EiCLaR White Paper for Public procurement personnel

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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.

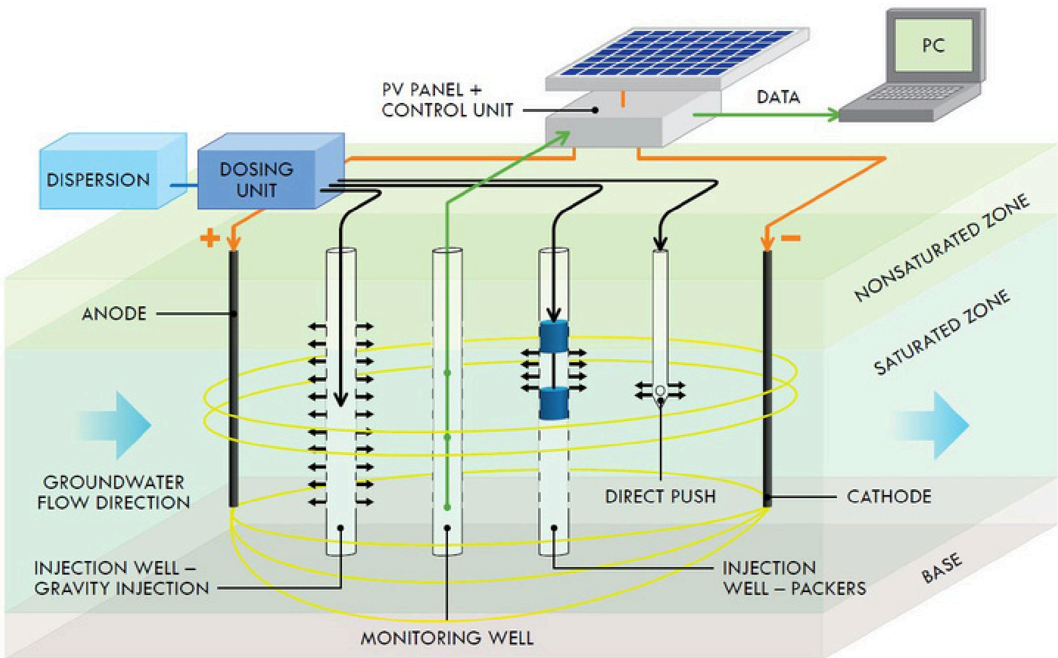

Figure 1: Conceptual scheme of the ENB technology

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.

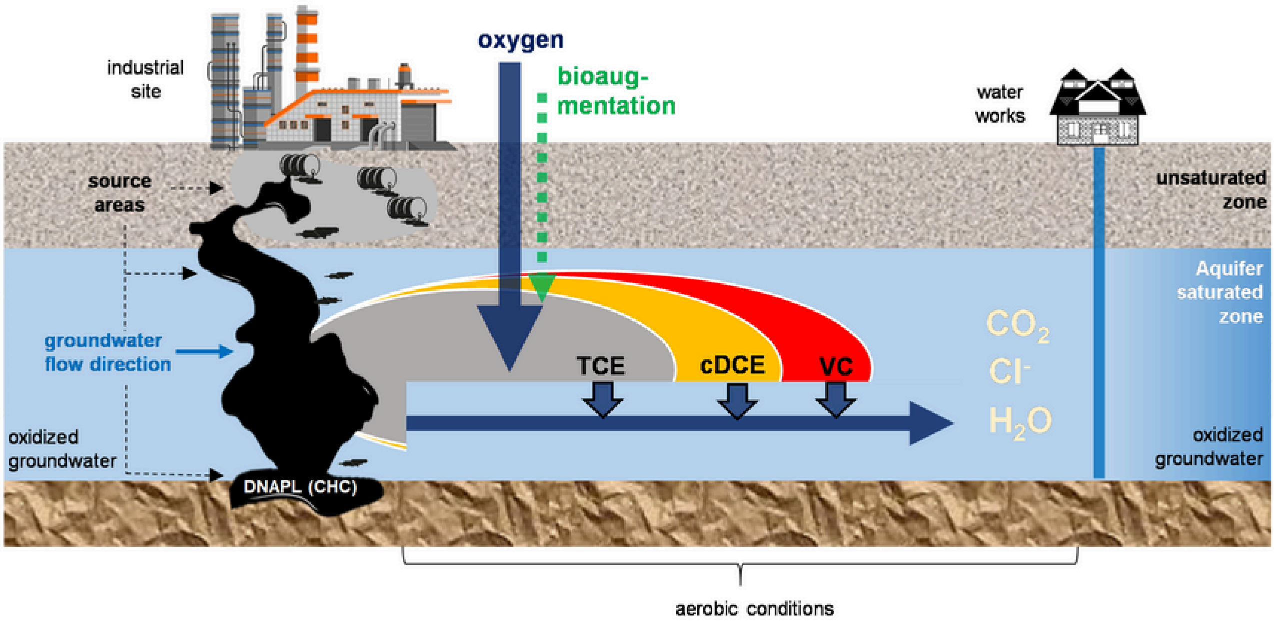

Figure 2: Process schematic for biodegradation of chloroethenes through bioaugmentation with aerobic metabolic chloroethene degraders and oxygen infiltration

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.

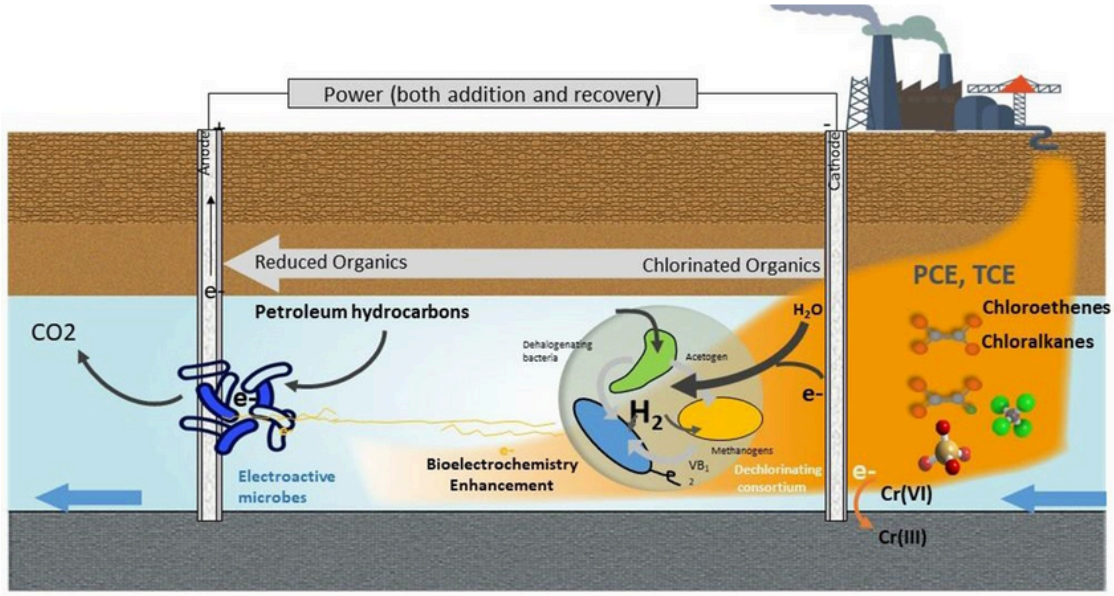

Figure 3: Conceptual scheme of the BER technology

- **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.

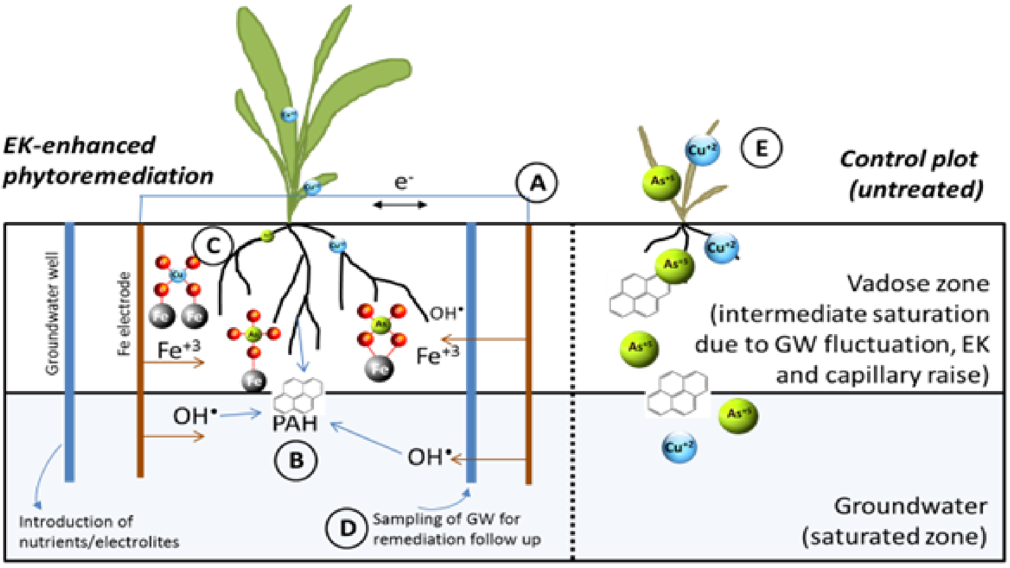

Figure 4: Principles of the enhanced phytoremediation approach - Integrated Contaminant Stabilization and Degradation Technology

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.

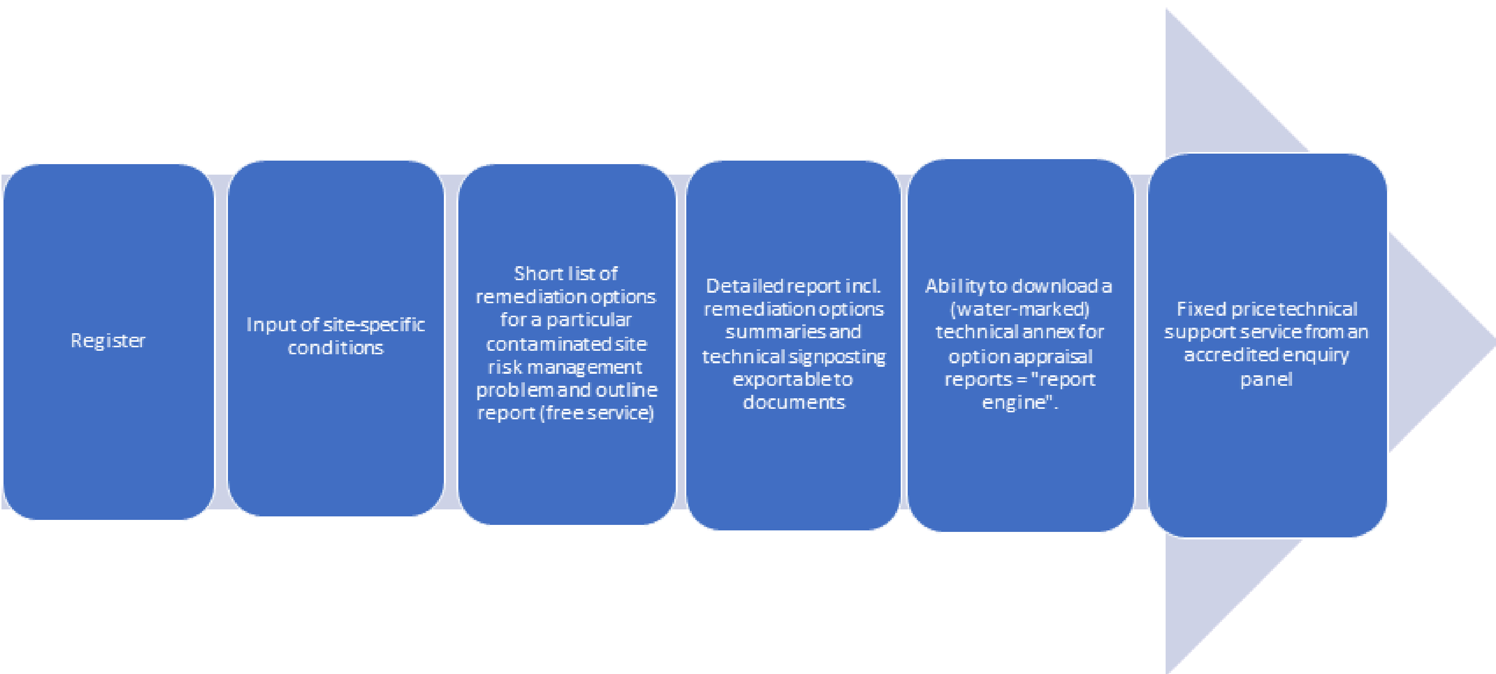

Figure 5: Front-end workflow of the Decision Support Tool.

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:

- **<u>Electro-nano bioremediation (ENB)</u>**:
  - 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.

- **<u>Monitored Bioaugmentation (MBR):</u>**
  - 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
    - CO2, H2O 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 Public procurement personnel

The EiCLaR technologies represent advanced in-situ sustainable solutions designed to address a variety of pollution challenges efficiently, sustainably, and cost-effectively.

As the demand for more sustainable and cost-effective remediation solutions grows, public procurement personnel in Europe are encouraged to consider four innovative technologies - Electro-nano bioremediation (ENB), Monitored Bio-Remediation (MBR), Bioelectrochemical Remediation (BER) and Enhanced Phytoremediation (EPR) - as viable alternatives to traditional “dig and dump” methods for soil and groundwater contamination. Below are recommendations for integrating these technologies into the terms of reference (ToR) when selecting remediation solutions for remediation projects.

- **Electro-nano bioremediation (ENB):**

Why consider ENB:

- ENB combines electrokinetics, nanotechnology, and bioremediation, offering a comprehensive solution for the treatment of complex and persistent pollutants, such as aromatic hydrocarbons and chlorinated solvents, in soil and groundwater.
- This technology avoids excavation, using in-situ treatment to break down contaminants, making it a sustainable and cost-efficient option.

How to integrate in the Terms of References (ToR):

- **Incorporate sustainability in procurement criteria:** Include environmental and economic sustainability as key factors in the ToR, emphasizing ENB's low energy requirements, reduced material use, and cost-effectiveness compared to traditional methods. Highlight the technology’s ability to treat high-concentration pollutants, making it ideal for complex contamination sites.
- **Highlight versatility for various contaminants:** Ensure that the ToR allows for ENB’s application on a wide range of pollutants, including both organic and inorganic compounds.
- **Mandate real-time monitoring and adaptive control:** Specify the need for continuous monitoring and adjustment of the electrochemical and microbial processes to optimize remediation efforts and reduce material usage.

- **Monitored Bioaugmentation (MBR):**

Why consider MBR:

- **MBR** represents a **sustainable, cost-effective** method for remediating chloroethene-contaminated groundwater without the need for additional chemical additives or substrates. It is highly efficient in mineralizing contaminants into harmless byproducts such as CO_2, H_2O, and Cl^-.
- By promoting aerobic microbial degradation, **MBR avoids harmful side reactions** such as methane and sulphide formation, commonly associated with anaerobic methods.
- **MBR** is particularly suitable for aerobic or superficial aquifers, where the natural presence of oxygen **prevents the production of potentially hazardous volatile contaminants**, such as vinyl chloride (VC).

How to integrate in the ToR:

- **Specify the need for oxygen-efficient systems:** Include technical specifications for systems that optimize oxygen use, enhancing cost-effectiveness and reducing environmental impact.
- **Encourage the use of bioaugmentation:** Mandate the inclusion of these techniques where necessary to boost microbial activity and accelerate contaminant degradation.
- **Incorporate monitoring systems:** Require the monitoring of oxygen levels, microbial activity, and contaminant breakdown to track the success of the remediation efforts and ensure the system operates efficiently.

- **Bioelectrochemical Remediation (BER):**

Why consider BER:

- BER utilizes the **combined power of electrochemical processes and microbial activity** to degrade complex contaminants such as aromatic hydrocarbons and chlorinated solvents without excavation or disposal, offering a **low-cost and effective alternative.**
- It also **recovers energy from the contaminants**, which can reduce operational costs, providing both **environmental and financial benefits**.

How to integrate in the ToR:

- **Emphasize in-situ remediation:** Specify that BER should be applied in a manner that **minimizes site disruption,** leveraging existing infrastructure (e.g., wells) for electrode placement and treatment.
- **Focus on energy recovery and cost-saving aspects:** Encourage the inclusion of **energy recovery goals** and cost reduction through efficient use of electricity and materials
- **Incorporate adaptive control and monitoring:** Require **real-time monitoring of microbial electrolysis** and contaminant degradation at the electrodes to ensure ongoing treatment optimization.

- **Enhanced Phytoremediation (EPR):**

Why consider EPR:

- EPR offers a **cost-effective and environmentally friendly solution** for sites with mixed contaminants (both organic and inorganic). It avoids the need for excavation and disposal, minimizing disruption to the site and surrounding environment.
- The method enhances **natural remediation processes**, leveraging plants and microorganisms to degrade contaminants, making it a **sustainable and low-impact alternative** to traditional excavation-based approaches.

How to integrate in the ToR:

- When procuring soil remediation services, prioritize technologies that provide **sustainable, cost-effective solutions** for complex contamination problems, such as the EPR technology.
- The integration of **multiple remediation methods** (phytoremediation, chemical immobilization, and electrochemical oxidation) ensures a holistic approach, enhancing the **long-term effectiveness** of remediation projects.
- Evaluate the **environmental benefits**, including CO_2 emission reductions, when assessing the feasibility and sustainability of remediation options, especially for sites requiring in situ treatment.

General Considerations for Integrating the EiCLaR Bio-Remediation Technologies

When drafting the ToR for remediation projects, public procurement personnel should:

- **Prioritize sustainability and cost-efficiency:** Ensure that the selected technologies offer environmental benefits, such as reduced waste generation, minimal disruption, and lower material use.
- **Consider long-term effectiveness and scalability:** Include criteria for evaluating the long-term performance and scalability of the technologies across different site conditions.
- **Support innovation and field trials:** Encourage procurement processes that allow for pilot trials, enabling the testing of new technologies before large-scale implementation.

By incorporating these advanced remediation technologies into procurement processes, public sector projects can benefit from innovative, sustainable, and cost-effective alternatives to traditional remediation methods, leading to more successful environmental remediation outcomes across Europe.

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

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.