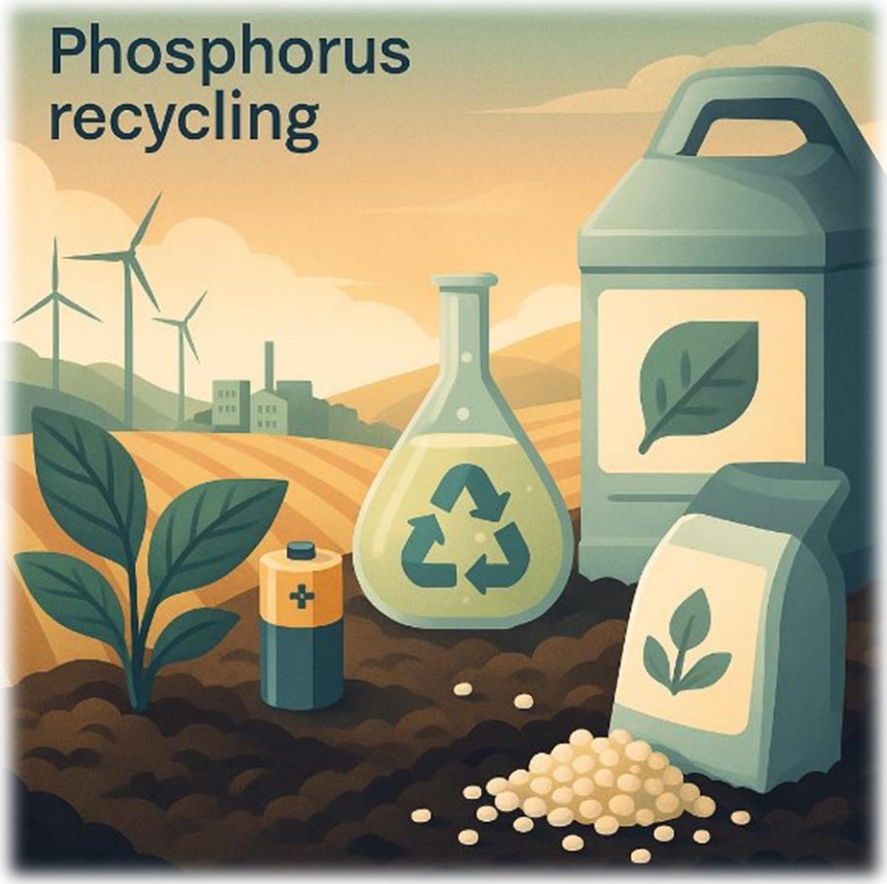
RDEL 10: Phosphorus Pilot Preliminary Feasibility Study

Deep Demonstration of a Circular, Regenerative, and Low-Carbon Economy in Slovenia: Implementation of Phase 2

Work Package 1: Systems Innovation – Portfolio Design, Composition & Governance Support



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Contents

EXECUTIVE SUMMARY **3**

INTRODUCTION **4**

EUROPEAN POLICY CONTEXT 4
HIGH-LEVEL OPPORTUNITIES FOR SLOVENIA 5
METHODOLOGY AND PROCESS 6

PHOSPHORUS PILOT – SCOPE AND OBJECTIVES **8**

PURPOSE AND SCOPE 8
OBJECTIVES 9

WHY A PHOSPHORUS PILOT? **9**

VALUE PROPOSITION 10
STAKEHOLDERS, ROLES, AND INTENDED BENEFICIARIES 11
PILOT SCHEME 11

TECHNICAL FEASIBILITY **12**

INPUT ASSESSMENT 12
PARTNER NEEDS 14
PRELIMINARY BUDGET CONSIDERATIONS 18
KEY CHALLENGES 19

PILOT LOCATION **19**

FUNDING SOURCES AND OPPORTUNITIES **19**

ENVIRONMENTAL AND SOCIAL FEASIBILITY **22**

PILOT DEVELOPMENT PLAN **23**

POTENTIAL STAGES OF DEVELOPMENT AND IMPLEMENTATION 23
GOVERNANCE MECHANISMS 24

CONCLUSIONS AND RECOMMENDATIONS **26**

RECOMMENDED NEXT STEPS FOR THE PHOSPHORUS PILOT 26
POLICY AND STRATEGIC RECOMMENDATIONS FOR ENABLING ENVIRONMENT 27

APPENDICES **31**

LIST OF STAKEHOLDERS ENGAGED 31
STAKEHOLDER EVENTS ORGANIZED AND KEY MULTISTAKEHOLDER MEETINGS 33
REFERENCES 34

Executive summary

Over a 9-month period, **Climate KIC**, together with the **National Institute of Chemistry (KI)** and key regional partners, has developed an initial feasibility assessment for a phosphorus recycling pilot in Slovenia. The pilot sits within Slovenia's Deep Demonstration work on Critical Raw Materials and responds directly to the **EU Critical Raw Materials Act (CRMA)** and broader EU circular economy ambitions. Unlike existing nutrient-recycling practices in agriculture, this initiative focuses on recovering phosphorus from wastewater-derived streams and landfill leachate to produce high-added-value chemicals and advanced materials, including inputs for cleaning products and next-generation battery systems.

The concept is exploratory since the pilot is at an early stage. Building on strong R&D capacity at **KI/ Center for Demonstration of Low Carbon Technologies (DUBT)**, the pilot will test multiple recovery routes from activated sludge, sludge ash, biochar, landfill leachate, and selected industrial residues, and evaluate their suitability for different end-uses. A regional value chain is emerging around **Zasavje**, with **Ceroz d.o.o.** and **Surovina d.o.o.** providing access to real waste streams and **TKI Hrastnik d.d.** and other industry partners exploring downstream integration into phosphate-based products. Initial mapping confirms the technical potential and strategic relevance, but key parameters such as preferred technology route, target products, scale, and economics still need to be validated through systematic sampling, bench-scale testing, and market dialogue.

The study identifies promising **funding pathways** (RRI, STEP, Horizon Europe, LIFE, and other EU instruments), while underlining the need for a modular, multi-source financing strategy and a business-led consortium to access cohesion funds. Main risks relate to input variability and contamination, uncertain product markets and specifications, and the early **TRL** of several recovery options.

Overall, the feasibility work concludes that phosphorus recovery from wastewater and landfill streams is a strategically important and technically promising opportunity for Slovenia. The recommended next steps are to mature the concept through targeted laboratory work and environmental assessment, refine roles and governance with regional partners, and prepare a first wave of funding applications to support bench-scale validation from 2026 onwards.

Introduction

As part of the work on **Critical Raw Materials (CRMs) of the project** "Slovenia's Deep Demonstration for a Circular, Regenerative, and Low-Carbon Economy in Slovenia", two task forces -**Phosphorus and Magnets–Rare Earths (REE)** - were set up for the development of pilots on circular critical raw materials. **Why circular CRM pilots?** To address the necessity of strengthening and increasing the resilience of European and Slovenian CRM value chains in a sustainable and circular manner in response to the **EU Critical Raw Materials Act (EU CRMA) requirements.**[3]

The selected CRMs that the pilots focus on are a result of desk research integrated with stakeholder input and validation from leading research institutions such as the National Institute of Chemistry (KI), the Jožef Stefan Institute (IJS), the Slovenian National Building and Civil Engineering Institute (ZAG), and the Geological Survey of Slovenia (GeoZS). The consultation and stakeholder engagement process included also the Chamber of Commerce and several Ministries - Ministry of Economy, Tourism and Sport (MGTŠ), Ministry of Cohesion and Regional Development (MKRR), Ministry of Environment, Climate, and Energy (MOPE), Ministry of Public Administration (MJU), and the Ministry of Higher Education, Science and Innovation (MVZI).

This endeavour aims to build upon national Research, Development, and Innovation (RDI) capacities in the field and foster **multistakeholder collaboration, bringing together research, industry, and policy.**

The phosphorus pilot is led by the **National Institute of Chemistry (KI) and aims to recycle phosphorus to produce high-added-value circular products by using sludge, landfill leachate, and industrial phosphorus waste streams as inputs.**

The present feasibility study aims to provide a clear overview of the pilot's concept, the methodology used during the process, the rationale, its scope, and value proposition, while providing indicative information regarding costs, fundraising options, and a proposed pilot implementation plan.

European policy context

To mitigate the supply chain vulnerabilities, reduce dependency on imports from single-source suppliers, and to foster strategic partnerships, the European Union adopted the **EU Critical Raw Materials Act (CRMA)** in 2024. The CRMA sets ambitious targets for CRM extraction, processing, recycling, and diversification of imports:

- Extract and produce at least 10% of the EU annual CRM consumption,
- Process at least 40% of the EU annual consumption,
- Recycle at least 25% of the EU's annual consumption,
- No more than 65% of each material originates from a third country.

One specific article of the EU CRMA is of utmost relevance for the pilot:

- **Article 26 'National measures on circularity'** states that each member state has two years to adopt and implement national programmes with measures such as improving technology and resource efficiency to moderate CRM demand, increasing re-use and repair of components with CRM, increasing collection, sorting, and processing of waste with relevant CRM recovery potential, etc.

High-level opportunities for Slovenia

Between April and August 2025, Climate KIC wrote a **Scoping report of critical raw materials in Slovenia**, providing an overview of the current status of the CRM landscape in the country, while identifying challenges and high-level opportunities.

In the context of the EU CRM strategy and industrial policy, Slovenia has several strategic opportunities ahead:

Mapping resource base and national strategic direction

- Identify and assess its domestic CRM potential through systematic reconnaissance and exploration;
- Define a CRM National strategy and action plan;

Innovation capacity

- Strengthen its participation in European research and innovation projects;

Regional positioning

- Position itself as a niche player in sustainable and circular CRM supply chains;
- Position itself as a regional player for CRM circularity in synergy with its bordering countries and the Western Balkans.

Methodology and process

The methodology for the assessment, selection, and development process of this pilot concept was structured as follows:



1. **Exploration**

The exploration process used desk research, including international reports and strategies, complemented by stakeholder engagement inputs and validation. This process led to a multistakeholder meeting on **May 27**, which confirmed the interest of stakeholders to work on a CRM pilot project initiative and increased understanding of the CRM context in Slovenia, including its key stakeholders and capacities. The meeting led to the development of a mapping table of CRM initiatives in Slovenia.

2. **Assessment and validation**

The matrix allowed Climate KIC to work on the assessment of projects and initiatives already present in Slovenia for several CRMs. The assessment produced a shortlist based on three main indicators: **Economic importance (EI)** and **Strategic Relevance (SR)** based on the EU CRMA, the **Circular Economy Potential (CEP)** based on expert feedback and national capacities, and the **Availability (A)** of the CRM streams.

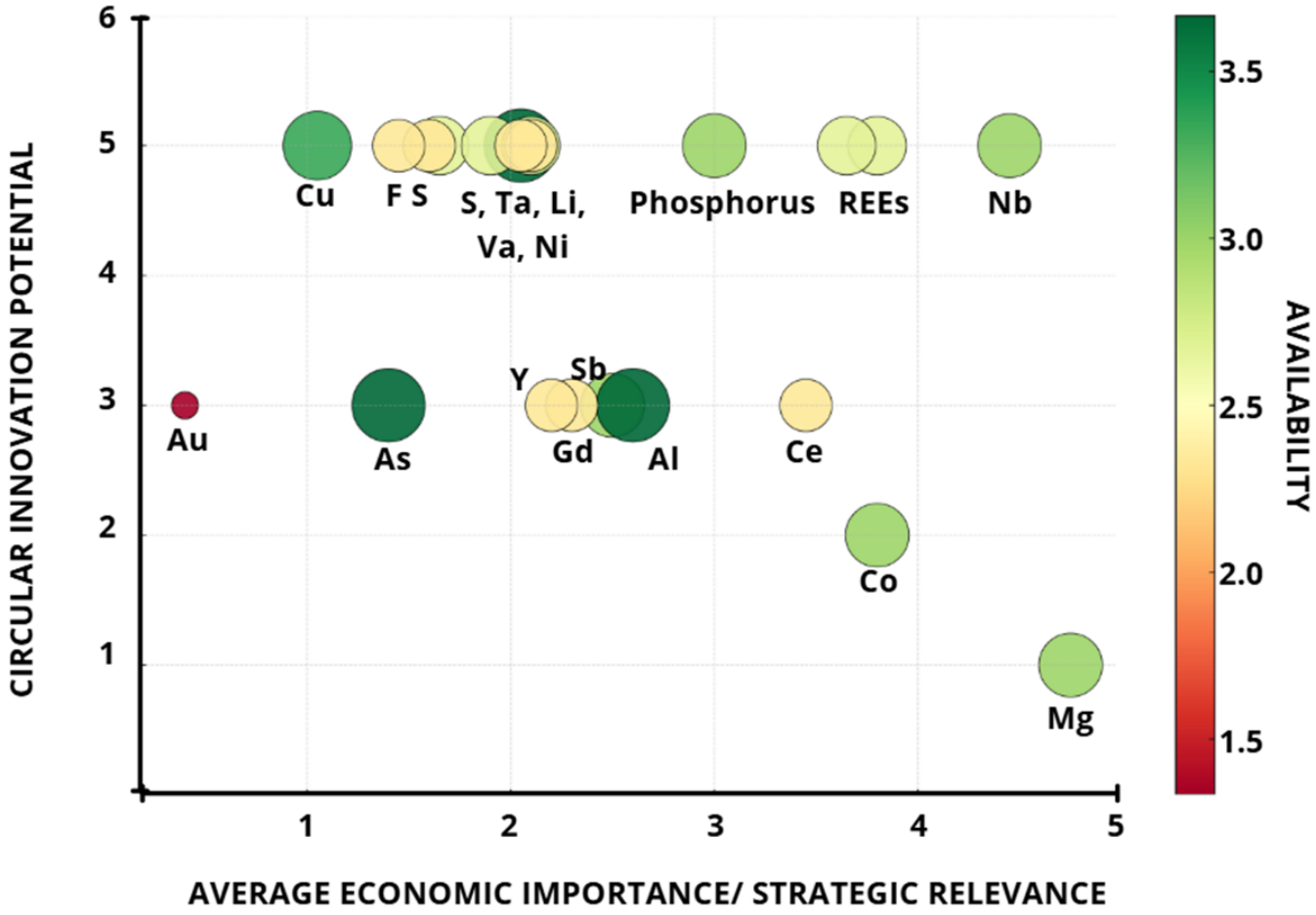


Figure 1 – Assessment of CRMs for prioritisation

On June 10, a prioritisation meeting was held at the National Institute of Chemistry (KI) with the aim of shortlisting up to two CRM streams of the highest potential and relevance for Slovenia and narrowing down the scope of the pilot. The outcome was a shortlist of three following value chains: **Phosphorus, Heavy and Light Rare Earth Elements (HREE-LREE), and batterie**s.

3. **Stakeholder orchestration and drafting**

A taskforce was developed around the pilot based on key industry players relevant to the topic already working in collaboration with the National Institute of Chemistry.

A series of explorative **trilateral meetings between KI, Climate KIC,** and each phosphorus pilot taskforce stakeholder was carried out between **July and August, including Ceroz, Surovina, TKI Hrastnik, ACIES BIO, and ZAG**. Such interviews served to present the initiative and preliminary concept of the pilot to the stakeholders and assess their potential interest, role, needs, and challenges. This allowed to confirm the stakeholders of the taskforce and provide a well-defined

overview to start working in the technical details. **On August 7**, a meeting with the **Regional Development Agency of Zasavje** served to validate the initiative and concept of the pilot from the regional perspective, and to ensure that the pilot is in line with the regional direction of development.

On September 10, the first in-person **meeting of the entire taskforce** took place during the joint multistakeholder workshop of the CRM workstream of the Deep Demonstration project. This workshop included the presence of both taskforces, phosphorus and REEs. The stakeholders from the phosphorus taskforce who participated included the National Institute of Chemistry (KI) and Slovenian National Building and Civil Engineering Institute (ZAG) as technical partners, and industry players such as Ceroz, ACIES BIO, and Surovina. The meeting explored the technical, logistical, and economic aspects of phosphorus sourcing from activated sludge in Slovenia, the technical aspects of phosphorus availability and chemical form in activated sludge, and the feasibility of processes led by industry partners. Most importantly, it led to the definition of the potential scope of the pilot and identification of key questions, challenges, and issues to be addressed.

Following the workshop, interviews were conducted with all stakeholders to build a comprehensive overview of needs, priorities, and refine the concept of the pilot.

All the above contributed to the content of this document.

Phosphorus pilot – Scope and objectives

Disclaimer: *At the current stage, several processing routes remain under consideration.*

Purpose and scope

Phosphorus recycling already exists within Slovenian agricultural practices based on composting and anaerobic digestion practices that use sludge and manure as secondary sources rich in phosphorus. While the need to close phosphorus nutrient loops in the food system is of great concern and relevance for Slovenia, this pilot focuses on the **recycling of phosphorus needed to produce high-added-value products from municipal wastewater sludge** (from here on referred to as “sludge”).

The pilot initiative will explore the use of **excess activated wastewater sludge, ashes, and biochar** resulting from sludge processing/treatment, **landfill leachate, and potential industrial effluents and residues with high phosphorus**. Potentially, other sources might be added as the pilot develops and also depending on commercial and industrial opportunities. Collaboration among different research institutions and industry players will allow for the testing and exploration of the production of **cleaning products** (in collaboration with TKI Hrastnik d.d.) and the use of recycled phosphorus for its use in **novel batteries** (in collaboration with the Centre for Demonstration of Low Carbon Technologies (DUBT)).

Objectives

The pilot's implementation will contribute to:

- **Developing a regional circular value chain:** Establishing a regional circular value chain for phosphorus recycling centred in Eastern Slovenia with an epicenter in Zasavje, and a potential for national and cross-border expansion.
- **Demonstrating recovery technologies:** Optimising phosphorus extraction from activated sludge, related derivatives (ash, biochar) and landfill leachate, and enabling the production of high added-value phosphorus-based chemicals.
- **Supporting prototype battery material development and performance testing:** This will be achieved in collaboration with DUBT, including the use of phosphorus compounds in novel battery chemistries and recycling of $LiFePO_4$ (LFP) battery materials.
- **Assessing phosphorus availability and composition in input secondary streams** through systematic sampling and characterisation, in collaboration with Ceroz d.o.o., Surovina d.o.o., and other waste operators.

Why a Phosphorus pilot?

The **EU Critical Raw Materials Act (EU CRMA)** includes phosphorus and phosphate rock in its critical raw materials (CRMs) list. Furthermore, the incoming **EU Circular Economy Act** is expected to address phosphorus circularity.

Phosphorus is used in a wide variety of products, including **cleaning products rich in phosphates,** and its use is currently being researched in **novel battery technologies**. Thus, sustainable and circular sourcing becomes essential for a **green chemical industry** in Europe, and potentially a key contributor to the **green transition and clean technologies**.

Phosphorus is a precious resource and is mainly obtained from **mined phosphate rock**. Slovenia and Europe are highly dependent on imports from countries such as Morocco and China, which makes phosphate rock **highly sensitive to geopolitical risk**. Its reserves are also depleting over time. At the same time, phosphorus is highly used for the production of **synthetic fertilizers** for the agricultural sector worldwide, which highlights the need to address the sourcing of phosphorus in a sustainable manner that doesn't threaten **food security**.

In this context, increasing the circularity of phosphorus and phosphate through recycling offers an opportunity for Europe and Slovenia. In particular, it could **reduce import dependency**, **secure supply** for the EU, while increasing the **circularity** of value chains.

A demonstration pilot for phosphorus and phosphate recycling represents a great opportunity for Slovenia to position itself as a strong macroregional[1] player on sustainable innovation and circular CRM value chains.

Value proposition

This pilot initiative offers strategic, environmental, and economic advantage for Slovenia and its region (Adriatic, Western Balkans, and Central Europe):

- **Contributing to closing the materials loop and increasing phosphorus circularity**: Recycling and transforming sludge waste to potentially close the phosphorus loops and contribute to the production of phosphorus-based chemicals for novel battery technologies that currently use virgin phosphorus.
- **Driving innovation:** Demonstrating the feasibility and scalability of domestic phosphorus recycling for high-added-value products, contributing to chemical production and innovation of battery technologies.
- **Enhancing supply security**: Establishing a regional phosphorus recycling capacity that, with proper scale-up, can support mitigating supply chain disruptions and reduce import dependency.
- **Environmental burden:** Reduce the environmental burden of wastewater treatment outputs, landfill leachate, and potentially industrial waste containing phosphorus.
- **Supporting policy objectives**: Aligning with the EU's **Critical Raw Materials Act**, and fulfillment of article 26. Aligning with the **European Green Deal**, and **Circular Economy Action Plan** by demonstrating practical implementation of sustainable materials recovery, and with the new **EU Bioeconomy Strategy,** since it will use activated sludge as the main resource input.
- **Fostering industrial collaboration**: Building a network that connects recyclers, material scientists, and industry by creating a regional circular value chain.

[1] In the context of the Adriatic, Western Balkans and Central Europe.

Stakeholders, roles, and intended beneficiaries

The phosphorus taskforce working on the pilot includes the Slovenian chemical and materials industry (new products, inputs), waste and wastewater management companies, landfill operators (reduced disposal burden, new revenue streams), national innovation institutions (new R&D and demonstration capacity in circular CRMs), and the Regional Development Agency of Zasavje (green jobs).

Taskforce members	
Role	**Name of the organization**
Technical lead	National Institute of Chemistry (KI)
Supporting research institutions	Slovenian National Building and Civil Engineering Institute (ZAG)
Industry representatives	TKI Hrastnik d.d., Mikrobium d.o.o., ACIES BIO d.o.o.
Waste management companies	Surovina d.o.o. , Ceroz d.o.o.

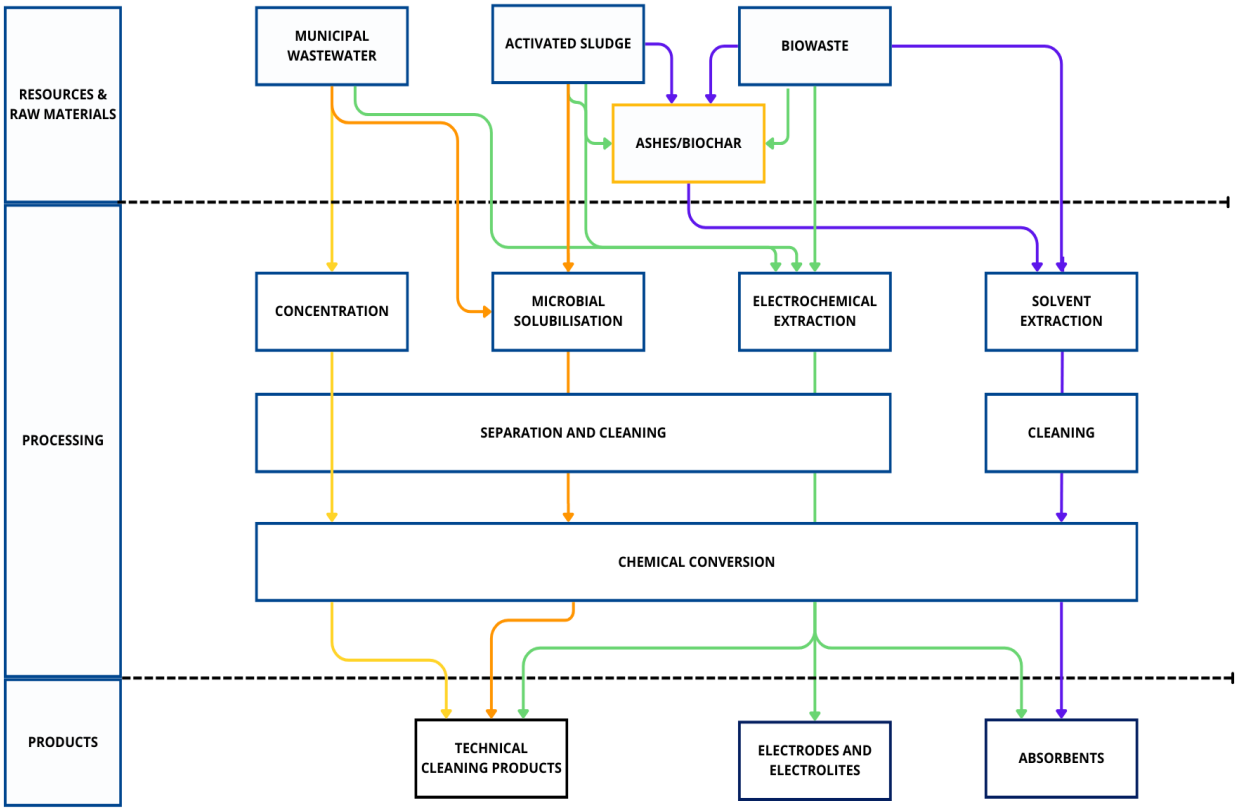
Pilot scheme

Input materials: The pilot is currently considering activated sludge from wastewater treatment facilities and landfill leachate due to their high content of phosphorus. Alternative sources will be evaluated, including biochar and ashes from sludge, and potential industrial waste and wastewaters rich in phosphorus. The latter will be based on an opportunity basis.

Output materials: Currently, final products are being considered and will be tested. The potential output materials include phosphate-rich chemicals, phosphate components for Lithium batteries, and other advanced materials.

Final product prioritisation will be determined during pilot testing and stakeholder validation.

Figure 2 – Phosphorus pilot technical scheme



Technical feasibility

Input assessment

Stakeholder meetings, literature review, and consultations allowed to identify and preliminarily assess input-specific characteristics and challenges/uncertainties, presented in the table below:

Input assessment and characterisation					
Input Source Category	**Material Form**	**Phosphorus Content Characteristics**	**Contaminants / Impurities of Concern**	**Logistical Considerations**	**Key Uncertainties / Challenges**
Activated sludge	Dewatered sludge (≈20–30%	Typical P content 1–3% P (dry basis), varies by wastewater	Heavy metals (Zn, Cu, Pb, Cd), pathogens, pharmaceuticals,	High mass and volume due to moisture. Possible frequent	Uncertainty over the chemical form of phosphorus

	dry matter)[2]	type, and seasonally within a specific wastewater treatment facility[3]	PFAS, microplastics[4]	collection cycles required	and its variability
Sludge ash (post-incineration)	Dry inorganic ash (90–100% dry matter)	Elevated heavy metals (Cd, Pb, Cu, Zn), refractory mineral phases	Elevated heavy metals (Cd, Pb, Cu, Zn), refractory mineral phases	Limited availability in Slovenia (low mono-incineration capacity)	Limited incineration process in Slovenia that could provide it.
Biochar from sludge pyrolysis	Sterilised carbon-rich solid	P often enriched compared to raw sludge, but bioavailability varies[5]	Metals concentrated in char; possible PAHs depending on pyrolysis conditions	Emerging in Europe; dependent on pyrolysis facility proximity	
Industrial phosphorus-rich residues (e.g., TKI Hrastnik streams)	Process-specific sludges or filtrates	Highly variable P concentration – Industry-specific	Chemical residues, salts, process-specific metals	Stream-specific logistics	Highly variable P concentration depending on industrial process
Other potential secondary sources (to be identified)	-	-	-	-	-

[2] Werther & Ogada (1999); EU JRC (2019).
[3] Adam et al. (2009)
[4] EU JRC (2019)
[5] Méndez et al. (2014)

Partner needs

Stakeholder meetings and consultations were held to identify and preliminarily assess partner needs and challenges.

The partner ecosystem assembled around the phosphorus pilot spans the entire emerging value chain, from secondary raw-material access to advanced recovery technologies, to product development and industrial integration. The **National Institute of Chemistry (KI) and its Centre for Demonstration of Low-Carbon Technologies (DUBT)** form the technological core of the pilot, providing multi-TRL capabilities for phosphorus extraction, purification, electrochemical recovery, and advanced material development, including pilot-scale capacities for battery testing and LFP recycling. These capabilities define the technical boundary conditions for early bench-scale experimentation and determine the quantities and qualities of input materials required for testing.

Ceroz contributes a continuously available source of landfill leachate and the operational environment needed for real-stream validation, enabling exploration of treatment upgrades and new recovery pathways directly at landfill facilities. **Surovina** ensures access to dehydrated wastewater sludge and, where available, sludge ash, acting as the primary logistics and supply partner for municipal secondary phosphorus streams. **TKI Hrastnik** represents the downstream industrial integration pathway, with laboratory-scale extraction systems for phosphoric-acid. Their engagement provides essential market orientation and defines quality requirements for potential phosphate-based chemicals developed through the pilot.[6]

Additional research and innovation partners, including **Mikrobium, ACIES BIO, and ZAG**, offer complementary capabilities in biotechnological processing, enzymatic or microbial treatments, and the valorisation of phosphorus-containing by-products (e.g., for environmental or construction applications). Their specific roles and quantitative needs will be further refined as the pilot narrows its technical routes.

Collectively, the partners create a coherent early-stage value chain: **Surovina and Ceroz supply real secondary streams**, **KI/DUBT lead technological development and validation**, **industrial actors define market entry points**, and **specialised R&D organisations expand the scope of feasible valorisation routes**. This configuration provides a strong basis for a modular, exploratory pilot capable of adapting as technical insights and funding windows evolve.

[6] Note: The extent of the roles of partners might vary depending on funding streams and final organisational agreements.

Stakeholder technical characterisation			
Organisation of the taskforce	**Stage of value chain**	**Existing process capacities**	**Technology description and organizational requirements**
National Institute of Chemistry (KI) /DUBT	All phases of the value chain, except final use / market deployment	• **Phosphorus precipitation, designer-solvent work, sorbent preparation:** batch sizes up to **100 L**. • **High-pressure / high-temperature precipitation and sorbent development:** batch sizes up to **10 L**; sorbent testing columns up to **3 L bed volume**. • **Electrochemical phosphorus recovery:** in-house electrolyser systems up to **1–2 kW nominal power**; scaling to larger systems possible via collaboration with partners. • **Battery systems:** pilot line for **pouch and prismatic cells**, climate-chamber testing capacity with **~500 testing positions** (up to **500 A**), enabling degradation studies and optimisation of	KI develops and maintains processes at various TRL levels for the recovery and purification of phosphorus from various sources: (i) a developed and patented process for obtaining orthophosphate and other phosphorus compounds from ash and excess activated sludge; (ii) a platform for the development of designer solvents for purification processes and selective separation of compounds; (iii) capabilities for designing and developing electrochemical separation processes for dissolved phosphorus compounds in complex samples, with the potential for the simultaneous recovery of hydrogen, ammonia, and other valuable resources. **Advanced materials and novel battery technologies** KI does not supply unused raw materials for pilot operations. Instead, it develops and maintains advanced recovery and purification processes at multiple TRL levels for obtaining phosphorus from various secondary sources. These include: • **A patented process** for producing orthophosphate and other phosphorus compounds

		battery performance. Further data will be determined based on laboratory and pilot needs. This parameter might be influenced by available funding calls but also based on ongoing exchange and discussions with the Ministry of Environment, Climate, and Energy.	from sludge ash or excess activated sludge. • **A designer-solvent development platform** enabling selective purification and separation of phosphorus-containing compounds. • **Electrochemical separation processes** for recovering dissolved phosphorus species from complex matrices, with the potential for **simultaneous hydrogen and ammonia generation** as valuable co-products. KI also develops **advanced phosphorus-containing materials** for industrial pre-development, including: • Modified phosphorus compounds to improve sorption and surface properties of biosorbents for capturing CO_2, N_2O, NH_3 and other gases. • Modification and incorporation of phosphorus compounds for **next-generation battery systems**, including selective recycling of **$LiFePO_4$ (LFP)** battery materials and resynthesis of LFP precursors ($FePO_4$, Li_2CO_3, phosphate anions). Partial or full recycling of LFP enables the recovery of components—partially recycled $FePO_4$ or fully recycled Li_2CO_3, phosphate anions, and iron compounds—which serve as the basis for resynthesizing LFP battery material.

Ceroz	CEROZ aims, through collaboration with the DUBT Centre (National Institute of Chemistry), to improve the treatment system for landfill leachate as a raw material and potential phosphorus source.	Quantities depend on process design and pilot configuration; landfill leachate is available on a continuous basis. Untreated landfill leachate contains **approx. 20 mg/L of phosphorus).**	The project will enable an independent treatment stage, or an additional treatment step for untreated/treated leachate fractions, reduce the need for re-disposal of untreated fractions (and the associated accumulation of soluble pollutants in the landfill), and enable the creation of new chemical products and material streams that convert these substances into useful forms of raw materials.
Surovina d.o.o.	Collection, pre-treatment, and supply of wastewater sludge (and, where applicable, sludge ash)	Can supply dehydrated municipal sludge from wastewater treatment plants across Slovenia. Requires information from the consortium on the quantities needed for processing and testing. Sludge samples are typically supplied in **5-litre containers.**	Surovina handles wastewater sludge: Dehydration of municipal wastewater treatment sludge, and ashes from incinerated sludge.
TKI Hrastnik	Downstream integration of recycled phosphorus into existing and new phosphate-based chemical products	• **Phosphoric acid purification tests:** laboratory-scale volumes of approx. 1 litre per run, using mixer–settler equipment for solvent extraction. **Product development:** development-	TKI Hrastnik purchases technical-grade phosphoric acid and can purify it to food-grade quality. The so-called “green phosphoric acid” is sourced on different markets, depending on price. Most often, they purchase it from Lebanon, Serbia, or Morocco. They have developed their own extraction process for purifying phosphoric acid from technical grade

		laboratory capacity ranging from 1 kg to 100 kg per batch, using intensive mixers, fluid-bed dryers, and other drying equipment. Quantities ultimately depend on the purity, composition, and consistency of recycled phosphorus streams delivered by the pilot.	to high-technical grade. They also have processes for defluorination, decadmization, dearsenization, and purification using activated-carbon columns. All these processes are the result of their own research and development and many years of experience.
Other partners (e.g. Mikrobium d.o.o., ACIES BIO d.o.o., ZAG)	R&D, process innovation, testing, and potential use of by-products	To be determined in the ongoing design phase based on partner inputs.	Other partners may contribute to biotechnological process steps, microbial or enzymatic treatments, development of specific high-value products using recycled phosphorus, and assessment of potential uses of phosphorus-containing by-products (e.g. in construction materials or environmental applications). Their specific roles, quantitative needs, and organisational requirements will be defined during the next phase of concept maturation and pilot design.

Preliminary budget considerations

Based on the technical scope, expected equipment needs, laboratory and pilot-scale infrastructure, and the personnel effort required across KI/DUBT, Ceroz, Surovina, TKI Hrastnik and other partners, the foreseeable budget for the Phosphorus pilot is estimated at **approximately €10 million**[7]**.** This budget would cover modular technology development (chemical, electrochemical, and separation processes), sampling and analytical campaigns, prototype installation at DUBT and Ceroz, product

[7] This a preliminary approximate value based on the potential scope of the pilot, technologies required, personnel, energy and other costs.

validation with industry, and project management and staffing over a multi-year period. **The estimate remains indicative and will be refined during detailed design but provides a realistic order of magnitude to guide consortium formation and funding-strategy development.**

Key challenges

Given the early-stage status of the pilot, several key technical challenges can be identified:

- **Input variability and complexity:** Phosphorus content and chemical form vary across sludge, ash, biochar, and leachate streams. Contaminants (metals, organics, microplastics, PFAS) complicate recovery processes.
- **Low concentrations in some streams:** Landfill leachate and certain industrial effluents have relatively low phosphorus concentrations, requiring energy- and cost-efficient concentration and separation technologies.
- **Selection of viable recovery routes:** Multiple recovery pathways (chemical, thermal, electrochemical, biological) exist, but their performance, costs, and environmental footprints must be compared under Slovenian conditions.
- **Quality requirements for end-products:** Integration into cleaning products, fertilisers or advanced materials requires tight control of impurities and stable product specifications.
- **Scale and TRL limitations:** Most processes are currently at laboratory or bench scale and will need optimisation and de-risking before any larger-scale investment is justified.

This list is not exhaustive, and further challenge assessment will be undertaken as the pilot progresses.

Pilot location

The pilot location will be in the Zasavje region, one of the Just Transition regions in the East of Slovenia. More specifically, the pilot components will be distributed among the facilities of the Centre for Demonstration of Low Carbon Technologies (DUBT) of the KI, and the waste management company Ceroz d.o.o - both in Zagorje ob Savi.

The possibility of using the facilities of Ceroz d.o.o. provides the advantage of having the necessary environmental waste management permits required to handle sludge. Ongoing exchange with MOPE is supporting the assessment of the potential need for further permitting.

Funding sources and opportunities

Several opportunities for funding were identified and assessed. It is clear that no single source of funding will be enough to cover the whole amount of funding required, thus, more sources are targeted.

Given that the pilot will be located in the region of Zasavje, funds allocated to the Just Transition regions are a key opportunity. This includes both the RRI ongoing call and two future calls that will

be implemented in Slovenia (one for East Slovenia and the other for West Slovenia). Such calls require a consortium where the lead beneficiary is a business, and the consortium members are located in East Slovenia. However, this is not an obstacle, since most pilot partners are located there (KI and DUBT, Surovina, Ceroz d.o.o., and Mikrobium d.o.o.). Since, the JTF funding cycle is coming to its end, timing and acceleration over the pilot's concept development and final partner agreements are of top priority.

Horizon Europe Innovation Action and LIFE calls are also of high priority since they have no requirements for the nature of the beneficiary, and research institutes are eligible.

The calls listed below are currently waiting for confirmation, but represent useful sources for future endeavours.

Name of funding call/stream	Geographic scope	Source of funding	Timeframe	Issuer	Lead bidder
RRI Razpis	Regional - Cohesion	Public	Published: Oct Deadline: 15 Jan 2026	ARIS	Businesses
STEP Razpis	National	Public	Yet to be published	ARIS	Businesses
EU CRMA	European	Public	Published: Oct Deadline: 31 Jan 2026	European Commission	Businesses
Horizon IA calls in January	European	Public	Mar 2026	European Commission	All
IPCEI on circularity/strategic value chains.	European	Public	Waiting confirmation	European Commission	All under MS
CBE JU 2026	European	Public	TBC (call usually published in spring/summer)	European Commission	All
European Circular Bioeconomy Fund	European	Private	Open / rolling (typical VC model)	Venture capital	All
ReSourceEU	European	Public	Awaiting more details from	European Commission	Awaiting more details from

			European Commission		European Commission

Funding Risk Assessment (Preliminary)

A number of financial risks remain at this stage, reflecting the early phase of project preparation and the dependency on multiple public funding mechanisms. The pilot requires a significant upfront investment but can be approached in a modular process, adapting to funding instruments' availability and requirements. Keeping in mind that no single existing funding instrument can cover the amount required for the overall concept. As a result, the project is exposed to certain risks:

1. Cost uncertainty
The location is confirmed, but costs, space requirements, or potential adjustments to facilities, could increase budget needs. Location-related risks are somewhat lower, as key sites in Zasavje (DUBT and Ceroz) are already identified; however, CAPEX and adaptation costs remain uncertain.

2. Dependency on multi-source financing
The pilot relies on the combination of Cohesion funding (RRI, STEP, JTF), Horizon Europe, and potential industry co-financing. Delays or negative outcomes in any single source could impact the project's overall financial feasibility. Because the funding timetable alignment across these instruments is uncertain, there is a risk of gaps between secured funds and required implementation timelines.

3. Eligibility constraints

Several high-potential funding mechanisms, such as RRI and STEP calls, require a *business-led consortium*. This introduces legal and organisational risks related to consortium formation, equipment ownership, and intellectual property, which must be resolved before funding applications are submitted. Failure to establish an eligible consortium structure may limit access to critical funding windows.

4. Limited industry co-financing commitments at present
Although initial conversations with TKI Hrastnik and have occurred, and others indicate interest in participating, no formal co-financing commitments have yet been secured. Industrial participation is essential for covering funding gaps towards precommercial and commercial upscaling and ensuring long-term operational sustainability. Delays in industry engagement could slow consortium formation or weaken future scaling potential.

At this stage, the industry remains slightly reluctant to invest upfront in the pilot, clearer information, KPIs, and ROI would be needed. More exploration work is required in order to evaluate and pursue private financial commitments.

Given these uncertainties, the nature of funding instruments available and the potential budget required, the timing of equipment procurement and facility setup will depend on synchronising multiple funding instruments.

Environmental and Social Feasibility

At this stage, pilot-specific environmental performance data (e.g. energy demand of individual process steps, chemical consumption, emissions, and residue streams) are not yet available; however, existing literature and practice on phosphorus recovery from wastewater sludge and sludge-derived ashes provide a solid theoretical basis to anticipate net environmental benefits compared to linear "treat-and-dispose" pathways.

By redirecting excess activated sludge and its derivatives (ashes, biochar) into phosphorus recovery processes, the pilot has the potential to **reduce reliance on imported phosphate rock** and associated mining impacts, **lower the phosphorus load ultimately discharged to the environment,** and thus contribute to reduced eutrophication risk[8] of water bodies and environmental discharge, and **decrease the volume of sludge requiring landfilling or incineration** without material recovery, consequently **reducing public spending for treatment and removal.**

At the same time, the pilot will need to carefully **manage environmental trade-offs** linked to energy use, reagent consumption, and management of co-contaminants present in sludge (e.g. heavy metals, organic pollutants, microplastics), which will require appropriate process design, monitoring, and pretreatment of waste streams.

[8] Increasing of nutrient inflow into water bodies can create higher risks of eutrophication, causing algae overgrowth and oxygen depletion.
European Environment Agency. (n.d.). *Eutrophication*. EEA Glossary. Retrieved December 1, 2025, from https://www.eea.europa.eu/help/glossary/other-eea-terms/eutrophication

Pilot Development Plan

Potential stages of development and implementation

Given the exploratory nature of the phosphorus pilot, a phased development approach is proposed.

Phase 1 – Concept Maturation (2025–2026)

- Refinement of the pilot concept and mapping of possible phosphorus recovery routes.
- Systematic sampling and characterisation of key input streams (sludge, sludge ash, biochar, leachate, industrial residues).
- Screening-level assessment of technical options (chemical, thermal, electrochemical, biological).
- Initial stakeholder workshops to refine roles, expectations, and product priorities.
- Preparation of funding proposals (RRI, STEP, Horizon, LIFE).

Phase 2 – Laboratory-scale testing and validation on real streams (2026–2027)

- Laboratory and bench-scale testing of selected recovery routes on real input streams.
- Optimisation of process parameters and preliminary estimation of yields, reagent consumption and impurity removal.
- Initial environmental assessment, including mass and energy balances for candidate processes.
- Early assessment of product quality vs. market and regulatory requirements (e.g. for cleaning products, advanced materials).

Phase 3 – Prototype Demonstration (2027–2028)

- Selection of one or more promising technology routes for integrated bench/pilot demonstration (e.g. at DUBT and/or Ceroz).
- Design and installation of prototype modules (e.g. extraction, filtration, electrochemical units) at relevant sites.
- Extended test campaigns to validate process robustness, environmental performance, and product quality.
- Engagement with TKI Hrastnik and other industrial partners on product integration and potential offtake.

Phase 4 – Regional Scaling Options (post-2028)

- Based on Phase 3 results, development of scale-up scenarios for broader deployment in Slovenia and potentially the region (e.g. replication at other regions, with sludge and leachate from different wastewater treatment facilities and landfills).

- Detailed techno-economic analysis and business model development (service model, technology licensing, joint ventures).
- Exploration of international collaboration and replication opportunities, linked to EU-level initiatives on phosphorus recovery and circular CRMs.

Governance mechanisms

Given the early-stage nature of the pilot, governance will remain flexible and is expected to evolve as the technical concept and industry partnerships stabilise. Formal structures will be defined in the next phase together with KI, ZAG, DUBT, and industry partners.

Monitoring framework and key performance indicators

KPI Category	KPI Name	Definition / Intention	Metric Type	Validation Stage
Input Supply	Diversity of phosphorus sources	Number and type of secondary sources successfully sampled (sludge, ash, biochar, leachate, industrial residues).	Qualitative + count	Phase 1–2
	Stability of supply	Variability of P-content and impurities across sampling rounds.	Variability index (to be defined)	Phase 2
	Volume accessible for testing	Quantity of real material available for bench-scale work.	Indicative ranges per stream	Phase 1
Technology Development	Extraction efficiency	Share of total P extracted from each stream using selected routes.	% (to be defined per method)	Phase 2
	Impurity removal performance	Reduction of metals, organics and other contaminants.	% reduction	Phase 2
	Technology robustness	Ability to operate under real-input variability.	Qualitative	Phase 2–3
Product Development	Product quality consistency	Purity of recovered phosphorus compounds meeting industrial partner specs (TKI, DUBT).	Specification alignment (yes/partial/no)	Phase 2–3
	Application feasibility	Compatibility of recovered P for cleaning chemicals, advanced materials, or battery precursors.	Go/No-Go	Phase 2–3
Environmental	Reduction of sludge disposal burden	Volume of sludge/ash diverted from disposal.	Indicative tonnage	Phase 3
	Estimated CO_2-equivalent savings	Derived from avoided phosphate rock imports and improved waste treatment.	Modelled estimate	Phase 2–3
Collaboration Social and regional	Industrial engagement	Number of partners participating in testing and validation.	Count	Phase 1–3

	Regional development contribution	Estimated jobs supported in Zasavje (lab, pilot operation, logistics).	Qualitative + estimate	Phase 3

Conclusions and Recommendations

This feasibility study addresses phosphorus recovery from wastewater-derived streams and landfill leachate pilot. The importance of the phosphorus resources, Slovenia's import dependency, and the environmental burden created by wastewater treatment sludge could give strategic national relevance to the pilot. Although the pilot is still at a conceptual and exploratory stage, the combination of strong research capacity (KI, DUBT, ZAG), engaged waste operators (Ceroz, Surovina), and interested industrial partners (TKI Hrastnik, Mikrobium, ACIES BIO), creates favourable conditions for a meaningful demonstration of phosphorus circularity.

This feasibility study marks the transition of the phosphorus pilot from strategic exploration to structured implementation readiness. **Over the next 12–24 months following December 2025**, success will be defined by the completion of laboratory-scale validation on real streams, the identification of one to two technically and economically viable recovery routes, and the establishment of a business-led consortium capable of securing blended funding from cohesion and EU instruments. Achieving these milestones would position the pilot as a concrete implementation vehicle for Slovenia's obligations under the EU Critical Raw Materials Act, while simultaneously supporting green reindustrialisation and skilled job creation in the Zasavje region. With continued policy backing and coordinated funding support, the phosphorus pilot can evolve into a replicable national reference for circular critical raw materials and waste-to-resource innovation.

Recommended next steps for the Phosphorus pilot

Technical route selection & validation

- Finalise the shortlist of recovery routes to test (e.g., chemical precipitation/extraction, electrochemical recovery, purification via designer solvents), and define decision criteria (yield, impurity tolerance, energy/reagent use, product fit).

Sampling & characterisation campaign

- Launch systematic, multi-round sampling of priority streams (activated sludge, ash/biochar where available, landfill leachate, selected industrial residues), including contaminant profiling (metals, organics, PFAS/microplastics where relevant) and variability mapping.

Site readiness & operational setup in Zasavje

- Confirm operational setup across **DUBT (KI)** and **Ceroz** (permitting, handling procedures, HSE protocols, storage/logistics), and define which activities run at which site.

Consortium & governance

- Formalise roles, decision-making, data/IP arrangements, and identify a **business lead** (or structure) suitable for cohesion calls (RRI/STEP), while keeping KI/DUBT as technical anchor.
- Translate TKI Hrastnik and DUBT needs into clear product specifications (purity thresholds, allowable contaminants, form/grade), and agree testing workflows (e.g., **TKI**: 1 L purification trials; **1–100 kg** product development batches).

Funding

- Build a modular funding plan and submit priority applications (RRI, STEP, Horizon, LIFE), with a staged CAPEX/OPEX roadmap that aligns procurement and staffing to call timelines.
- Develop a detailed cost breakdown for further feasibility assessment and participation for funding calls.

Environmental permitting and environmental priorities and concerns

- Organise a follow up meeting with the MOPE waste management team to address the needs of permitting, environmental burden and validation of priorities.
- Organise a meeting with MVZI to address priorities and funding options.
- Present the advanced pilot concept to the Director General of MGTŠ.

Monitoring & KPIs

- Define KPI baseline for Phase 1–2 (source diversity, supply variability, extraction efficiency, impurity removal, product-spec alignment, partner engagement), so results can directly support funding decisions and scale-up planning.

Policy and Strategic recommendations for enabling environment

Strategy and policy

- Adopt a national strategy for circular critical raw materials with a dedicated REE–magnet pillar.
- Develop a national CRM programme to foster research, innovation, circular value chains and the strategic development of the CRM sector in Slovenia

- Support CRMA implementation through strategic pilot projects by prioritising circular CRM demonstrations—such as phosphorus recovery—that directly contribute to national recycling, processing, and supply-security targets.
- Streamline regulatory and permitting pathways for testing waste-to-resource processes and clarify quality and safety requirements for recovered phosphorus entering chemical or battery-material applications.
- Clarify and streamline permitting and environmental procedures for CRM recycling facilities.

Funding

- Use cohesion policy and Just Transition funding (RRI, STEP, SPP) to anchor green reindustrialisation in Zasavje, enabling new infrastructure, technology development, and long-term green job creation.
- Provide coordinated public co-financing and funding alignment to help early-stage pilots progress from lab scale to demonstration scale, ensuring smooth transitions between national and EU funding instruments.
- Establish a dedicated national CRM circularity fund or programme that can support multiple pilots over different TRLs (from lab to demonstration), smoothing the transition between EU-level funding (Horizon, LIFE) and regional/Cohesion funds. This reduces fragmentation and improves the viability of both phosphorus and REE projects.

Skills and jobs

- Invest in national skills and workforce development for circular materials, supporting education and training programmes that strengthen Slovenia's capacity in recycling technologies, advanced materials, and green industrial innovation:
    - Linking pilot infrastructure to applied training and apprenticeships, including technician- and operator-level roles supporting laboratory operation, waste handling, pre-processing, and equipment maintenance alongside researchers and engineers.
- Invest in education, training, and workforce development for circular materials economy.
    - Addressing the shortage of technical staff by explicitly supporting technician training programmes (e.g. laboratory technicians, process operators, safety and waste management specialists) that complement scientific and engineering expertise and are essential for pilot and demonstration-scale operations.
    - Create and fund interdisciplinary training programmes covering waste-to-resource engineering, electrochemical recovery, materials processing, purification, product integration, regulatory compliance.
    - Leveraging existing national and EU instruments (e.g. Just Transition Fund, Cohesion Policy, Erasmus+, Horizon Europe training components) to co-finance skills development linked directly to pilot implementation and scale-up.Target regions where the pilot infrastructure is located or has potential to be located to foster local

employment and build a skilled workforce ready to support both phosphorus and REE value chains.
    - Piloting place-based skills development in host regions (e.g. Velenje and other potential pilot locations), aligning training provision with the needs of REE and phosphorus value chains to foster local employment, reskilling of transitioning workers, and long-term regional industrial capability.
- Target regions where the pilot infrastructure is located or has potential to be located to foster local employment and build a skilled workforce ready to support both phosphorus and REE value chains.

International collaboration and leadership

- Strengthen Slovenia's regional role in circular CRM value chains and strengthen international collaboration and Slovenia's regional leadership in circular CRMs:
    - Embedding the Slovenian REE pilot as a technical building block within larger EU and international CRM initiatives (e.g. CRMA Strategic Projects, Horizon Europe consortia), providing specialised recycling, testing, and validation capabilities.
    - Establishing structured bilateral and regional cooperation agreements (MoUs, joint work programmes) with neighbouring countries and existing initiatives (e.g. Italy, Croatia, Western Balkans) to secure feedstock flows, exchange technical know-how, and coordinate scale-up pathways.
    - Positioning Slovenia as a regional knowledge and testing hub for magnet and REE circularity through shared access to the CRM Laboratory, joint pilot campaigns, and industry validation activities.
    - Actively participating in EU-level platforms and working groups related to CRMA implementation, magnet recycling, and circular raw materials, contributing data, pilot results, and policy-relevant insights.

Appendices

List of stakeholders engaged

The list below includes the stakeholders engaged during the whole work regarding critical raw materials.

No	Institution	Name and surname
1	**ACIES BIO**	Martin Kavšček and Bor Klančič
2	**Blok**	Mojca Jerina and Željka Borić
3	**Ceroz**	Enes Rakovič
4	**Cinkarna Celje**	Dejan Verhovšek
5	**GeoZS**	Urška Šolc and Slavko Šolar
6	**Jožef Stefan Institute**	Sašo Sturn, Kristina Žužek, Benjamin Podmiljšak and Gašper Tavčar
7	**Italian EU CRMA Strategic pilot INSPIREE**	Laura Mascheretti, Luca Campedello
8	**National Institute of Chemistry**	Gasan Osojnik, Maja Čič, Robert Dominiko, and Blaž Likozar
9	**Kolektor**	Ana Drmota Petrić, Karla Kosmač, and Boris Saje
10	**Magneti Ljubljana**	Matej Zaplotnik and Gregor Telgetja
11	**Ministry of Cohesion and Regional Development**	Bojan Suvorov, Marko Hren and Matej Forte

12	**Ministry of Economy, Tourism and Sport**	Mateja Mlakar Papič, Marija Čebular Zajec, and
13	**Ministry of Environment, Climate, and Energy**	Jasmina Karba, Tanja Bolte, Peter Tomše
14	**Ministry of Higher Education, Science and Innovation**	Damjana Karlo, Doroteja Zlobec
15	**Municipality of Kranj**	Tomaž Lanišek, Eva Romih and Polona Prosen Šprajc
16	**Municipality of Velenje**	Igor Kapš, Karla Sitar, and Iztok Mori
17	**Regional Development Agency of Zasavje**	Kristijan Adamlje
18	**RRI Committee**	
19	**Surovina**	Tina Frangež and Nastja Tjukajev
20	**TKI Hrastnik**	Rok Petrič
21	**ZAG**	Mateja Košir, Alenka Mauko, Primož Oprčkal, Vilma Ducman, and Dragica Marinič
22	**ZEOS**	Damir Huremovič

Stakeholder events organized and key multistakeholder meetings

No	Institution	Date	Attendees	Purpose
1	**Kickoff** **Location: Ministry of Economy, Tourism and Sport (MGTŠ), Ljubljana**	13 March	MGTŠ: Mateja Mlakar Papič, Natalija Medica, Maruša Vidmar MNVP: Galena Debevec Jordanova, Marko Maver MOPE: Peter Tomše MJU: Marjana Dermelj GeoZS: Urša Šolc, Meta Dobnikar GZS: Antonija Božič Cerar, Grit Ackermann IJS: Kristina Žužek, Gašper Tavčar ZAG: Mateja Košir	Explorative and first stakeholder meeting of the CRM value chain work
2	**Exploration meeting** **Location: Virtual**	27 May	MGTŠ: Mateja Mlakar Papič, Maruša Vidmar MOPE: Jasmina Karba MJU: Marjana Dermelj MKRR: Matej Forte MVZI: Doroteja Zlobec IJS: Benjamin Podmiljšak and Gašper Tavčar KI: Gasan Osojnik and Blaž Likozar IMT: Bojan Podgornik	Discuss the potential of creating CRM demonstration centre and gauging the interest of stakeholders as well discussing the national initiatives and capacities
3	**Prioritisation meeting** **Location: National Institute of Chemistry, Ljubljana**	10 June	MGTŠ: Mateja Mlakar Papič, Marija Čebular Zajec, Maruša Vidmar MJU: Marjana Dermelj MKRR: Matej Forte	Prioritising efforts of the critical raw material pilots by assessing a shortlist of CRMs and selecting the definitive CRMs the pilots would focus on

No	Institution	Date	Attendees	Purpose
			IJS: Benjamin Podmiljšak and Gašper Tavčar KI: Gasan Osojnik and Blaž Likozar IMT: Bojan Podgornik ZAG: Mateja Košir GeoZS: Urša Šolc	
4	**REE Taskforce 1st meeting**	17 June	Benjamin Podmiljšak and Gašper Tavčar / Tina Frangež / Damir Huremovič / Ana Drmota Petrič / Bojan Suvorov / Marjan Dermelj	Discussing between industry and research what are the main challenges of the pilot and exploration of interest from industry and potential roles
5	**RRA Zasavje** **Location: DUBT, Zagorje**	24 July	RRA Zasavje: Kristijan Adamlje MJU: Marjana Dermelj	Explorative meeting to assess the interest of RRA Zasavje and compatibility of the phosphorus pilot initiative with its prioririte s.
6	**ZAG meeting** **Location: ZAG headquarters, Ljubljana**	4 August	KI: Gasan Osojnik ZAG: Mateja Košir, Primož Oprčkal, and Alenka Mauko	Definition of ZAG's role in the phosphorus pilot and potential role in the REEs-magnets pilot.
	Multistakeholder joint taskforce meeting **Location: Ministry of Public Administration, Ljubljana**	10 September	MKRR: Bojan Suvorov MJU: Marjana Dermelj MGTŠ: Maruša Vidmar Municipality of Kranj: Eva Romih and Polona Prosen Šprajc KI: Gasan Osojnik IJS: Benjamin Podmiljšak and Gašper Tavčar ZAG: Primož Oprčkal GeoZS: Urša Šolc Ceroz: Enes	First in person meeting of the CRM pilot taskforces to discuss key challenges and prioritise efforts. Preliminary exploration of synergies.

No	Institution	Date	Attendees	Purpose
			TKI Hrastnik: Rok Petrič ACIES BIO: Martin Kavšček Surovina: Tina Frangež and Nastja Tjukajev Cinkarna Celje: Dejan Verhovšek	
7	**Municipality of Velenje** **Location: Virtual**	10 November	Igor Kapš, Karla Sitar, Iztok Mori	Gauging the interest of Velenje to host the REEs pilot and assess compatibility with local priorities
8	**Location of REEs 2nd pilot meeting** **Location: Institute Jožef Stefan, Ljubljana**	19 November	IJS: Sašo Sturn, Kristina Žužek, Benjamin Podmiljšak and Gašper Tavčar MGTŠ: Marija Čebular Zajec and Nataša Florjančič MKRR: Bojan Suvorov MVZI: Damjana Karlo MJU: Marjana Dermelj Municipality of Velenje: Iztok Mori, Karla Sitar, and Igor Kapš.	Exploring the type and details of collaboration between IJS and Velenje and assess the options for location/facilities of the pilot
9	**Italian pilot INSPIREE 1st meeting** **Location: virtual**	7 August	Erion: Laura Mascheretti IJS: Benjamin Podmiljšak	Explore the synergies between the REEs pilot and the CRMA Strategic project INSPIREE
10	**Italian pilot INSPIREE 2nd meeting** **Location: virtual**	6 October	Erion: Laura Mascheretti and Luca Campadello MJU: Marjana Dermelj	Explore the synergies between the REEs pilot and the CRMA Strategic project INSPIREE
11	**MOPE Director General** **Location: Virtual**	7 November	MOPE: Tanja Bolte, Peter Tomše IJS: Gašper Tavčar and Benjamin Podmiljšak KI: Gasan Osojnik ZAG: -	Explore the policy challenges, environmental and permitting concerns of the CRM pilots as well

No	Institution	Date	Attendees	Purpose
12	**RRI Committee Location: Ministry of Economy, Tourism, and Sport, Ljubljana.**	28 November	MGTŠ: Jernej Salecl and Mateja Mlakar Papič MKRR: Marko Hren MVZI: Damjana Karlo MJU: Marjana Dermelj MOPE: MORS: Ajda Vodlan ARIS:	Present the CRM pilots initiatives to the RRI Committee to raise visibility of the pilots, and strategically discuss priorities with Director Generals