White paper summarising SURRI research agenda

Towards a Sustainable Europe:
A Strategic Agenda for the Remediation of Radionuclide-Impacted Sites and Recovery of Critical Materials

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Abstract
Radionuclide contamination of land and water represents a significant and long-standing environmental and health challenge across Europe. While considerable research has focused on organic and inorganic pollution, the management and remediation of radionuclide-impacted sites, particularly those associated with legacy uranium mining and naturally occurring radioactive materials (NORM), remain underexplored. This white paper presents the outcomes of the SURRI (Sustainable Remediation of Radionuclide Impacts on Land and Critical Materials Recovery) project, supported by Horizon Europe. We outline here a stakeholder-informed research agenda for sustainable site management, supported by technological innovation in electrochemical and microbiological methods, and a vision for a virtual European Centre of Excellence coordinated by TUL (Technical University of Liberec). The paper evaluates the environmental, social, and economic benefits of the proposed agenda, providing a strategic foundation for future policy development, industry collaboration, and research funding.

1. Introduction

In the last century Germany, former Czechoslovakia (now the Czech Republic and Slovakia), France, Hungary, Bulgaria and Romania were the largest uranium producers globally. Consequently, there are many radionuclide impacted sites across Europe. These sites create impacts in soil and water. A particular problem in CZ is the impact of substantial uranium mining activity which was carried out at 23 locations either in open cast mining, subsurface mining or in situ acid leaching, largely driven by the policies of the Communist era (Figure 1). These sites are now in the hands of a state owned company DIAMO, who are already engaged with the SURRI proposal development. Perhaps the site most damaged by acid leaching in all of Europe is at Straz pod Ralskem (CZ), where a mixture of sulphuric and nitric acids was injected via 6,000 wells up to 220 m deep into the ground, with over 3,000 uranium leachate recovery wells. From the late 1960s until the mid-1990s four million tonnes of acid were pumped into the ground. As a result about 270 million m^3 of groundwater have been severely contaminated. The ongoing remediation will take around 30 more years and cost over €2 billion [2]. An additional legacy of uranium mining is the processing of mined materials or leachates, which has led to extensive areas of tailings, currently effectively considered as economically untreatable. Tailings continue to be generated by uranium mining in CZ today.

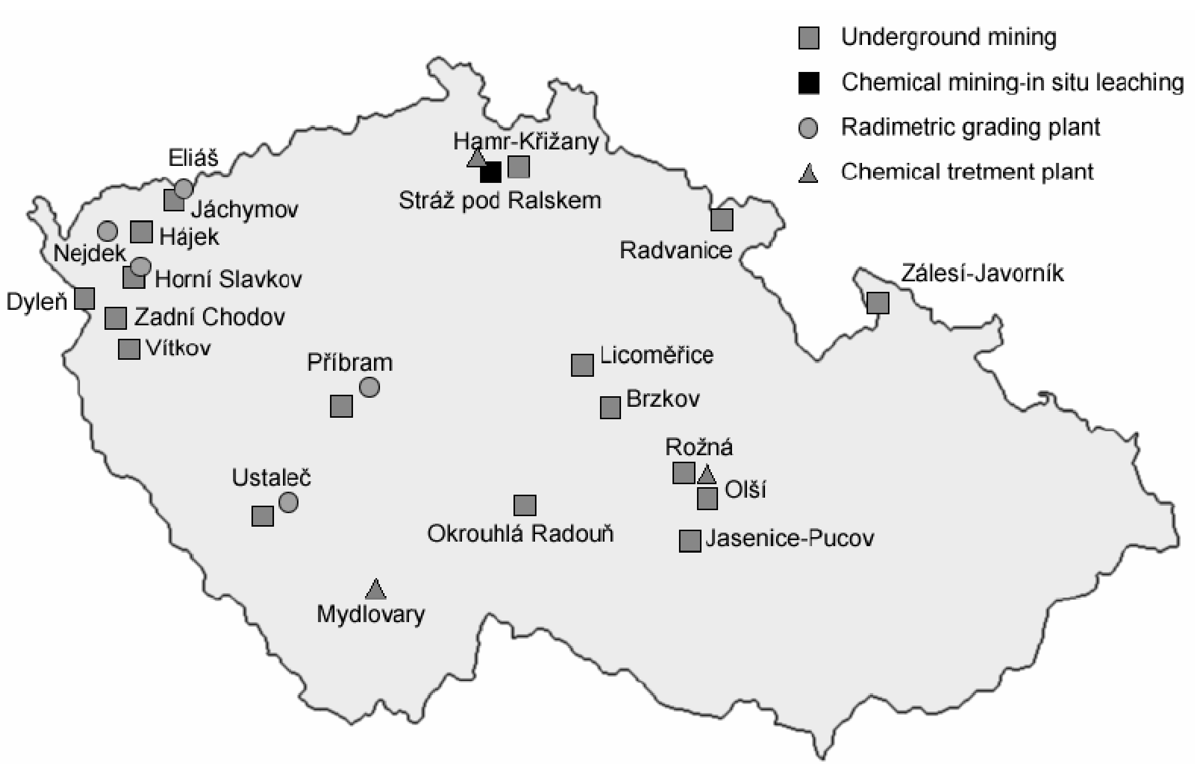


Fig. 1*: Uranium mining sites in CZ (Rapantova et al., 2014)*

The research concept underpinning SURRI's aims is based on the integration of electrochemical and microbiological interventions, which can be applied, in situ or ex situ, to provide new technologies to unlock the remediation of radionuclide affected sites, and facilitate the recovery of material resources from radionuclide impacted wastes, and so reduce reliance of virgin sources [3-6]. While this integration has recently begun to be developed for chemically impacted sites and effluents (e.g. EICLaR project [7]), it is innovative for radionuclide-impacted sites and wastes.
In terms of practical applications, SURRI's starting point focuses on (a) rehabilitation of uranium mining tailings, and (b) recovery of REE and other high value elements from uranium tailings, and other uraniferous (or elevated radioactivity) wastes. Recovery of high value from tailings may be a means of making their remediation economically feasible, as well as contributing to sustainable supply of critical materials and the circular economy.
This white paper is a document designed to inform researchers, policy makers and practicioninst on a specific issue, challenge, and opportunity of remediation of post-uranium polluted water and getting critical elements from it. It serves as a bridge between presenting well-founded arguments and actionable insights for a clearly defined audience such as decision-makers, industry leaders, funding bodies, or the public.

2. Scientific and Technical Background

Radioactive contamination of land and surface – and ground-waters can be derived from various sources, including nuclear fuel cycle activities (including mining and purification of uranium, fuel fabrication (and reprocessing), and nuclear site operation and decommissioning), nuclear accidents, nuclear weapons testing, and various industrial activities that may produce enrichments of naturally-occurring radioactive materials (NORM). Radioactively contaminated sites therefore vary in scale (and complexity), meaning that there is no "one sits fits all" solution to their remediation and risk management. For waste materials and decommissioning activities at nuclear sites, operation tends to be in accordance with the Waste Hierarchy shown in **Figure 2**, whereby prevention of waste generation is the top priority, with remaining priorities (in order) being minimisation, re-use, recycling and disposal. Despite this, in conventional site management and remediation there remains an emphasis on disposal, or sealing / storage of radioactive materials, rather than recycling, recovery and re-use (although less radioactively-contaminated, or out of scope, materials such as waste concretes, metal rebar etc are frequently recycled or re-used).

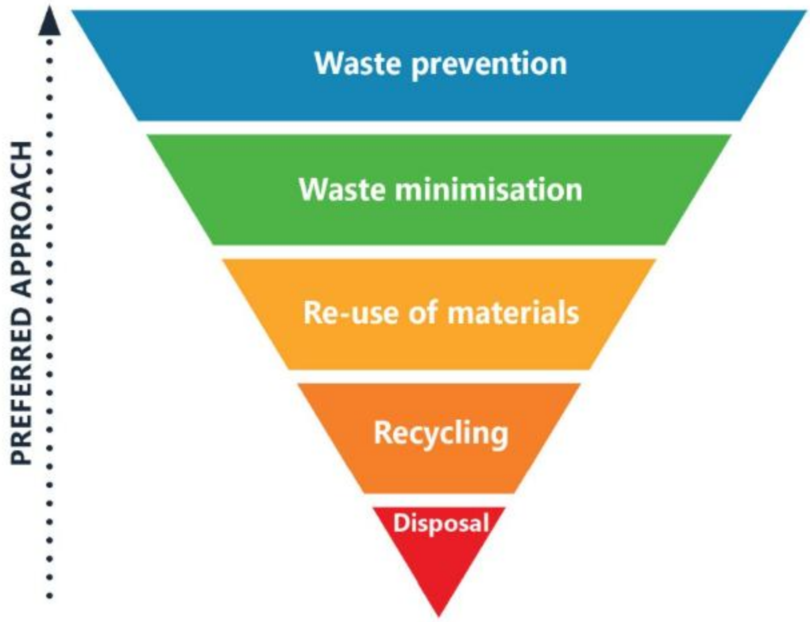


Fig. 2: *The radioactive waste hierarchy, a priority list of how to manage waste to create more sustainable practices. Waste prevention is considered the ideal outcome, with reuse, recycle, and disposal further down the hierarchy (NDA, 2023)*

For contaminated land and waters, typical risk management or clean-up processes include pump and treat, and excavate and dispose, alongside containment approaches such as capping, permeable reactive barriers, adsorption/coagulation (for waste waters) and others. Recent work however has suggested that alternative techniques such as phyto-and bio-remediation (part of a group of nature-based remediation solutions termed Gentle Remediation Options, or GRO), alongside emerging physicochemical techniques including electrokinetic or electrochemical treatment, may provide more sustainable (and effective) treatment and risk management, particularly where these techniques allow element recovery and re-use. Here, the economic cost of remediation may be offset by the commercial value of the recovered element(s), particularly where these have high value or are Critical Elements, alongside wider benefits that may be derived from "greening" and regeneration of legacy waste sites. Applying these techniques effectively at an individual site may require the combination of a number of approaches, in an integrated or "treatment train" approach, for effective risk management and element recovery. It is this integrative concept, combined emerging biological and physicochemical remediation and element recovery techniques, that forms the central focus of the SURRI project.

3. Methodological Approach

During the project, configurations ranging from small to medium-large were evaluated, beginning with a small-range compact U-tube setup followed by column and planar set up.

3.1 U-tube experiment

The U-tube setup system consisted of silicone tubing (20 cm long, 8 mm inner diameter; packed-bed length 10 cm), stainless-steel or carbon electrodes (length 2 cm), and a DC power supply.

In the first set of experiments evaluated electromigration of tracer dyes (add) toward the oppositely charged electrode, while the ionic strength of the electrolyte was varied to assess its effect on tracer transport (**Figure 3**).

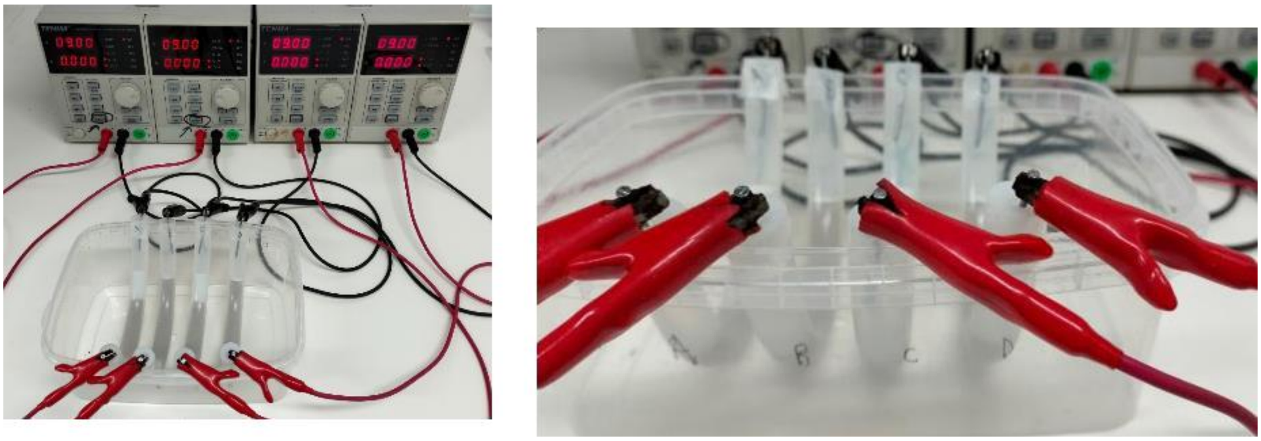
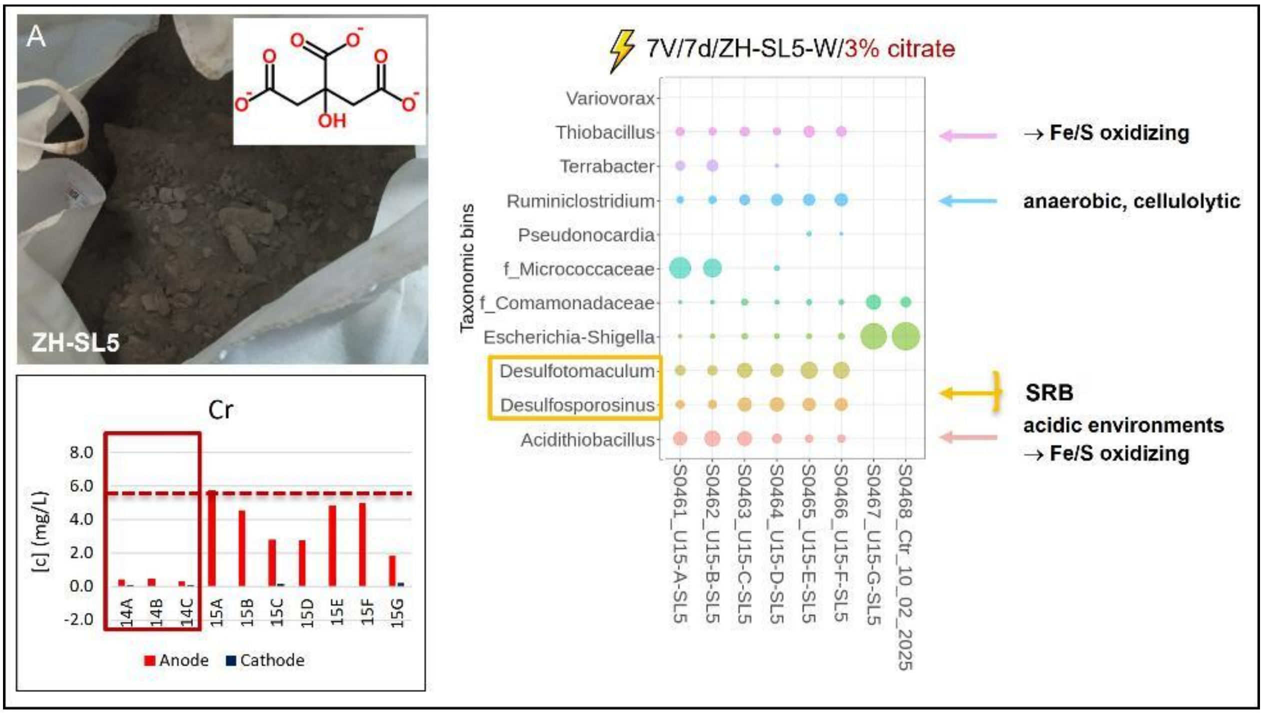


Fig. 3: *U-tube experimental set-up, sand and various tracers*

Second set of experiments using U-tube setup (**Figure 4**) focused on the viability of bacteria at a given voltage and in a given environment. Sludge and sediment leak from the Zlaté Hory tailings were selected for these experiments as a matrix containing heavy metals. The effect of voltage and the ability of the bacteria present was monitored a) for the autochthonous bacterial community and b) for the added culture of bacteria tolerant to heavy metal toxicity, such as *Variovorax* and *Microbacterium*, isolated within the SURRI project.



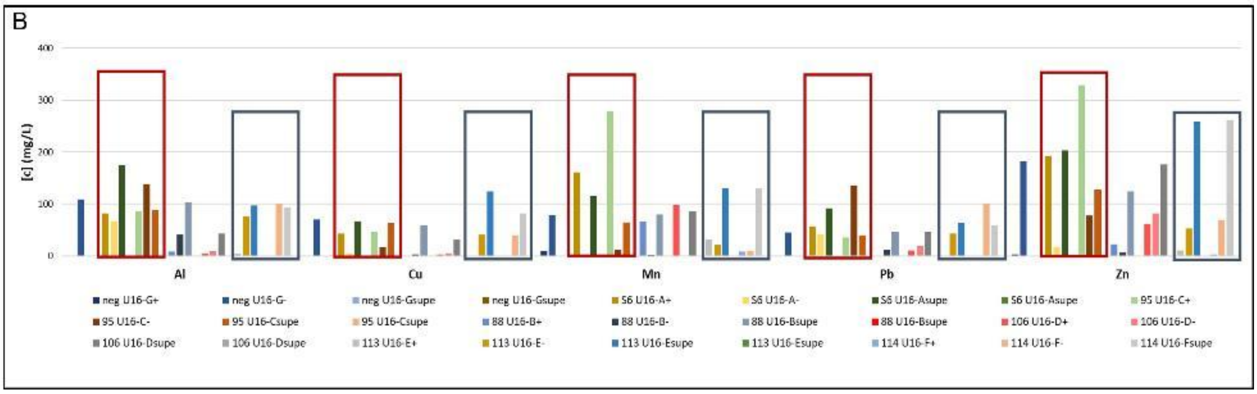


Fig. 4: *(A) Determination of bacterial survival upon given voltage and extraction of metals by autochthonous bacterial community from tailings' sludge. (B) Effectivity of metal extraction using voltage, 3% citrate and chosen bacterial monoculture*

3.2 Column tests

After completing the tube experiments, the test was scaled up to a column reactor. The equipment comprised three main components: a DC power supply, two columns filled with sand and external electrolyte reservoirs (**Figure 5**). Each column (47 cm) was filled with sand washed with deionized water and dried at 105 C for 24h. The reservoirs were filled with 15 L of deionized water and NaCl (7 g/L) as the electrolyte, ensuring a stable ionic environment throughout the run.

At first, different electrodes were tested to find the most suitable material for the test. Steel electrodes showed corrosion and release of metals that made it complicated to trace the zinc concentration, so graphene electrodes were chosen. The electrodes were placed in the center of the canisters containing the electrolytes. To the system was applied 32 V and current of 0.10–0.15 A. To trace migration under the applied field, 1 mL of a concentrated zinc acetate stock solution (430 g/L) was injected at two predefined locations along the flow path.

Sampling ports spaced every 9 cm allowed periodic withdrawal of water; the aliquots were filtered (0.45 µm) and analyzed for dissolved zinc.

Fig. 5: *Column setup used for the test*

3.3 Final test set-up

For the final setup, a reactor that simulates real electrokinetic-remediation conditions was used. The test employed real sludge from Zlaté Hory containing a mixture of metals such as zinc, manganese and lead among others. The sludge (1 L) was placed at one end of the reactor, while the remaining space was filled with sand (2 L). An additional 3.7 L of water was added to the reactor (**Figure 6a**). Graphite electrodes were placed near the opposite edges of the reactor: the positively charged electrode on the sludge side and the negatively charged electrode on the sand side.

There were four sampling points. The first was located at the boundary between mud and sand (P4), the second 5 cm away from the sludge (P3). Two other points (P5, P6) were placed 10 cm away from the sludge and about 4 cm to the right and left of P4 (**Figure 6b**).

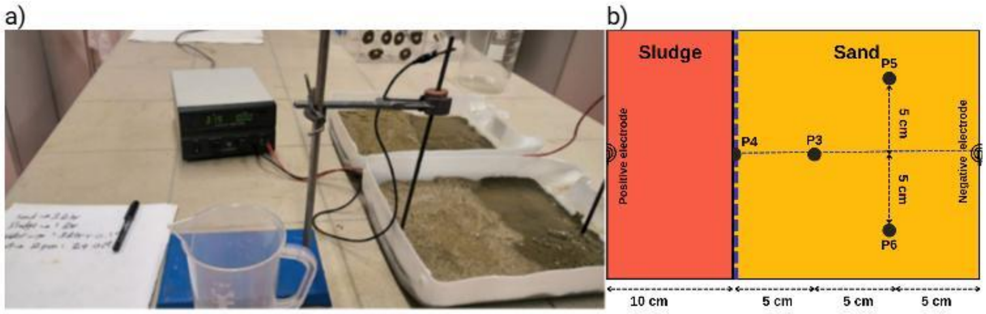


Fig. 6: *a) Setup used for simulating real field condition.*
Experiment condition: Voltage: 32 V, Current: 1 mA, graphite electrodes, b) sampling points

4. Expected Scientific and Societal Impacts

Legacy uranium mining sites in the Czech Republic present persistent environmental, public health, and socio-economic challenges. These sites contain complex, often poorly characterized mixtures of uranium and other NORM wastes posing risks to soil, water, ecosystems, and communities. SURRI develops integrated, scalable, and sustainable remediation and recovery solutions, building on state-of-the-art research in electrokinetics, biotechnologies, and critical metal recovery. The expected impacts span scientific advancement, regulatory support, and substantial environmental and socio-economic benefit, all aligned with major EU policy frameworks.

Environmental impacts

Our remediation and recovery work is aimed first at reducing environmental burdens at the selected Czech legacy sites. **Low-voltage electrokinetic treatment** (at milliampere currents) is being adapted to site-specific geochemistry (e.g., carbonate-rich sludge) so that **U and co-occurring metals—Zn, Fe, Cu, As** can be **mobilised, separated and recovered in situ**, minimising excavation and transport. **Bioremediation and nature-based solutions** are being advanced concurrently: **indigenous microbial communities** (including tolerant strains such as *Trichoderma* spp. and *Dioszegia* spp.) are profiled to inform **radionuclide reduction/immobilisation**, and **phyto-recovery** with **duckweed and sunflowers** is being trialled to support metal uptake, suppress dust and establish early green cover. These actions are **consistent with the EU Green Deal** zero-pollution ambition and **contribute to Water Framework Directive (WFD, 2000/60/EC) objectives** by limiting leaching from source zones to groundwater and surface waters.
(https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691,
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2025:2:FIN&qid=1738746144581)
By restoring soil function with locally adapted microbes and plants—and screening choices against **ISO 18504:2017** sustainable-remediation principles (life-cycle impacts, risk balancing, stakeholder input)—the approach **addresses pollution at its source and prepares degraded land for responsible, future use**.

Societal impacts

Benefits to nearby communities are pursued through **in situ, lower-disturbance approaches** (electrokinetics, microbial pathways and phyto-recovery) that are intended to **lower exposure pathways**, particularly dust and contact with impacted media, while keeping disruption on site to a minimum. The emphasis on **indigenous organisms** and **rehabilitated rhizosphere communities** makes the methods locally understandable and easier to accept. Planning and communication is designed to reflect **Aarhus Convention** principles—accessible information, opportunities to comment and participation in choices—so that communities can follow progress and the basis for decisions as results evolve. (https://unece.org/environment-policy/public-participation/aarhus-convention/text) As the work advances, this provides a **clear platform for informed discussion of future land use and reuse options**, linking environmental improvement to public-health protection and local expectations.

Economic impacts

Remediation and resource recovery are being advanced together to **improve resource efficiency** and open **innovation routes**. From mine drainage and process effluents, **bioleaching** by bacteria isolated from former mining sites has yielded **ZnO nanoparticles**, and **laser-based strategies** are being used to **generate and valorise multimetallic (Au- and Fe-based) nanoparticles** with potential application in **catalysis, sensing and energy storage**. (10.1039/D4GC06174H) This contributes to the **EU Critical Raw Materials Act (2023)** and demonstrates **Circular Economy Action Plan** principles by turning legacy streams into secondary resources rather than liabilities.
(https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN)
Because **in situ electrokinetics** can reduce excavation and transport, there is **potential for cost avoidance** relative to conventional dig-and-dump approaches—an aspect to be evaluated alongside **technical performance and cost-effectiveness** before any scale-up. In the longer term, the planned **multinational virtual centre** is intended to connect results to partners and markets, supporting innovation without pre-empting integration or upscaling claims at this stage.

5. Policy and Innovation Recommendations

In this project, innovative techniques have been developed for the recovery of critical metals from mining processes. Leveraging the expertise and contributions of universities, new knowledge and technical advancements have been achieved, particularly in the application of electrokinetics and adsorption-based technologies. These approaches aim to improve efficiency and sustainability in metal recovery while mitigating environmental impacts from mining waste. Although the current results are mainly derived from laboratory-scale experiments, they show strong potential for industrial application. However, moving from lab success to large-scale implementation requires addressing scalability, cost-effectiveness, and regulatory compliance. In the next stage, the scope will be extended to include research and innovation funding strategies, regulatory and legislative support needs, enhanced collaboration with industry and SMEs, and the development of public awareness and communication tools. These steps will strengthen both the technical and strategic foundations for adoption in real-world mining operations.

5.1 Research and innovation funding strategies

The SURRI project, funded under the EU Horizon Europe Twinning program, aims to develop advanced, sustainable technologies for the remediation of radionuclide-impacted sites and recovery of critical materials from mining processes [1]. A strategic framework for its research and innovation funding can be effectively shaped by the **Triple Helix Model of Innovation** [2], which fosters collaboration between **universities**, **industry**, and **government** to accelerate technological development and ensure impactful outcomes.

Universities, led by the Technical University of Liberec (TUL) and its international partners, contribute scientific expertise and technical innovation, particularly in electrokinetic, electrochemical, microbiological, and phytoremediation methods. Through structured work packages, they drive knowledge generation, capacity building, and the creation of a virtual research and innovation center. These activities not only strengthen institutional capabilities but also position SURRI's outputs for future funding opportunities through competitive EU and national research grants.

Industry, represented by DIAMO and potentially other SMEs, provides critical access to former uranium mining sites such as Stráž pod Ralskem, Zlaté Hory, Kaňk, and Jáchymov. These real-world environments allow for pilot-scale validation of remediation and recovery technologies, creating a direct feedback loop between field implementation and academic R&D. Such collaboration opens pathways for co-investment models, public–private partnerships, and industry-driven funding streams aimed at commercialization and deployment.

Government involvement, through Horizon Europe funding and alignment with EU policy priorities like the Green Deal and circular economy, ensures that SURRI's objectives fit within broader societal and environmental strategies. By demonstrating measurable impacts in environmental restoration and resource efficiency, SURRI can influence future regulatory frameworks, enabling targeted legislative support and structured innovation funding instruments that promote technology adoption.

In the **next phase**, the project will expand its strategic scope to include:

- **Research and innovation funding strategies** aligned with EU and national priorities, leveraging competitive grants, industry co-funding, and public–private financing models.
- **Regulatory and legislative support** to enable and accelerate technology implementation.
- **Collaboration with industry and SMEs** to foster innovation ecosystems and supply chain integration.
- **Public awareness and communication tools** to build societal trust, enhance policy backing, and secure stakeholder engagement.

The conceptual model for the nexuses between different hubs during the policymaking process is demonstrated based on **Fig. 7**.

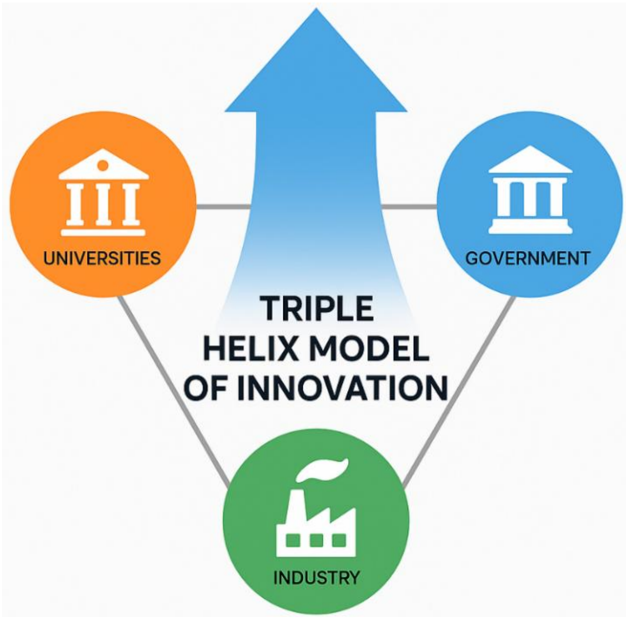


Fig. 7: *The conceptual model of Triple Helix Model of Innovation through SURRI project*

5.2 Regulatory and legislative support needs

The Regulatory Impact Assessment (RIA) model [3] offers a structured approach to ensure that policy and legal environments actively enable the adoption of SURRI's innovations. The RIA begins by clearly defining the regulatory context and identifying gaps in current environmental, radiation safety, and waste management legislation that may limit the deployment of electrokinetic, microbiological, and phytoremediation technologies. For SURRI, these gaps are particularly relevant in target areas such as Stráž pod Ralskem, Zlaté Hory, Kaňk, and Jáchymov, where existing laws may not reflect the capabilities of emerging remediation methods.

Next, the RIA aligns regulatory objectives with overarching policy priorities, including the EU Green Deal, the Circular Economy Action Plan, and the Critical Raw Materials Act. This ensures that any legislative adjustments promote environmental protection, sustainable resource recovery, and public health while supporting innovation. Possible policy options might involve updating contamination threshold definitions to integrate advanced monitoring tools, introducing certification schemes for novel remediation technologies, or establishing fast-track approval pathways for pilot projects.

A key step in the RIA process is assessing the economic, environmental, and social impacts of these policy options, from cost savings in remediation and value creation through recovered metals to improved land usability, job creation, and community health benefits. Stakeholder consultation, following the Triple Helix Model, is central—bringing together universities for scientific validation, industry for feasibility insights, government agencies for compliance perspectives, and local communities for social acceptance.

By applying the RIA framework, SURRI can ensure that legislation becomes a catalyst rather than a barrier, creating a policy environment that accelerates technology uptake, supports funding access, and bridges the gap between research success and full-scale deployment. The proposed policies and structures are mentioned as per **Fig. 8**.

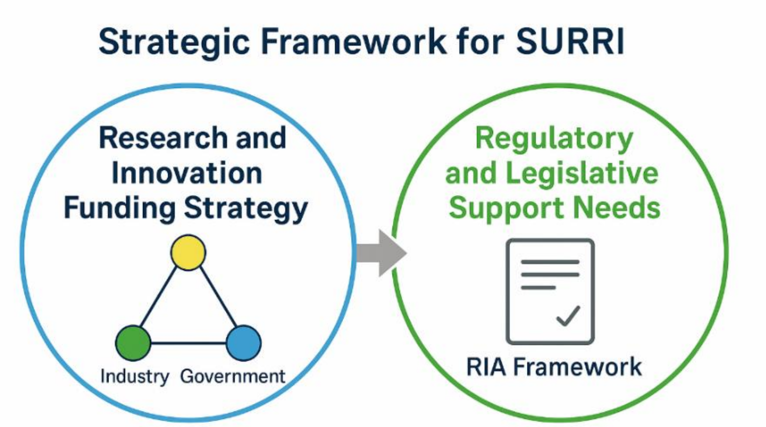


Fig. 8: *The conceptual model of Regulatory Impact Assessment in SURRI project*

5.3 Collaboration with industry and SMEs

For the SURRI project, the **Open Innovation Ecosystem Model** [4] provides a dynamic framework for fostering collaboration with industry and SMEs. By enabling the open exchange of ideas, technologies, and expertise, this model accelerates the development and adoption of SURRI's remediation and critical material recovery solutions. Through **inbound innovation**, SMEs and industrial partners can contribute specialized tools, field-tested methods, and niche capabilities to enhance pilot-scale trials at former mining sites. **Outbound innovation** allows SURRI to share research findings, prototypes, and datasets, enabling SMEs to adapt and commercialize technologies, while creating opportunities for licensing and spin-offs.

Joint **co-creation environments** such as testbeds, field labs, and innovation hubs support iterative development in real-world conditions. By embedding SMEs into this open ecosystem, SURRI leverages their agility, creativity, and market insight, ensuring that innovations are not only scientifically advanced but also practical, scalable, and positioned for broad industrial uptake. The proposed structure is mentioned in **Fig. 9.**

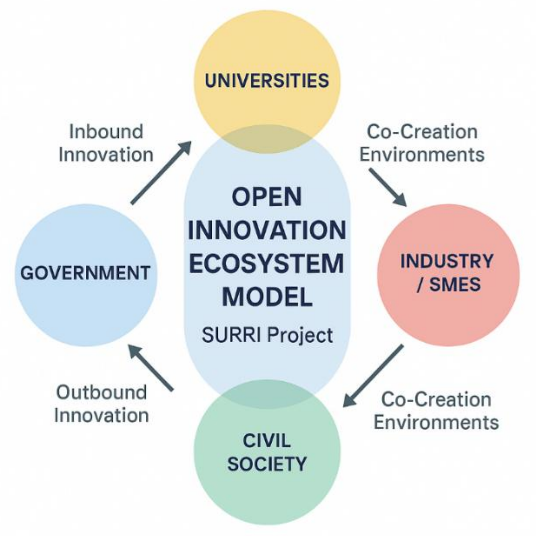


Fig. 9. *The structure of Open Innovation Ecosystem Model in SURRI project*

5.4 Public awareness and communication tools

For the SURRI project, the **Communication for Development (C4D) Model** [5] provides a strategic, participatory framework for building public awareness and engagement around remediation and critical material recovery activities. It focuses on audience-centered design, ensuring messages are tailored to the needs, cultural context, and priorities of different stakeholders, including local communities near former mining sites, policymakers, industry partners, and civil society groups. By employing a multi-channel strategy combining social media campaigns, local media coverage, community events, educational workshops, and open days at pilot sites SURRI can share project goals, scientific progress, and environmental benefits in an accessible and transparent manner. Central to the model is two-way engagement, where stakeholders are encouraged to provide feedback, share concerns, and participate in decision-making processes, fostering trust and ownership. Continuous monitoring and evaluation of communication activities allow SURRI to refine its messaging, improve outreach effectiveness, and ensure that communication tools remain relevant, impactful, and aligned with the project's sustainability and policy objectives. The suggested concept is demonstrated in **Fig. 10.**

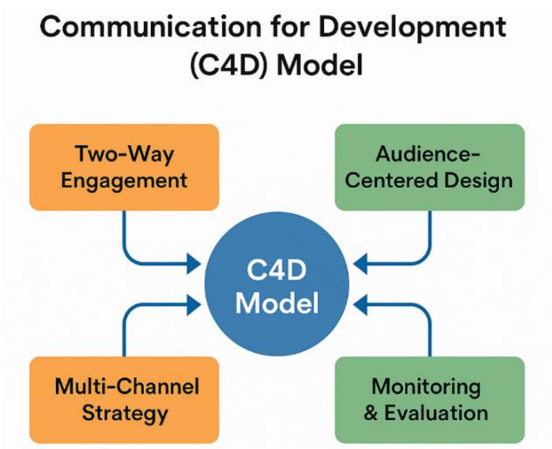


Fig. 10: *The framework of Communication for Development (C4D) Model in SURRI project*

5.5 Executive summaries for general public and decision makers

For the general public

Past uranium mining has left polluted soils and waters in parts of Europe, especially in the Czech Republic. These sites can affect health, nature, and local communities. The SURRI project is testing new, low-energy methods that use electricity, microbes, and plants to clean the land and water. At the same time, it looks for ways to recover useful metals from waste. This approach is less disruptive, more sustainable, and helps turn an environmental problem into a resource for the future.

For decision makers

SURRI offers a practical strategy that supports the EU Green Deal and Circular Economy goals. Key points are:

- **New methods**: Low-energy electrochemical and biological techniques reduce contamination while allowing recovery of valuable materials.
- **Benefits**: Lower risks to soil and water, better protection for communities, and restored land for safe future use.
- **Opportunities**: Linking remediation with resource recovery improves cost-effectiveness and supports innovation.
- **Next steps**: Pilot projects at Czech sites, stronger policy support, long-term funding, and clear communication with the public.

SURRI shows that legacy mining waste can be managed in a way that protects people and the environment while also strengthening Europe's supply of critical raw materials.

6. Conclusions, next actions

The SURRI project has laid the groundwork for a strategic, Europe-wide approach to sustainable remediation of radionuclide-impacted sites and the recovery of critical raw materials, focusing primarily on legacy uranium mining locations in the Czech Republic and similar sites across Europe.

1. Technological Innovation

SURRI developed integrated electrochemical, microbiological, and phytoremediation methods for in situ and ex situ treatment.

These solutions enable mobilization, separation, and recovery metals (e.g., Zn, Fe, Cu, As) with minimal excavation, aligning with EU Green Deal and Circular Economy Action Plan goals.

Pilot experiments showed:

- Electrokinetic remediation works at low energy consumption.
- Bioleaching bacteria can generate high-value products such as ZnO nanoparticles.
- Nature-based solutions like phytoremediation with duckweed and sunflowers improve soil restoration and dust suppression.

2. Environmental and Societal Benefits

Significant potential to reduce long-term contamination risks for soil and groundwater.

In situ techniques minimize disruption to communities, improve acceptance.

Rehabilitation prepares land for safe future use and protects public health while creating opportunities for green regeneration.

3. Economic Opportunities
Combining remediation with critical raw material recovery improves economic feasibility.
Demonstrates a circular economy approach, turning contaminated tailings into resources.
Reduces costs compared to traditional dig-and-dump methods, while creating opportunities for spin-offs and licensing.

4. Policy and Governance Recommendations
Adoption of Triple Helix Innovation Model:
- Universities provide scientific expertise and innovation.
- Industry offers real-world sites for validation and commercialization.
- Governments align regulatory frameworks and provide funding mechanisms.

A Regulatory Impact Assessment (RIA) process is essential to remove legal barriers and support fast-track approvals for innovative remediation technologies.
Public awareness must be fostered through a Communication for Development (C4D) framework, ensuring transparent, two-way engagement with communities and stakeholders.

5. Establishment of a Virtual Centre of Excellence
SURRI has initiated the creation of a virtual European Centre of Excellence, coordinated by TUL and key partners, open to:
- Academic institutions,
- Industrial partners,
- Funders,
- Policymakers.
- The centre's goal is to advance technologies from laboratory scale → pilot trials → full-scale deployment, following environmental, economic, and social sustainability principles.

6.1 Next Action Plan

1. Pilot Demonstrations (term depends on financial sources)
Objective: Validate technologies in real-world environments.
Deploy pilot-scale systems at target sites (e.g., Stráž pod Ralskem, Zlaté Hory, Kaňk, Jáchymov).
Test integration of electrokinetic, microbiological, and phytoremediation techniques.
Collect technical, environmental, and socio-economic data for scale-up feasibility.
Lead actors: CXI TUL, DIAMO, university partners.

2. Strengthen Policy Alignment (2026–2028)
Objective: Ensure a supportive legal and regulatory framework.
Conduct a Regulatory Impact Assessment (RIA) to:
- Identify gaps in current laws for radiation safety, waste management, and remediation.
- Propose updates to contamination thresholds and certification schemes for novel technologies.
- Develop fast-track approval pathways for innovative remediation projects.

Lead actors: CXI TUL, EU policymakers, national environmental agencies.

3. Funding and Innovation Ecosystem (2025–2030)

Objective: Secure resources for long-term sustainability.

Build a Triple Helix network to co-create:

- EU research funding strategies (e.g., Horizon Europe, FP10),
- National innovation funding,
- Public–private financing models.

Engage SMEs and industrial partners through open innovation hubs, fostering commercialization opportunities.

Establish a financial plan for the Virtual Centre of Excellence.

4. Public Awareness and Community Engagement (Continuous)

Objective: Gain societal trust and stakeholder buy-in.

Launch community engagement campaigns using the C4D model:

- Educational workshops,
- Open days at pilot sites,
- Clear, transparent updates via media and online platforms.

Gather feedback to integrate community priorities into remediation plans.

5. Scaling Up and European Integration (term depends on financial sources)

Objective: Expand SURRI outcomes across Europe.

Gradually transition from pilot-scale to full-scale remediation projects.

Establish formal European Centre of Excellence with shared infrastructure and expertise.

Position SURRI technologies as EU-wide standards for sustainable remediation and critical materials recovery.

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Participating institutions and stakeholders

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