EiCLaR White Paper for Site owners and managers

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1. Introduction and technology description

EiCLaR developed scientific and technical innovations for in-situ bioremediation technologies.

Four in-situ bioremediation technologies were developed into industrial processes for the rapid efficient cost-effective treatment of a range of environmental pollutants, such as chlorinated solvents, heavy metals, hydrocarbons. These technologies show great promise in addressing environmental pollution challenges while minimizing the need for disruptive excavation or costly conventional remediation methods.

The aim of the “White papers” is to provide a technical briefing for each of the EiCLaR technologies, targeted to the different practitioner audiences:

- « White paper » for site owners/ managers (including real estate developers)
- « White paper » for regulators
- « White paper » for service providers
- « White paper » for environmental service procurement personnel

Enhanced Innovative *In Situ* Biotechnologies for Contaminated Land Remediation

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°965945.” https://cordis.europa.eu/project/id/965945 and from the National Natural Science Foundation of China http://www.nsfc.gov.cn.

This “White paper” provides the following key informational content:

- Identification of the most likely EiCLaR application niches in the near, medium and long term in consultation with a range of market opinion formers, technology users, site managers and regulatory interests ;
- Guidance on most appropriate use of EiCLaR technologies, matching technologies to problems and site characteristics ;
- Synthesis across EiCLaR technologies that identifies the most significant technology development opportunities to TRL9 on the basis of likely cost competiveness, time to completion, usage of space, risk management performance and sustainability, benchmarked against currently available solutions ;
- Conclusion and recommendations.

The EiCLaR technologies are summarized below:

Electro-Nano bioremediation (ENB)

Electro-nano bioremediation is an innovative and advanced remediation technology that combines three key processes to efficiently clean up contaminated environments. ENB integrates Electro-kinetics, nanotechnology, and bioremediation processes to tackle complex and persistent pollutants in soil and groundwater. The combined use of electrokinetics, nanotechnology, and bioremediation in Electro-nano bioremediation provides a synergistic effect, leading to faster and more efficient cleanup of contaminated sites. This technology shows great promise in addressing contaminant source treatment while minimizing the need for disruptive excavation or costly conventional remediation methods.

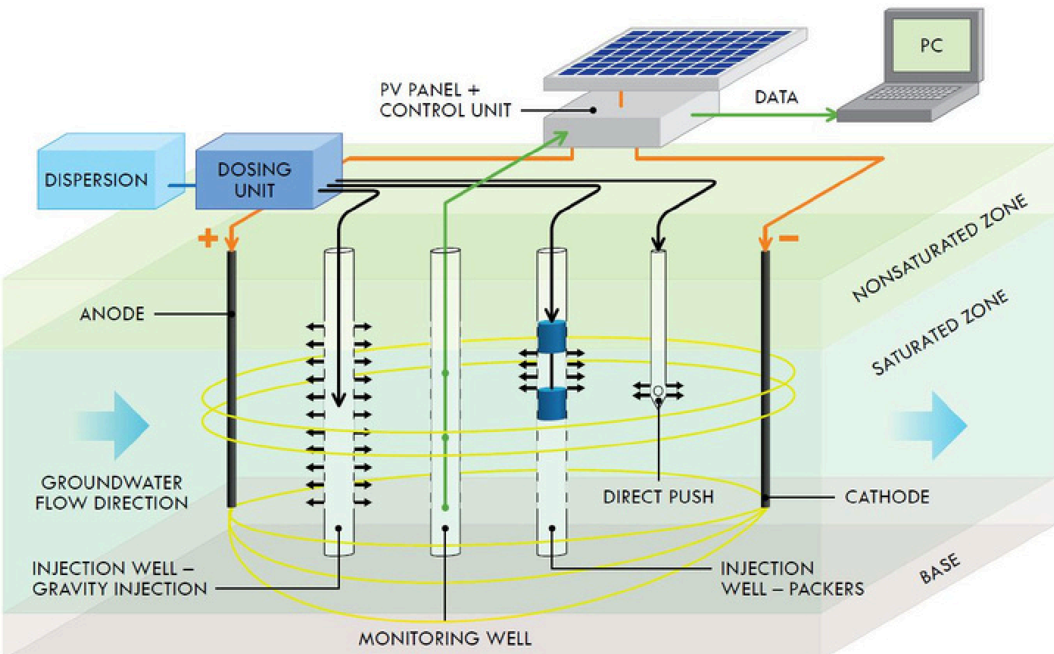

Figure 1: Conceptual scheme of the ENB technology

Monitored Bioaugmentation Remediation (MBR)

The aerobic metabolic degradation represents a new and promising process to remove chloroethenes from the subsurface environment. Aerobic chloroethene biodegradation can occur under natural conditions and after addition of oxygen in engineered systems in-situ or on-site. The aerobic degradation without the need for auxiliary substrates has a high potential for practical application. While the bacteria do not seem to be present in sufficient numbers at many polluted sites, bioaugmentation in combination with electrode application and specific qPCR monitoring has been developed in EiCLaR. This aerobic technology targets chloroethene contaminated groundwater and provides an important alternative to anaerobic approaches.

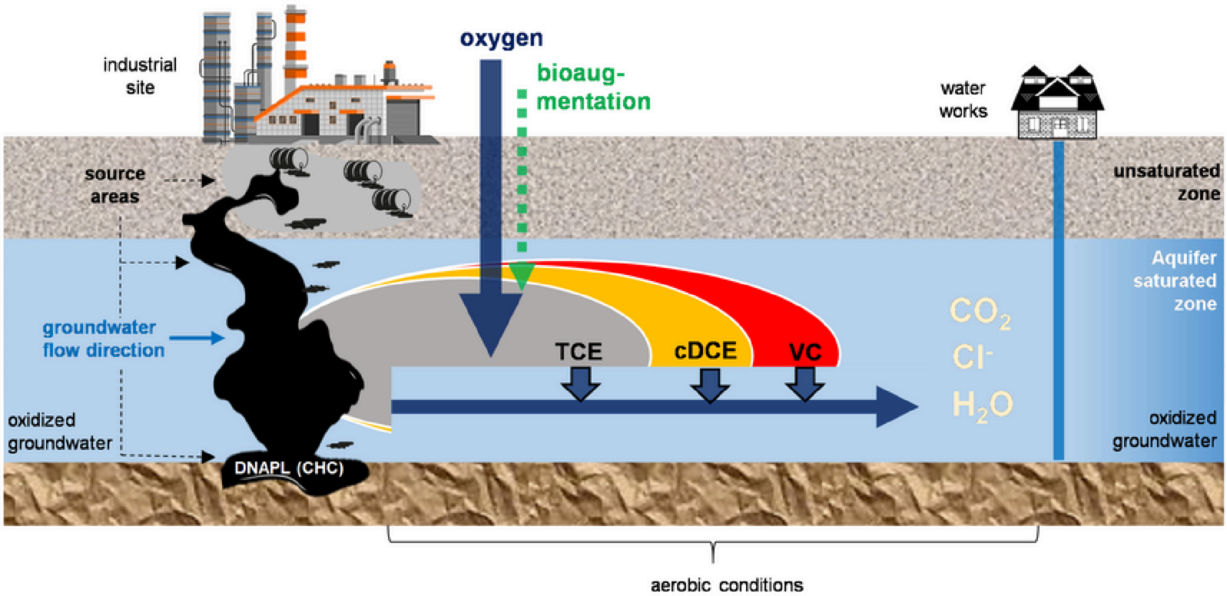

Figure 2: Process schematic for biodegradation of chloroethenes through bioaugmentation with aerobic metabolic chloroethene degraders and oxygen infiltration

Bioelectrochemical Remediation (BER)

BER can simultaneously remove pollutants and recover energy from the contaminant. Up to now, most studies of bioelectrochemical systems have targeted treating wastewater or novel compound synthesis. In EiCLaR, the bioelectrochemical system approach has been developed for industrial sites polluted with mixtures of pollutants. With BER, we have targeted typical soil and groundwater contaminants, including aromatic hydrocarbons (e.g. PAH) and chlorinated solvents. In addition to straight-forward degradation at both electrodes, we have also included pollutant and substrate monitoring at the anode and microbial electrolysis to fuel chosen reactions at the cathode. A wide range of redox reactions catalysed by the microbial population present at/or near the electrodes includes anaerobic oxidations of reduced contaminants at the anode and the reduction of chlorinated compounds at the cathode. This inexpensive technology enhances natural attenuation and actively degrades groundwater contaminants.

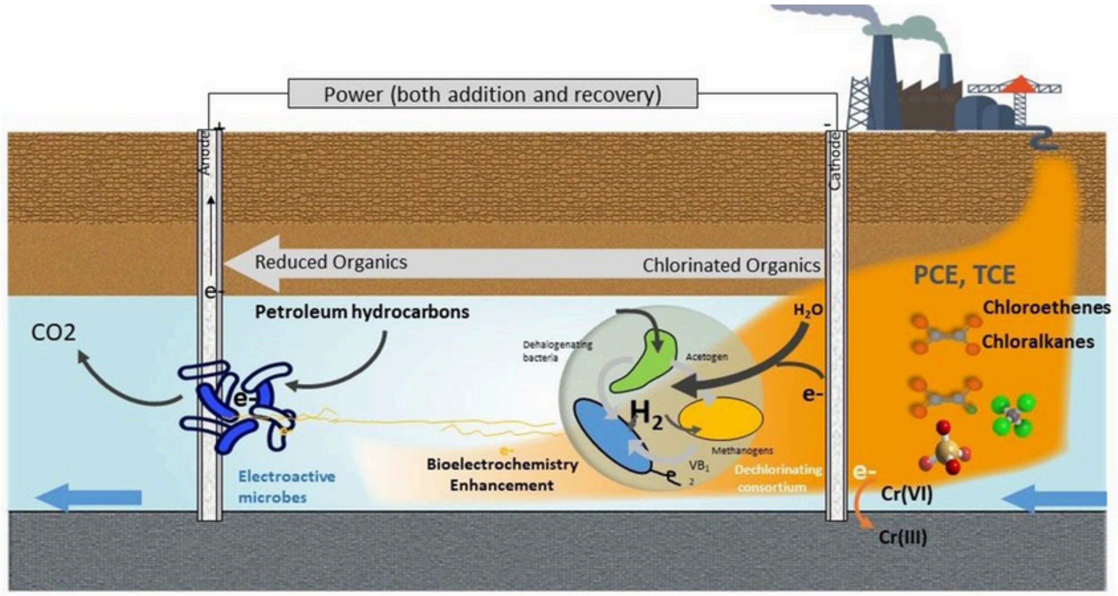

Figure 3: Conceptual scheme of the BER technology

- **Numerical reactive transport model for aerobic chloroethene bioaugmentation (within the MBR) and bioelectrochemical systems (within the ENB)**

The aim of this software is to describe the aerobic chloroethene degradation including electro-bioaugmentation and electrokinetic transport and finally, to optimize the in-situ bioremediation for the ENB and MBR technologies. The numerical model will be able to simulate the recently discovered aerobic TCE degradation. The model can accompany microcosm testing, medium-scale pilots and full field applications.

Enhanced Phytoremediation (EPR)

Phytoremediation is a cost-effective and environmentally friendly remediation technology, however, for plants to thrive, soil toxicity must first be reduced and the treatment is traditionally applied for surface soils. EiCLaR has developed an approach that combines two processes – phytoremediation for shallow contamination and electrochemical oxidation for deeper soil contamination. Low-voltage electricity is applied to iron electrodes inserted into the contaminated soil and helps immobilize metals, while also stimulating soil bacteria to aid in the degradation of organic contaminants. The injection of mycorrhizal inoculum further enhances the synergistic interactions between plants, microorganisms, and mycorrhizae, facilitating the degradation or immobilization of contaminants in the topsoil. This technique is intended to reduce metal toxicity through immobilization, promote the phytodegradation of organic pollutants in shallow soil layers, and induce bioelectrochemical oxidation in deeper soil layers. The treatment of mixed heavy metal and organic pollutants are targeted by this approach.

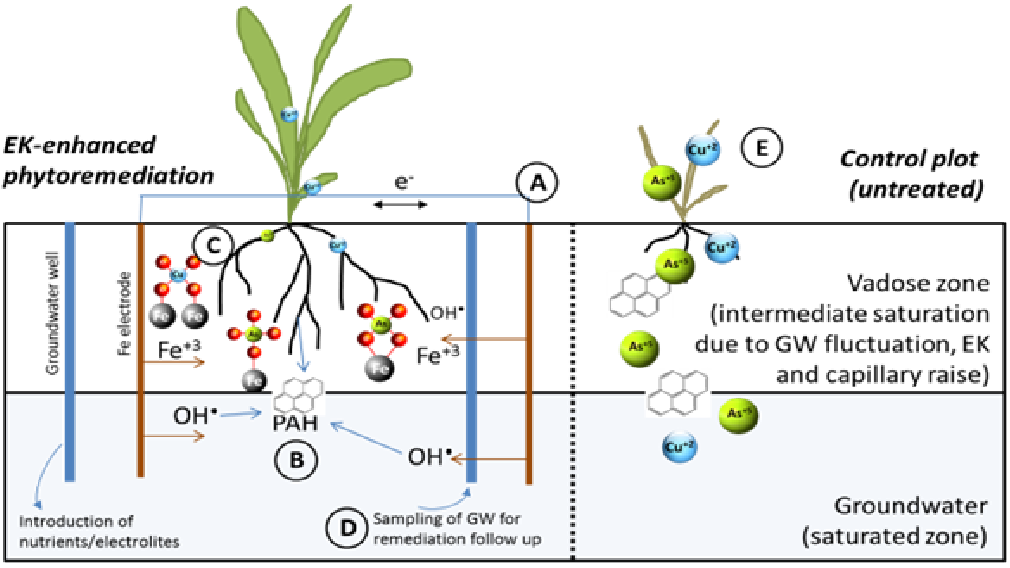

Figure 4: Principles of the enhanced phytoremediation approach - Integrated Contaminant Stabilization and Degradation Technology

EiCLaR Decision Support Tool (DST)

The Decision Support Tool (DST) can be used to determine whether a potential treatment technology (in total 24 technologies including the four EiCLaR technologies (ENB, MBR, BER, EPR) is a viable candidate to remediate a given contaminated site. The DST is a simple online resource to identify likely technology fitness for purpose for specific site characteristics, particularly for new users and smaller organisations. The tool provides users and organisations with a limited remediation know-how. The DST is organised in a comprehensible and user-friendly way to provide easy access to understanding operational performance in real-world applications. The DST supports this service with unique remediation option appraisal engine and support for document drafting.

Figure 5: Front-end workflow of the Decision Support Tool.

2. Applicability of the EiCLaR technologies

Introducing the applicability of the EiCLaR technologies involves outlining how each technology can address specific contaminants and their associated treatment feasibility. They are summarised in the tables below:

Table 1: Target contaminants by the 4 EiCLaR technologies

Process acronym		Electro-nano-bioremediation (ENB)	Monitored Bioaugmentation (MBR)	Bioelectrochemical Remediation (BER)	Enhanced Phytoremediation (EPR)
Treatable contaminants	Halogenated organic compounds	Prime targets: Cl-ethenes, Cl-methanes, brominated aliphatics, HCH, lindane Possible targets: Cl-ethanes,Cl-benzenes	Prime target: Chloroethenes (TCE/cDCE/VC)	Chlorinated solvents and microbial monitoring at the cathode	
	Non-halogenated organic compounds			Petroleum hydrocarbons and compound concentration monitoring at the anode	Petroleum hydrocarbons
	PAH = non halogenated	No		Petroleum hydrocarbons and compound concentration monitoring at the anode	PAH
	PFAS	Yes, with adopted design and operation		To be determined	No
	PCBs (halogenated organic compounds)	Efficient for some congeners, must be tested in laboratory in advance		Chlorinated compounds at the cathode	
	Cationic Trace Elements	Cr, As, Cu, durability/ stability/ permanency of metal stabilisation must be evaluated.		Possible metal redox reactions at the cathode	Cu, Cr

Treatable contaminants	Oxyanionic Trace Elements	U, Zn			As
	Others	Nitrates, suplhates, phosphates			
	Max. concentration	Not limited	~50mg/L TCE	Dissolved phase within or outside the source zone	Unlimited for layers below root zone

Table 2: Feasibility protocol for the 4 EiCLaR technologies.

Technology acronym		**Electro-nano-bioremediation (ENB)**	**Monitored Bioaugmentation (MBR)**	**Bioelectrochemical Remediation (BER)**	**Enhanced Phytoremediation (EPR)**
Site requirements/ Limitations	Saturated zone (below water table, no soil air)	Suitable	Suitable	Suitable	Suitable
	Unsaturated zone (includes root zone)	Not suitable	Suitable	Not suitable	Potentially suitable
	Plume (dissolved phase)	Suitable	Suitable	Suitable	Suitable
	Residual phase NAPL (discontinuous phase)	Suitable	Suitable	Suitable	Suitable
	NAPL pool (continuous phase)	Potentially suitable	Not suitable	Not suitable	Suitable
	Sorbed	Suitable	Potentially suitable	Suitable	Not suitable

3. Technical performance and benefits of the EiCLaR technologies

The EiCLaR technologies offer innovative, cost-effective solutions for soil and groundwater remediation by combining electrochemical, biological, and nanotechnological processes, enhancing treatment efficiency and reducing chemical usage. These technologies provide adaptable, environmentally friendly methods that improve contaminant degradation, minimize side effects, and lower operational costs compared to traditional approaches.

The main **benefits** of using the four EiCLaR technologies are summarised below:

- **Electro-nano bioremediation (ENB)**:
  - The combination of electrochemical processes, nanotechnology and bioremediation leads to quicker remediation compared to traditional methods.
  - Environmentally friendly process using small doses of environmentally friendly materials - ZVI and carbon substrate, chemical reducing agents enhanced electrokinetically and biologically using synergistic effects of both biological and electrochemical processes, leading to increased reactivity of zvi reagents, improved efficiency (also in lower permeable soils and more persistent contaminants) and reduced costs and lower chemical usage;
  - No contaminant concentration limits - chemical reduction suitable and cost effective for higher contaminant loads, bioreduction for lower contaminant concentrations; the system is easily adaptable to various contaminant compositions;
  - Compared to conventional pure ZVI/ biodegradable system - ENB represent "engineered solution" as DC system can optimize and control in-situ reduction process in real-time depending on monitoring results measured in real-time. This allows to adjust and control remotely conditions for nanoremediation and biostimulation without further addition of chemical additives, reagents, and buffers and to make important savings of costs (material and O&M).
  - The method stimulates microbial activity, promoting natural bioremediation processes in conjunction with electrochemical treatment.

- **Monitored Bioaugmentation (MBR):**
  - No need for auxiliary substrates
  - Less oxygen needed for site remediation (since oxygen is used more efficiently compared to co-metabolic processes)
  - Complete mineralization of contaminants
    - CO_2, H_2O and Cl^- as product of contaminant degradation
    - No risk of accumulation of cDCE or VC
  - Aerobic process
  - No unfavourable anaerobic side reactions such as sulphide and methane formation

- **Bioelectrochemical Remediation (BER)**:

  - Wide range of compounds to be degraded
  - Setup costs are low compared to other technologies
  - Maintenance and energy costs are minimum (monitoring requires input less than 9V battery)
  - Natural attenuation is enhanced by the presence of the electrodes
  - Simple installation (does not requires specific knowledge)
  - Extremely low overall cost

- **Enhanced Phytoremediation (EPR):**

  - Simultaneously targeting mixed contaminants to completely degrade organic molecules and immobilise inorganic contaminants in situ/on site
  - Innovative use of stimulated phyto(bio)remediation via and electric field and additional amendments, e.g. arbuscular mycorrhizal fungi (AMF), for degradation/ immobilisation of contaminants
  - Facilitated distribution of nutrients and immobilising agents through the soil profile

For a more detailed description of each of the EiCLaR technologies, please refer to the Technical Bulletins: claire.co.uk/eiclar.

To enhance the selection process for remediation technologies, the Decision Support Tool (DST), developed in EiCLaR project, provides a powerful resource that combines expert analysis with practical usability. This tool is designed to assist users in evaluating and ranking remediation technologies based on site-specific conditions, promoting sustainable decision-making.

- **Key features of the DST** include:

  - Evaluation of conditions and rules, and determination of a suitability score using a fuzzy logic approach.
  - Ranking of the EiCLaR technologies by their estimated degree of sustainability and provision of a ranked shortlist of remediation technologies and either a generic or custom report.
  - Web interface with the ability to save, return and modify technical inputs
  - Extensible for both technologies and parameters.
  - Free to use after registration.
  - Generic downloadable PDFs will be free.

The DST is available on the following website: contaminatedland.info.

4. Conclusions and recommendations for Site owners and managers

The EiCLaR technologies represent advanced in-situ sustainable solutions designed to address a variety of pollution challenges efficiently, sustainably, and cost-effectively. As the environmental remediation landscape evolves, four advanced technologies—Electro-nano bioremediation (ENB), Monitored Bioaugmentation (MBR), Bioelectrochemical Remediation (BER) and Enhanced Phytoremediation (EPR) present significant opportunities for efficient and sustainable site management. Below are recommendations for adopting these technologies at polluted industrial sites:

Electro-nano bioremediation (ENB)

Site owners should consider the following to leverage ENB for their sites:

- **Assess the suitability of the technology** for diverse contaminant types, including organic and inorganic pollutants. ENB is highly versatile and can be adapted to sites with varying contamination profiles, making it a practical solution for complex contamination scenarios.

- **Focus on in-situ treatment** to avoid the need for disruptive excavation or costly traditional methods. ENB allows for the effective breakdown of pollutants without significant site disruption, reducing operational downtime.

- **Leveraging ENB for efficient bioremediation in highly contaminated saturated zones**, as this process allows for the use of electro-nano technology to achieve a significant reduction in contamination, creating the optimal conditions for bioremediation to complete the treatment in highly contaminated saturated zones.

- **Invest in real-time monitoring systems** to track site conditions and optimize the electrochemical and microbial processes. Regular monitoring and adaptive control of the system's parameters can enhance its efficiency, minimize material usage, and reduce operational costs.

- **Optimize energy and material use** by utilizing environmentally friendly materials (e.g., ZVI and carbon substrates). This not only lowers treatment costs but also minimizes the environmental footprint of remediation efforts.

Monitored Bio-Remediation (MBR)

For effective MBR implementation, site managers should:

- Ensure **sufficient oxygen levels** for optimal aerobic conditions. The system operates efficiently under conditions with low oxygen requirements, making it a cost-effective option for groundwater contamination sites.

- **Leverage bioaugmentation** to boost microbial activity and accelerate contaminant degradation. This can enhance the natural attenuation process and improve site remediation performance.

- **Monitor groundwater conditions** to ensure the aerobic process remains effective, tracking factors such as oxygen distribution, microbial activity, and contaminant degradation progress. Regular monitoring is essential to maintain the system's efficiency.

- Collaborate on **pilot trials** to test the system's scalability and effectiveness at your site, helping to refine the approach for broader deployment and maximize long-term success.

Bioelectrochemical Remediation (BER)

To maximize the benefits of BER technology, site owners and managers should:

- BER is an **extremely low cost** retrofit technology for industrial sites that provides pollutant degradation and continuous **on-line data** on pollutant degradation rates.

- **Leverage existing wells** or drill new ones as needed, ensuring easy access to groundwater and optimal electrode placement. The system's performance can be monitored on-line to adjust conditions for effective treatment.

- **Assess groundwater flow direction** and water levels to strategically position electrodes. This ensures optimal remediation of contaminated zones and maximizing pollutant degradation.

- **BER monitors microbial electrolysis activity** that fuels reactions at the anode and cathode and enhance contaminant reduction.

- **Emphasize energy recovery and cost reduction** by utilizing BER's ability to recover energy from contaminants, further reducing the financial and environmental impact of the remediation process.

Enhanced Phytoremediation (EPR)

For effective application of EPR, site owners and managers should:

- **Tailor remediation practices** based on site-specific soil profiles, including nutrient supplementation and targeted treatments for different soil depths. Ensure that the system is adapted to the unique contaminant composition and site conditions.

- **Implement flexible strategies** that accommodate mixed contaminant profiles (both organic and inorganic pollutants). This technology's adaptability allows it to target diverse contamination issues, ensuring more comprehensive site cleanup.

- **Monitor key parameters** such as soil oxidation, moisture, residual contamination and nutrient levels regularly. Developing a detailed monitoring plan will help track system performance and enable timely interventions to optimize remediation efforts.

5. Additional information and contacts

- **Electro-Nano Bioremediation (ENB):**

Simon Kleinknecht - Research Facility for Subsurface Remediation (VEGAS)

Petr Kvapil - Photon Water

Jaroslav Nosek - Institute for Nanomaterials, Advanced Technologies and Innovation

- **Monitored Bioaugmentation Remediation (MBR):**

Andreas Tiehm and Steffen Hertle - Technologiezentrum Wasser

- **Bioelectrochemical Remediation (BER):**

Timothy Vogel - Microbiome Engineering

Azariel Ruiz-Valencia - Centre National de la Recherche Scientifique

Xin Song - Institut of Soil Science, Chinese Academy of Sciences

- **Numerical model:**

Matthias Loschko and Luca Trevisan - BoSS Consult

- **Enhanced Phytoremediation (EPR):**

Jurate Kumpiene, Ivan Carabante and Kim Johansson - Lulea University of Technology

Antoine Joubert - Serpol

Erkki Lindberg - Ekogrid

- **Decision Support Tool (DST):**

Paul Bardos, Matthias Loschko, Jonas Allgeier, Helen McLennan
https://contaminatedland.info/

- **Publisher:**

Marta Popova - SPAQUE

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