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multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

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TECHNICAL REFERENCES

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PP = Restricted to other programme participants (including the Commission Services)

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ABSTRACT

Task 5.4 aimed to advance sustainable remediation approaches for contaminated soils, groundwater, and mining-impacted areas through an integrated combination of laboratory experiments, field investigations, numerical modeling, and sustainability assessment. The overarching objective was to develop, test, and evaluate innovative technologies capable of reducing contaminant mobility, enhancing degradation processes, and supporting long-term environmental recovery, while ensuring technical feasibility and alignment with sustainability principles.

The activities undertaken addressed three complementary domains. First, new theoretical and numerical models were developed to simulate non-isothermal water flow, vapor transport, and contaminant migration in unsaturated porous media, providing predictive tools essential for understanding pollutant behaviour and for designing effective interventions. Second, experimental work at both laboratory and field scale supported the development and performance assessment of bioremediation and phytostabilization strategies. These included the isolation and characterization of microbial strains capable of degrading hydrocarbons and chlorinated solvents, the design of microcosm studies to evaluate biostimulation and bioaugmentation, and the implementation of a mine-tailings experimental field to test bioaugmentation, amendments, and biogeochemical barriers for reducing metal and metalloid dispersion. Third, the task established a structured sustainability-assessment framework, supported by a review of international regulatory approaches and the definition of environmental, social, and economic indicators suitable for evaluating remediation technologies ex-ante.

Overall, the results demonstrate the feasibility and applicability of the developed methodologies and technologies, offering both operational tools and conceptual frameworks to improve the assessment of remediation performance. The outcomes contribute to the advancement of sustainable, science-based remediation solutions and provide a foundation for risk reduction and regeneration of contaminated, brownfield, and mining-affected sites.

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4.First Section

4.1 General overview

The activities conducted within Task 5.4 collectively address the need for sustainable, scientifically robust, and practically applicable remediation solutions for contaminated sites, brownfields, and mining-impacted areas. The work followed a multi-layered and integrated approach, combining experimental research, model development, field testing, and sustainability assessment to evaluate the performance of a wide spectrum of remediation methodologies.

The task encompassed three main thematic components. The first focused on understanding contaminant transport and transformation processes through theoretical modeling and laboratory-scale experiments, providing fundamental insight into how pollutants move, persist, or can be mobilized within soils and groundwater systems. The second component targeted the development and validation of innovative and sustainable bioremediation and phytostabilization strategies, employing microbial consortia, native plant species, and amendments to reduce contaminant dispersion and enhance ecosystem recovery, particularly in mining environments. The third component addressed the evaluation of remediation practices through the lens of sustainability, establishing a regulatory overview, selecting key indicators across environmental, social, and economic dimensions, and developing a structured framework to compare alternative remediation technologies.

By integrating these complementary activities, Task 5.4 produced a comprehensive and coherent body of knowledge that supports the assessment of remediation methodologies from both technical and sustainability perspectives. This holistic approach strengthens the capacity to design effective, site-specific interventions that align with principles of environmental protection, resource efficiency, and long-term land regeneration.

4.2 Detail of the activities

- Modeling and Assessment of Contaminant Transport

Development of a Theoretical Non-Isothermal Model: A theoretical model was created to simulate the non-isothermal infiltration and evaporation processes in unsaturated soil layers. This model provides a foundational understanding of water and contaminant movement in the subsurface, which is crucial for predicting the fate and transport of contaminants like mineral oils and BTEX.

Modification of the MNM Model Suite: The Micro- and Nanoparticle Transport, Filtration, and Clogging Model Suite (MNMs) was modified to accurately account for transport processes in porous media. This improved model is essential for evaluating the effectiveness of both engineered and naturally occurring nanoparticles in delivering treatment agents or assessing the risk of contaminant migration.

- Development of a toolbox for reducing the dispersion of metals and metalloids.
- Bioleaching processes in mining environments

The experimental work was focused on developing and testing a sustainable remediation toolbox for mine tailings, with a particular emphasis on bioaugmentation and its effects on native plant growth and metal and metalloid dispersion. The first step involved setting up an experimental field on the mine tailings, combined with a detailed characterization of the chemical, mineralogical, and microbiological composition of the substrate. The performance of a Viromine amendment was tested as a comparative benchmark. Native plant species already adapted to the polluted environment were identified, and seedlings were planted on the mine tailings to evaluate survival and growth under field conditions.

Parallel to the plant experiments, bacterial species with plant growth-promoting properties were isolated and selected from the site's soil. The composition of this bacterial pool was determined, and the selected microorganisms were applied as a bio-fertilizer, sometimes using zeolites as a supporting material. Continuous monitoring of biogeochemical parameters, including plant survival rates, chlorophyll content, and microbial community dynamics, allowed evaluation of the overall effectiveness of the toolbox in promoting plant establishment and influencing metal and metalloid dispersion in the tailings.

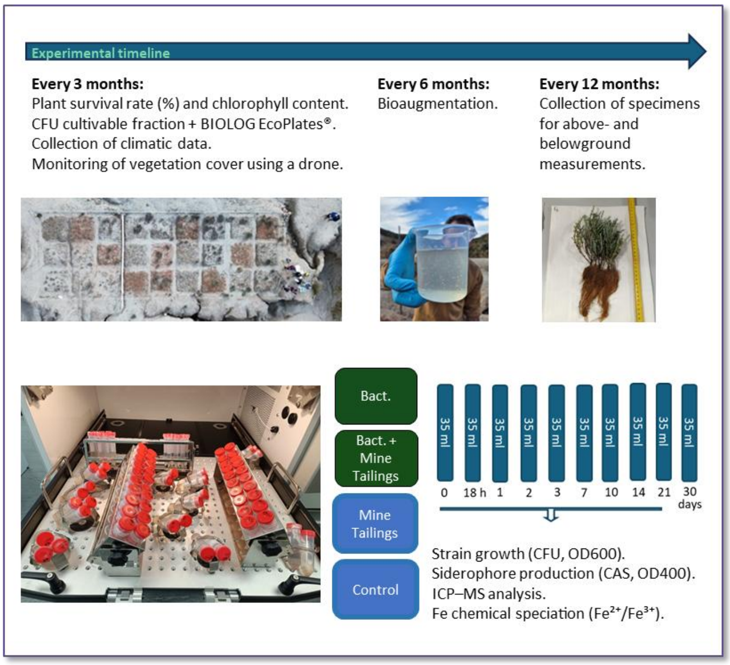

Figure 1. Bioleaching processes in mining environments. experimental timeline

In addition, bacterial species naturally responsible for leaching in rivers near mining sites were identified as potential tools for biomining applications. In particular, the strain *Pseudomonas protegens* FeIIC1 was tested on synthetic Goethite substrates and subsequently on real mine tailings, to assess its capacity to mobilize metals and explore its potential in bio-mining or bio-recovery strategies. This integrated approach combined plant-based stabilization, microbial bioaugmentation, and targeted biomining tests to develop sustainable strategies for the remediation and valorization of mine-impacted sites.

The monitoring of the experimental field at Ingurtosu, along with the implementation of biogeochemical barriers, provided effective proofs-of-concept for testing sustainable technologies aimed at reducing both human health and environmental risks associated with the management of mine waste, such as tailings deposits. This work demonstrated that targeted interventions, including the application of amendments and microbial bioaugmentation, can contribute to safer and more sustainable management practices for contaminated mining sites.

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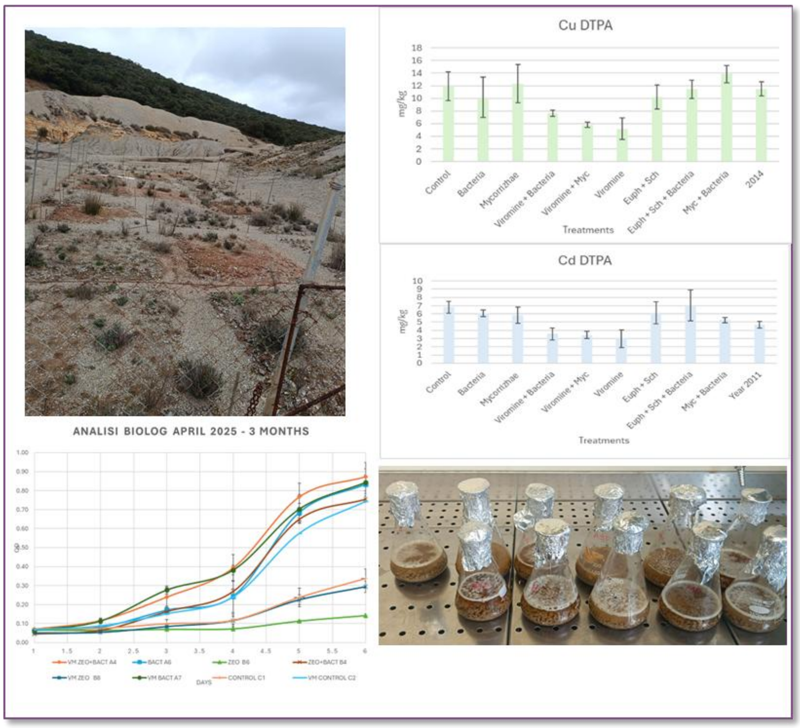


Figure 2 Bioleaching processes in mining environments. Results

- Laboratory-Scale Experiments for Evaluating Bioremediation Approaches

The activities focused on developing sustainable bioremediation strategies for contaminated sites. The work involved isolating, selecting, and characterizing bacterial strains and consortia capable of degrading hydrocarbons and chlorinated solvents. Laboratory-scale microcosms were set up to simulate different environmental conditions and evaluate bioremediation approaches, including biostimulation and bioaugmentation. Microbial community dynamics and contaminant removal efficiency were monitored to identify the most effective strategies, with the overall objective of supporting the design and implementation of efficient, sustainable remediation technologies.

- Setup and monitoring of microcosms for 1,2-DCA biostimulation: Laboratory-scale microcosms were designed to stimulate both anaerobic and aerobic dechlorinating bacterial communities in contaminated groundwater. Different biostimulation strategies were tested, including the addition of electron donors, nutrients, and oxygen sources, to evaluate their effectiveness in promoting 1,2-DCA dechlorination and mineralization. Microcosms were inoculated with either native microbial communities or previously enriched consortia. Analytical monitoring included periodic quantification of chlorinated compounds via gas chromatography and molecular analyses, such as qPCR and 16S rRNA sequencing, to identify active dechlorinating populations and track microbial community dynamics. These studies provided fundamental data for assessing bioremediation potential and scaling up to pilot or field applications.

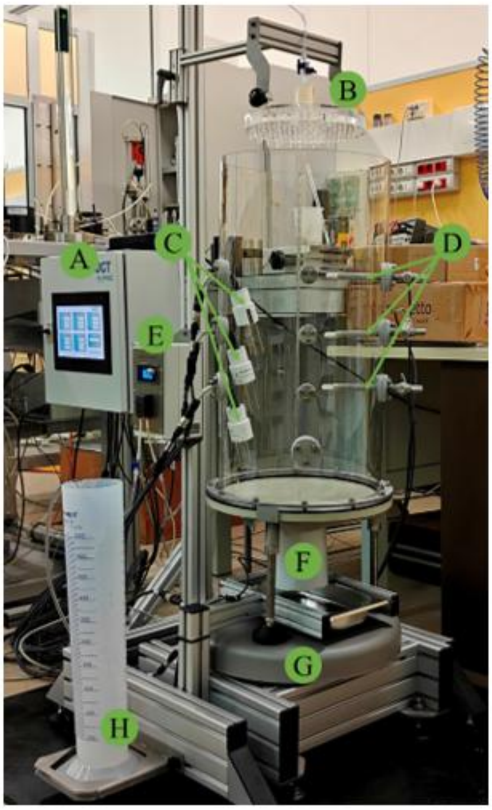
- Isolation and characterization of an Ancylobacter-dominated consortium: From aerobic microcosms, a stable dechlorinating consortium was obtained through successive enrichment cultures. Individual strains isolated from 1,2-DCA-contaminated groundwater were revealed, via Ion Torrent 16S rRNA gene sequencing, to be stable consortia dominated by *Ancylobacter*, with co-occurring genera such as *Ochrobactrum*. The consortium achieved complete degradation of 1000 ppm 1,2-DCA within three days, indicating high dechlorination efficiency. The presence of the dhlA gene, encoding the key hydrolytic dechlorination enzyme, was confirmed on the *Ancylobacter* chromosome through whole genome sequencing, together with flanking transposase genes suggesting horizontal gene transfer. qPCR analyses confirmed *Ancylobacter* as the main degrader, while minor community members likely contributed by removing toxic intermediates. The high degradation performance of the consortium highlights its strong potential for aerobic bioaugmentation applications.

- Aerobic Permeable Reactive Barrier (PRB) column simulations: Laboratory-scale columns were used to simulate aerobic PRB systems for 1,2-DCA-contaminated groundwater. The previously characterized aerobic dechlorinating community was inoculated into columns, with comparisons made between setups with and without an oxygen-releasing compound (ORC). Different microbial communities developed under these distinct conditions: in the absence of ORC, *Ancylobacter* was detected, while in the ORC-enriched column, *Pseudomonas* became dominant. The oxygen-releasing device enhanced 1,2-DCA removal efficiency, illustrating the role of controlled oxygen availability in promoting aerobic degradation and supporting the potential application of oxygen-managed PRBs in field-scale remediation.

- Sequential biostimulation and bioaugmentation for hydrocarbon-contaminated soils: Microcosm-scale experiments assessed the effectiveness of sequential treatments for diesel-contaminated soils. Two aerobic biostimulation approaches, landfarming (LF) and bioventing (BV), combined with nutrient addition, were followed by bioaugmentation using a hydrocarbon-degrading Actinobacteria consortium. Over 180 days, TPH concentrations were reduced by up to 40%, and microbial community analysis revealed significant enrichment of indigenous hydrocarbon degraders. LF and BV treatments induced shifts in microbial taxa, with Actinobacteria, Alphaproteobacteria, and Bacilli increasing under BV, and TM7-3 and Gammaproteobacteria increasing under LF. The combined biostimulation–bioaugmentation strategy promoted the growth of native degraders while ensuring the effective reduction of contaminants.

- Design of columnar tests and implementation of coupled numerical model to study the cover system's performance under different climatic boundary conditions

The activities carried out involved the setup and monitoring of a columnar lysimeter with a diameter of 30 cm and a height of 60 cm, equipped with tensiometers, HydraProbe Pro sensors, a precipitation simulator, an infrared radiation source, a leachate meter, and a precision scale. Soil moisture, temperature, electrical conductivity, dielectric permittivity, soil suction, and leachate production were continuously measured under controlled precipitation and radiation conditions to provide detailed information on water movement and evapotranspiration processes. Water and soil samples were collected and analyzed to quantify these processes and assess potential contaminant transport. The experimental data were then integrated into a coupled thermo-hydraulic numerical model implemented in COMSOL Multiphysics, simulating unsaturated liquid and vapor water flow, heat transport, and phase change phenomena within the soil column. The model was calibrated using the laboratory results to predict the performance of single-layer evapotranspiration cover systems under varying soil types, degrees of compaction, layer thicknesses, and vegetation cover. Based on these analyses, recommendations were developed for the experimental evaluation of treatability and the optimization of sustainable soil cover system design.



A	Control Unit with Programmable Logic Control Display
B	Precipitation simulator
C	HydraProbe Pro (ratiometric coaxial impedance dielectric reflectometer): it measures soil temperature, moisture, electrical conductivity, and dielectric permittivity
D	Tensio 160 (tensiometer): it measures the soil suction
E	Pump control unit (peristaltic pump) to control the precipitation rate
F	Tipping counter for quantitative determination of seepage water
G	Weighing plate
H	Water reservoir: it holds water for the precipitation

Figure 1 - Columnar laboratory apparatus

This study demonstrates the potential of single-layer evapotranspiration (ET) covers as sustainable, cost-effective alternatives for municipal solid waste management. To address the challenge of predicting their performance under variable climatic conditions, a coupled experimental and numerical framework was established. The experimental component utilized a columnar lysimeter equipped with a precipitation simulator, tensiometers, and dielectric reflectometers to monitor evapotranspiration, soil moisture, suction, conductivity, and temperature. Complementing this, a coupled thermo-hydraulic numerical model in COMSOL Multiphysics simulated water and heat fluxes, enabling analysis of infiltration and evaporation processes. Calibrated with experimental data, the framework provides a predictive tool to optimize ET cover design—considering soil type, thickness, and compaction—under realistic climatic conditions, supporting the development of efficient and sustainable landfill cover systems.

The activity successfully established a coupled experimental and numerical framework. The newly designed columnar laboratory apparatus proved to be a robust platform for data acquisition, enabling direct and reliable determination of real evapotranspiration as well as detailed monitoring of soil water content, suction, electrical conductivity, and temperature. In parallel, the coupled numerical model provided a tool to design efficient single-layer evapotranspiration cover systems, allowing optimization of parameters such as soil type, layer thickness, and degree of compaction. Sensitivity analyses based on anticipated climatic conditions further supported the development of tailored and resilient cover solutions.

- Assessment and Regulatory Framework

The work began with a comprehensive review of the regulatory framework for the sustainable management of contaminated sites in both European and non-European countries. This analysis aimed to understand the current level of maturity in selecting remediation interventions, particularly in relation to quantitative and qualitative assessments of sustainability across different remediation alternatives. Emphasis was placed on how sustainability principles are embedded within existing regulations and directives, and the study included a review of available tools for sustainability assessment, supported by the presentation of significant case studies. Building on this review, a structured framework for the sustainability assessment of remediation interventions was developed, with a particular focus on soil management. The primary goal was to provide a systematic approach to evaluate innovative remediation technologies as alternatives to conventional practices, such as Dig & Dump, which, although still widely employed in Italy, no longer align with the requirements for efficient resource and waste management. This framework enables the comparison of different remediation strategies, using a set of selected indicators to perform an ex-ante evaluation and determine which technology can be considered the most sustainable in a given context. The methodology was then applied to a case study developed within the work conducted for TS1 (WP4 Task 5.4.4), demonstrating its practical applicability in guiding sustainable remediation planning. The methodology began with a comprehensive review of the regulatory framework for the sustainable management of contaminated sites, considering both European and non-European contexts. Within Europe, regulations and technical standards from the EU and individual countries—including France, Germany, Denmark, the Netherlands, Belgium, Sweden, Finland, Spain, and the Czech Republic—were analyzed. The review also extended to non-European countries such as Norway, the UK, the USA, and Canada. This analysis included a comparison of available online tools and platforms for sustainability assessment, with particular reference to SRT, SiteWise, SURE, and ASTRA. Additionally, three case studies from the literature were examined to highlight the practical application of sustainability principles in remediation projects. Following this review, sustainability principles were defined, along with the characteristics that indicators should possess to ensure they can be effectively evaluated. Based on this, a set of sustainability indicators covering the three pillars of sustainability—environmental, economic, and social—was selected. The indicators were chosen through a combination of literature review and analysis of the capabilities of existing software tools, with particular attention to the feasibility of measurement and data availability. Finally, the selected indicators were applied to a case study developed within TS1 to test their applicability and to assess which indicators could be most effectively evaluated based on the quantity and quality of accessible data. This approach allowed a practical assessment of the potential of the framework to support ex-ante evaluations of remediation technologies from a sustainability perspective.

Acronym	Full name	Authors	Levels		
			1	2	3
SRT	Sustainable Remediation Tool	USA - Air Force Center for Engineering and the Environment (AFCEE)			
GoldSET	GolderSET-SR-cnSustainability Tool	Golder Associates			
SiteWise GSR Tool	SiteWise - Green Sustainable Remediation	US – Navy Department, USACE (United States Army Corps of Engineers), Battelle			
GREM	Green Remediation Evaluation Matrix	California Department of toxic substances control			
REC-tool	Risk Reduction Environmental Merit and Cost	n.d.			
SAF	Sustainable Assessment Framework	Syndial S.p.A. (now Eni Rewind S.p.A)			
CEEQUAL		BRE - Building Research Establishment			
SPeAR	Sustainable Project Appraisal Routine	ARUP - Regno Unito			
Greener Cleanups		EPA - Illinois			
BalanE3		ARCADIS			
MCEA Tool	Modified Cost-Effectiveness-Analysis	Agenzia per la protezione dell'ambiente, Austria			
DESYRE	Decision Support sYsyem for REhabilitation of contaminated sites				
MMT	Megasite Managemnt Toolsuite	Helmholtz Centre for Environmental Research – UFZ Germania			
SURE		Ramboll			
ASTRA	Advanced Sustainability Tool for Remediation Assessment	Eni Rewind, Fondazione Università Ca' Foscari			

Tools for sustainable remediation assessment

Sustainability indicators			
	E	S	G
Mineral resource scarcity (LCA midpoint)			
Solid waste production			
Global warming (LCA midpoint)			
Cumulative Energy Demand (CED)			
Expected duration of intervention			
Construction cost physical capital used in the intervention			
Intervention operating costs			
Increase in land value following reclamation			
Health impacts on workers and residents in communities adjacent to the remediation site			
Equity across generations and populations			
Negative externalities for residents and stakeholders			
Human capital (i.e. investment in training, experimentation, research and development)			

Selected sustainability indicators

The work encompassed the development of methodologies, roadmaps, proofs-of-concept, and guidelines aimed at supporting risk analysis, reduction, management, mitigation, and adaptation in the context of contaminated site remediation. A review of the national regulatory framework revealed a notable gap in the formal consideration of sustainability aspects compared to other European countries, highlighting the need for structured approaches to evaluate and guide remediation interventions.

To address this, twelve representative indicators were selected, evenly distributed across the three pillars of sustainability—environmental, social, and economic—ensuring a balanced assessment across all dimensions. Building on this, guidelines were defined to support ex-ante sustainability assessments of remediation technologies, prioritizing indicators characterized by high data availability and ease of application. This approach ensures that the methodology is both transferable and scalable, allowing its application across diverse contaminated sites within the national context.

Finally, the applicability of the selected indicators was tested on a case study associated with Task 5.4.4 TS1, including the integration of circular economy metrics. This practical evaluation demonstrated the feasibility of the proposed framework for guiding sustainable remediation decisions and for supporting the selection of technologies that optimize environmental, social, and economic outcomes.

4.3 TASK GOALS

The goal of Task 5.4 was to advance sustainable remediation strategies for contaminated sites, focusing on soils, groundwater, and mining-impacted areas. The task aimed to generate integrated knowledge and practical solutions to support the recovery, management, and regeneration of sites contaminated with hydrocarbons, chlorinated solvents, and metals/metalloids.To achieve this, a combination of experimental, modeling, and assessment activities was carried out. Innovative bioremediation approaches were developed through the isolation, characterization, and application of microbial strains and consortia, evaluating their effectiveness under controlled laboratory conditions and simulating field-scale interventions such as microcosms, aerobic permeable reactive barriers, and sequential biostimulation–bioaugmentation treatments. Parallel efforts focused on sustainable remediation of mining and industrial sites, integrating plant-based stabilization, microbial bioaugmentation, and targeted biomining strategies. These interventions were designed to reduce contaminant mobility, improve plant establishment, and promote ecosystem recovery. At the same time, experimental and numerical modeling approaches were implemented to investigate water and contaminant transport, evapotranspiration, and soil–plant–microbe interactions. These analyses supported the design and optimization of engineered and nature-based solutions, such as single-layer evapotranspiration covers, under realistic environmental conditions. Finally, a sustainability assessment framework was developed to guide the ex-ante evaluation of remediation technologies. A set of environmental, social, and economic indicators was selected to enable the comparison of alternative strategies, support decision-making, and ensure that remediation interventions align with circular economy principles. Overall, Task 5.4 provided a comprehensive, science-based approach for designing, assessing, and optimizing remediation strategies that are effective, scalable, and sustainable, ultimately supporting the safe and responsible management of contaminated sites.

5. CONCLUSION

The activities carried out within Task 5.4 provided a comprehensive evaluation of sustainable remediation strategies applicable to contaminated sites, brownfields, and mining-impacted areas. Through a combination of laboratory, pilot-scale, and field experiments, alongside numerical modeling and sustainability assessments, the work enabled a detailed understanding of contaminant behavior, treatment efficiency, and the interactions between remediation technologies and site-specific conditions. The development of a structured sustainability assessment framework allowed the systematic comparison of remediation alternatives, integrating environmental, social, and economic indicators. Experimental and modeling results demonstrated the feasibility of innovative approaches such as biostimulation, bioaugmentation, evapotranspiration covers, and mine tailings stabilization, showing their potential to improve contaminant removal while minimizing environmental impacts. Overall, the outcomes of Task 5.4 directly support the deliverable *Assessment of Remediation Methodologies Performances* by providing robust data, methodological guidance, and predictive tools. These outputs facilitate evidence-based decision-making, helping to identify the most effective and sustainable remediation solutions for a wide range of contaminated sites.

6. References

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