Life Sedremed

ENHANCED BIOREMEDIATION OF

CONTAMINATED MARINE SEDIMENTS

LIFE20 ENV/IT/000572

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Stakeholder and Market Analysis

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Abstract

The stakeholder and market analysis is a key part of the replication and transfer plan that has the objective to ensure that the LIFE SEDREMED project results can be transferred and replicated in other initiatives, projects, contexts and locations, thus maximising project impact and its long-term sustainability. It Identifies the key elements of the project that have the greatest potential for transfer and replication. These may include technologies, methodological approaches, best practices, scientific knowledge, collaboration models, knowledge exchanges, among others.

This document analyses the market context for bioremediation techniques, the technical and legislative drivers, provides a short comparison between Europe and North America, lists a series of potential replication opportunities in Belgium, Finland, Italy and Germany and finally briefly describes the stakeholder mapping that has been provided to project partners.

Acronyms and abbreviations

AA-EQS – Annual Average Environmental Quality Standards

ARPA – Regional Environmental Protection Agencies (Italy)

As – Arsenic

BSAP – Baltic Sea Action Plan

Cd – Cadmium

Cu – Copper

ELY – Regional Centers for Economic Development, Transport, and the Environment (Finland)

EPA – Environmental Protection Agency (USA)

EQS – Environmental Quality Standards

EU – European Union

FTR – Federal Remediation Technologies Roundtable (USA)

HCB – Hexachlorobenzene

HELCOM – Helsinki Commission (Baltic Marine Environment Protection)

Hg – Mercury

IED – Industrial Emissions Directive

IETcc-CSIC – Institute of Construction Science Eduardo Torroja (Spain)

INVITALIA – National Agency for Inward Investment and Economic Development (Italy)

ISPRA – Italian Institute for Environmental Protection and Research

ISS – Istituto Superiore di Sanità (Italian National Institute of Health)

LIPU – Italian League for Bird Protection

MAC-EQS – Maximum Allowable Concentrations Environmental Quality Standards

MASE – Ministry of Environment and Energy Security (Italy)

MSFD – Marine Strategy Framework Directive

OSPAR – Oslo and Paris Conventions for Marine Environment Protection

PAHs – Polycyclic Aromatic Hydrocarbons

PCBs – Polychlorinated Biphenyls

PCDDs – Polychlorinated Dibenzodioxins

Pb – Lead

SCI – Site of Community Importance

SDG – Sustainable Development Goals (United Nations)

SIN – Site of National Interest (Italy)

SPA – Special Protection Area

SYKE – Finnish Environment Institute

SZN –Stazione Zoologica Anton Dohrn (Italy)

TBT – Tributyltin

UN – United Nations

UNIVPM – Polytechnic University of Marche (Italy)

VOC – Volatile Organic Compounds

WFD – Water Framework Directive

Zn – ZincLUCAS – Land Use and Coverage Area Frame Survey

Introduction

LIFE SEDREMED is an EU-funded project for the development of an innovative solution to decontaminate polluted marine sites. This project intends to demonstrate the efficiency of a methodology based on bioremediation and electro-kinetics for the decontamination of coastal marine sediments. The project partners will develop a prototype for the application of microorganisms within the sediments and increase their bioremediation capacities thanks to the transmission of electric current, initially at laboratory-scale and then scaled-up on-site.

Specifically, the intervention will aim at reducing the concentration of organic contaminants (such as PAHs, PCBs, PCDDs) and the bioavailability of heavy metals like Pb, Hg, Cd, Cu, Zn and As. The project will showcase a new approach to avoid environmental risks and reduce financial costs incurred in dredging activities and ex-situ treatment of contaminated sediments.

The LIFE SEDREMED partnership is composed of a multidisciplinary and inter-sectoral group of 7 partners from 4 EU countries. The project is coordinated by the Stazione Zoologica Anton Dohrn and partners with the Site Manager, Invitalia, two technology providers, respectively Idrabel (Belgium) and Ekogrid (Finland), two academic monitoring partners Isodetect (Germany) and Polytechnic University of Marche, UNIVPM (Italy) and Nisida Environment (Italy) that manages the dissemination, communication and replication aspects of the project.

Bioremediation Market Report Highlights

- The *in-situ* bioremediation segment held the highest share of the global revenue in 2021 (latest data available) due to its cost-effectiveness, ease of use, and increasing applications for soil and groundwater treatment.
- Phytoremediation was the dominant technology segment in 2021. This can be attributed to the high demand for the technology for the removal of heavy metals, radionuclides, organic contaminants, and pesticides with the help of plants.
- The soil remediation segment dominated the industry due to the high demand generated from soil degradation caused by industrial pollutants, agrochemicals, and municipal and industrial waste.
- North America dominated the industry due to the presence of sophisticated infrastructure, high industrial growth & waste production, and presence of key market players, such as Regenesis Corp., Probiosphere, Inc., and Xylem, Inc.
- Asia Pacific is expected to register the fastest CAGR over the forecast period due to increasing awareness about environmental protection and the production of large quantities of hazardous waste caused by rising economic development in the region.[1]
- Growth in Europe is driven by stringent environmental legislation and high environmental quality standards, in addition for rising public awareness and necessity to reuse abandoned industrial areas for housing and recreational purposes.
- Increase in freight transport (and thus need for dredging) together with enhanced characterization of sediment contamination is expected to drive need for sediment decontamination.

Bioremediation Market Analysis

Market size

The global bioremediation market has shown significant growth in recent years and is poised for substantial expansion in the coming decade.[2]

In 2021, the market was valued at €11.42 billion and is projected to reach €26.68 billion by 2030, demonstrating a robust compound annual growth rate (CAGR) of 9.9%. This growth trajectory reflects the increasing demand for bioremediation technologies and services as industries and governments worldwide prioritize sustainable and environmentally friendly solutions for pollution control and waste management.

Focusing on Europe, the bioremediation technology and services market is also experiencing considerable growth. In 2021, the market was valued at €3,218.94 million, and it is expected to rise to €5,536.71 million by 2028. This represents a CAGR of 8.1% over the forecast period from 2021 to 2028. The expansion in Europe is driven by stringent environmental regulations, increased public awareness, and a growing commitment to addressing pollution and environmental degradation through advanced bioremediation techniques.

Specifically, within the European Union, countries such as Germany (DE), Finland (FI), Belgium (BE), and Italy (IT) are leading the charge in adopting and implementing bioremediation solutions. These nations are expected to contribute significantly to the overall growth of the market, further solidifying Europe's position as a key region in the global bioremediation landscape.[1]

Global Market Segmentation

The global bioremediation market can be segmented based on approach, technology, service and geographically.

a) Approach outlook:

1. In-situ
2. Ex-situ

b) Technology Outlook:

1. Biostimulation
2. Bioaugmentation
3. Electrokinetics
4. Phytoremediation
5. Fungal Remediation
6. Biofixation
7. Genome editing tools

c) Service Outlook

1. Soil Remediation
2. Sediment Remediation
3. Oilfield Remediation

d) Geographic outlook

1. North America
2. Asia Pacific
3. Europe

a) Approach outlook

In situ and ex situ: a substantial difference in remediation approach.

In situ bioremediation type involves the treatment of contaminants at the original site, while *ex situ* type includes offsite treatment by removal or excavation of contaminated materials.

In situ methods dominate the market due to their ease of use and feasibility for treatment of water sources, while *ex situ* methods are preferred for hydrocarbon degradation from contaminated soil. Furthermore, applications of *in situ* methods for degradation of pesticides and agricultural waste is expected to grow and drive the market growth in the near future. *In situ* bioremediation held the largest market share in 2021 and accounted for 56.06% of the market value.[17] The technique refers to treatment of contaminations at the original site without the need to excavate or pump out the contaminated materials. It involves the use of technologies such as bio-venting, bioslurping, biosparging, natural attenuation, and others. The technique can be controlled by manipulation of factors such as aeration, nutrient concentration, moisture content etc. to enhance the activity of organisms and accelerate the degradation rate. Hence, the method is highly suitable for applications such as treatment of groundwater with low contaminant concentrations, where oxygen availability can be increased by pumping air in the soil subsurface.

Expanding knowledge about degradation pathways in anaerobic organisms are propelling the application of monitored natural attenuation methods in *in situ* bioremediation. These methods rely on monitoring and enhancing the natural biodegradation processes and lead to generation of minimal remediation wastes, along with reduction in cross-media contaminant transfer. Such methods are anticipated to drive the demand for *in situ* bioremediation over the forecast period.

On the other hand, *ex situ* bioremediation involves the use of composting, landfarming, soil biopiles, and slurry reactors to treat the contaminated materials away from the original location. The technique is widely used for the treatment of contaminated soil for the removal of hydrocarbons.

However, excavation of contaminated materials can lead to additional expenses in the remediation process, which can limit the growth of the segment. [18]

b) Technology outlook

The growth of the bioremediation market is furthered by technological progress in remediation strategies. Demand for biological remediation of industrial pollutants is driven by key advantages offered by the technique over traditional physical and chemical methods. Traditional methods are non-specific and expensive to use.

1. Biostimulation

Biostimulation involves the addition of nutrients such as nitrogen, phosphorus, oxygen, and electron donors, which act as rate limiting factors in accelerating the natural biodegradation process. Addition of such nutrients to severely polluted sites result in stimulation of existing bacteria for degradation of toxic contaminants. Major applications of the technique include degradation of contaminants such as petroleum hydrocarbons, polyester polyurethanes, and sulphates. The technology is anticipated to witness an increasing demand due to the use of native organisms, which prevents any adverse effects or ecosystems disturbances to the environment. Biostimulation is also a cost-effective and well-studied method which adds to its utility and favors its adoption. However, the method is limited by its site specificity and dependency on environmental conditions which restrict its growth. [27][28]

2. Bioaugmentation

Many pollutants, especially highly complex compounds, are not efficiently biodegraded by native microorganisms; they may be resistant to biodegradation, and consequently persist in the contaminated matrix. To overcome these limitations, bioaugmentation strategies may be used. Bioaugmentation is the addition of microorganisms that can biodegrade recalcitrant molecules in the polluted environment. This approach is less-costly and friendlier to environment compared to the physico-chemical approaches. [27][29]

3. Elettrokinetic remediation through bioaugmentation: SEDREMED™ technology

Electrokinetic remediation has been widely studied in the remediation of heavy metal contaminated soils and sediments, demonstrating the feasibility of this technology.[28] It relies on the direct application of an electric field to the contaminated sample. The contaminants are removed by several combined mechanisms, mainly electroosmosis and electromigration. Its applications in the remediation of organic contaminants have been limited due to the low solubility of organics in water. To obtain high efficiency in the treatment of soil or sediments contaminated with organic compounds several techniques have been coupled to electrokinetic remediation. The conjunction of electrokinetic treatment with microbial bioremediation could be an environmentally friendly option to degrade in situ organic compounds. Under this hybrid technology, experimentation is underway for the remediation of contaminated sediments in the Bagnoli-Coroglio Bay as part of the LIFE SEDREMED project. The authors of Idrabel Patent (Bio-fixation method) indicated that the homogeneous distribution of microorganisms represents the main drawback of the treatment. This essential homogeneous distribution can be easily achieved with the action of the electrical field developed by Ekogrid, partner of LIFE project and Co-creator of this new technology.

4. Phytoremediation

Phytoremediation was the leading technology segment accounting for the largest share, euro 3,473.63 million, more than 30% of the global bioremediation revenue in 2021. The demand for the technology is fueled by its applications for the removal of heavy metals, radionuclides, organic contaminants, and pesticides with the help of plants. It involves the use of techniques, such as rhizodegradation, rhizofiltration, phytovolatilization, phytoextraction and phytostabilization, among others, for the treatment of pollutants. The segment is anticipated to grow further due to low costs of phytoremediation as compared to other technologies, and ability to sustainably remove organic and inorganic pollutants from soil and water. Phytoremediation technologies represent an attractive option for decontamination of hazardous wastes as it offers an economically feasible, autotrophic, solar-powered solution with low installation and maintenance costs. [27]

5. Fungal remediation

On the other hand, fungal remediation involves the use of robust fungal organisms that can tolerate high pollutant concentrations to degrade highly saturated contamination sites. Hence, the technology exhibits a high potential for lucrative growth over the forecast period. Fungal remediation is expected to grow at the fastest CAGR during the forecast period as fungi can demonstrate a wide range of metabolic capacities and can tolerate high concentrations of polluting agents. Fungi represent a promising option for the degradation of recalcitrant pollutants by the production of a variety of intracellular and extracellular enzymes, such as cytochrome P450 and peroxidases, respectively. These factors are likely to accelerate the adoption of fungal remediation technologies.

6. Bio-fixation

Biotechnological products allowing *in situ* biodegradation are also a growing trend. Bio-fixation method, which allows to immobilise different microorganisms on natural mineral supports, before transferring them to the habitat to be treated, is the technique at the core of the SEDREMED bioremediation project. Therefore, the use of this technology for utilizing the bio-degradative capabilities of enzymes or microorganism is expected to drive the industry. In addition, government authorities are raising awareness about the implementation of bioremediation strategies to drive the adoption of the technique. [28]

7. Genome editing tools

Advancements in genome editing tools, such as CRISPR-Cas and TALEN, are revolutionising metabolic engineering by enabling the development of optimised enzymes and metabolic pathways that enhance the biodegradation process. These tools allow precise modifications in microbial genomes, improving their efficiency in breaking down environmental contaminants. Additionally, quorum sensing-based microbial interactions are emerging as a powerful approach for designing gene circuits and microbial biosensors. These innovations enable the detection and degradation of persistent and recalcitrant pollutants, providing a targeted and effective solution to environmental challenges. The use of synthetic biology technologies is driving the industry by harnessing the biodegradative capabilities of enzymes and microorganisms. These biotechnological advancements allow for in situ biodegradation, meaning that pollutants can be broken down directly at the contamination site, reducing the need for costly and disruptive physical removal processes. Together, these cutting-edge technologies are poised to significantly impact the field of bioremediation, offering more efficient, cost-effective, and sustainable solutions for environmental restoration. [30]

c) Service outlook

1. Soil remediation

High extent of soil contamination and decreasing productivity of cultivable land are fueling the segment growth. The soil remediation segment dominated the market in 2021 and accounted for the maximum share of more than 38.85% of the global revenue. The service involves the removal of soil contaminants originating from sources, such as dumping of chemicals, improper waste disposal, pipe leaks & spills, and others. Demand for soil remediation is supported by the high extent of soil degradation caused by industrial pollutants, agrochemicals, and municipal and industrial waste. For instance, according to the United Nations, globally over 3.2 billion people are affected by the degradation of land and soils. Similarly, decreasing productivity of cultivable land due to such contaminants is driving an increasing need for soil remediation. These factors are expected to significantly contribute to the market growth.

2. Sediment remediation

The demand for increased navigability and climate change are fueling the segment growth. Sediments are soil particles found at the bottom of lakes, estuaries, rivers and oceans that are of mineral and organic origin. Sediments may include clay, silt, sand, gravel, decaying organic matter, and shells. It is estimated that over 200 million m3 of sediments are dredged every year only in Europe, with over half being contaminated. Contaminated sediments present risk to human health and the environment and limit the uses of many water bodies.

Sediments are heterogeneous and can be characterized by grain size distribution and density, water and organic matter contents. Contaminants tend to adsorb the smaller particle sizes due to higher surface area to volume ratios and higher organic matter contents.

Most of the particles are transported by wind, ice or water. The sediments are comprised of organic matter, iron oxides, carbonates, sulfides and interstitial water. Organic matter is derived from humus, decomposed plant and animal residues and other organic matter, such as algae, worms, amphipods that settle to the bottom of the body of water. Other woody or plant material, garbage, dead organisms and other debris can also become components of sediments. The characteristics of these sediments as low permeability, high salt, organic and water contents as well as the presence of organic and inorganic contaminants, hinder their remediation using conventional remediation technologies. In marine sediments persistent hydrophobic organic contaminants (HOCs) such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), dichloro-diphenyl-trichloroethane (DDT), and heavy metals can accumulate. Sediment-bound pollutants pose major concerns for human health and the environment, showing combined effects that are still largely unknown. As a result, remediation of contaminated sediments has raised a great deal of scientific and public concern around the world representing a huge actual challenge both under a technical and technological viewpoint. Sediment remediation techniques are also commonly classified as in situ and ex situ. Nevertheless, dredging remains an important issue; like for hotspots, dredging activities can heavily remobilize sediment like as the associated pollution via washing out events. The necessity for viable in-situ bioremediation options for contaminated sediments, that avoid removal and thus eliminate the risk of resuspension of the contaminants, will drive market growth in the coming years.

3. Oilfield remediation

Oilfield remediation is projected to grow at the fastest CAGR over the forecast period due to the rapid expansion of the crude oil industry and the development of eco-friendly oilfield remediation options. Surging oil prices in recent months have led to high pressure for increasing oil production in countries, such as the U.S. Moreover, recent advancements in omics technologies, such as metagenomics and meta transcriptomics, have enabled the use of microbial-based oilfield remediation strategies. Similarly, the use of biosurfactants for increasing the bioavailability of oil constituents has accelerated the adoption of oilfield bioremediation activities. Areas of intensive crude oil production may be susceptible to oil pollution arising from accidental spills and leaks, eventually leading to the pollution of bottom sediments. Effective cleaning of aquatic bottom sediments remains a challenge. The main pollutants in sediments resulting from oil production are heavy metals, salts, naturally occurring radioactive materials (NORMs), oil and grease (O&G), benzene, toluene, ethylbenzene and xylene (BTEX), total petroleum hydrocarbon (TPH), and polycyclic aromatic hydrocarbon (PAHs). These pollutants reach sediments and water resources via pipeline leaks, truck spills, improper waste disposal, and underground injection.

d) Geographical outlook

1. North America

North America dominated the market in 2021 due to local presence of established players and advanced infrastructure, it accounted for the largest share of more than 41% of the global revenue in 2021 and is projected to grow at the fastest CAGR over the forecast period. This is attributable to the presence of sophisticated infrastructure, high industrial growth & waste production, and presence of key market players. In addition, the region hosts substantial research potential for bioremediation that is likely to drive advancements in technology and promote industry growth.

2. Asia Pacific (APAC)

On the other hand, APAC is estimated to grow at the fastest CAGR during the forecast period. This high growth can be attributed to the production of large quantities of hazardous waste due to the rising economic development and the increasing awareness about environmental protection in the APAC region. Furthermore, the region consists of a large population and relatively under-developed waste management systems in developing countries, such as Pakistan, Cambodia, and others. These factors can lead to a worsening of contamination issues and, thus, are anticipated to accelerate the industry growth. In the replication chapter a specific case study is dedicated to India.

3. Europe

According to the European Environment Agency (EEA), approximately 300,000 contaminated sites in Europe still require clean-up, with nearly 2.8 million additional sites where potentially polluting activities are occurring. These sites may also need further investigation to determine the extent of contamination and whether soil remediation is necessary. This widespread contamination poses serious health risks, including congenital abnormalities, cancer, low birth weights, and high mortality rates. [6] [7]

Discrepancies in the reported number of contaminated sites across Europe can arise due to varying methodologies and criteria used to identify and classify these sites. The figure of 2.8 million includes sites where potentially polluting activities have occurred or are ongoing, not necessarily those confirmed as contaminated and requiring remediation. Once comparable national registers are fully developed, it is expected that at least 2 million of these sites will be officially registered as suspected contaminated sites. The figure of over 250,000, however, specifically refers to sites that have already been identified as contaminated and in need of remedial action.[8]

These statistics indicate a substantial and growing demand for bioremediation services across Europe. As more sites are identified and classified, the need for effective remediation strategies will increase, driving significant growth in the bioremediation market.

In 2016, 115.000 contaminated sites were remediated in the **EU**, representing 8.3% of the currently registered potentially contaminated sites. Based on current projections, at least 166.000 additional sites are expected to be in need of risk reduction measures or remediation. Assuming a cost of EUR 100.000 for a site to be remediated, a total of EUR 16.6 billion would be required to remediate remaining sites. Currently, with existing national implementation structures and funding, countries' progress in detecting, investigating and remediating contaminated sites varies considerably, from 20 sites/year to 3,000 sites/year. The total numbers of sites under remediation in 2006, 2011 and 2016 were 6,269, 12,073 and 10,539, respectively. To remediate all expected contaminated sites, it would take between 10 years (based on the average current remediation rate of 614 sites/year per country) and 47 years (based on a median remediation rate per country of 129 sites/year). Current efforts to monitor and remediate these sites vary markedly across Member States in Europe. Therefore, coherent efforts supported by an EU-wide policy are needed to fill gaps and speed up the identification and management of sites in need of risk reduction measures and remediation.

National registers cover contamination from ongoing and historical polluting activities. All Member States monitor emissions from ongoing industrial activities through national implementation of EU policies (e.g. the Seveso Directive, Industrial Emissions Directive, Waste Framework Directive). In contrast to emissions on air and water, contamination on land is currently hardly reported in the European Pollutant Release and Transfer Register. The management of historical contamination is also challenging (e.g. brownfields and orphan sites), and this concerns the majority of sites in national registers. In the absence of a dedicated EU soil legislation, the current management of such sites until now depends on national initiatives. The number of countries that report statistics on registered potentially contaminated sites increased from 18 in 2006 to 23 in 2016; however, only 12 have detailed registers. Ten countries either have still not yet developed any national register or consider only a very limited set of polluting activities in their approaches to site management.[36]

Factors Driving Market Growth

After having analyzed the segmentation of the market the document will now focus in describing the factors driving market growth, both technical and legislative, and will focus on the water and marine ecosystem.

Table 1. Key factors are driving the growth of the bioremediation market, reflecting the increasing global emphasis on environmental restoration and pollution control.

1. **Technological Advancements in Soil and Water Table Characterization**: The continuous progress in the technology used to characterize soils and water tables has significantly enhanced the effectiveness and efficiency of bioremediation processes. These advancements allow for more precise

identification and treatment of contaminated sites, thus boosting the demand for bioremediation services.
2. **Higher Remediation Objectives**: There is a growing trend toward achieving more ambitious remediation goals, moving from merely restoring brownfield sites to transforming them into green fields. This shift requires more sophisticated and comprehensive bioremediation techniques, driving the market's expansion as industries and governments aim for higher environmental standards.
3. **Rising Industrial Activity and Pollution**: The increase in industrial activities, particularly in sectors like oil extraction, has led to the release of persistent organic pollutants (POPs) into the environment. This rise in contamination necessitates more extensive and advanced bioremediation efforts to mitigate the environmental impact, contributing to market growth.[1]
4. **Freight Transport**: The expansion of freight transport, particularly through ports and coastal areas, has escalated the risk of contamination in sediments and water bodies. As a result, there is a heightened need for bioremediation solutions to address pollution in these critical areas, further fueling market demand.
5. **Increased Interest in Sediment Contamination**: With growing awareness of the environmental and health risks posed by sediment contamination, there is an increasing focus on cleaning up contaminated sediments in rivers, lakes, and coastal areas. This has led to a surge in demand for bioremediation technologies specifically tailored for sediment remediation.
6. **Impact of Climate Change**: Climate change is exacerbating environmental challenges, including the spread of pollutants and the degradation of ecosystems. The need to address these issues is driving the adoption of

bioremediation practices, as they offer sustainable solutions for mitigating the environmental impacts of climate change.

Recent industrial development has resulted in widespread contamination across various environmental landscapes, including oceans, freshwater systems, forests, and agricultural lands. The mismanagement of plastic waste, crude oil spills, and the escalating production of greenhouse gases (GHGs) have exacerbated environmental degradation. Additionally, the release of chemical pollutants such as polycyclic aromatic hydrocarbons, bisphenol A, pyrethroid pesticides, and dioxanes has further deteriorated ecological health, thereby increasing the demand for bioremediation services to mitigate these impacts.

The COVID-19 pandemic has heightened global awareness of the importance of disinfection, sterilization, and remediation of contaminated areas in both public spaces and private homes. As the SARS-CoV-2 virus continues to mutate, causing recurrent waves of infections worldwide, the need for bioremediation services to reduce contamination risks is expected to grow.[3]

Moreover, the pandemic has led to a surge in the use of Personal Protective Equipment (PPE) and face masks, which has created new challenges in medical waste disposal and treatment. These challenges present significant growth opportunities for the bioremediation market as it adapts to address the increasing environmental burdens associated with pandemic-related waste. [4]

Another significant factor contributing to the growing demand for bioremediation is the increase in freight traffic, particularly maritime transport. Maritime transport is on the rise due to its environmental and economic benefits, making ports a crucial component of the multimodal transport system in modern society. In countries like Sweden, for example, ports handle over 90% of the tonnage in trade. To manage this vast amount of trade efficiently, ports must operate robust, cost-effective, and environmentally sustainable infrastructure.

The surge in sea transport, along with the advent of longer, wider, and deeper-draught ships, has led to a substantial need for maintenance and development dredging of sediments in fairways and ports. In the coming years, several million cubic meters of sediments will need to be dredged in the Baltic Sea alone. A significant portion of these sediments is contaminated with heavy metals and organic pollutants, presenting a critical environmental challenge. The remediation of these contaminated sediments through bioremediation not only addresses these environmental concerns but also represents a significant market opportunity that is poised to drive the growth of the bioremediation industry. A new beneficial alternative use of marine dredged sediments is as a new material for cement production, an example of a significant, sustainable, market opportunity.[5]

Ecosystems most affected by contamination

In regions where factories are located near natural water sources, persistent water pollution issues often arise due to the contamination of local water supplies. Similarly, soil contamination from heavy metals like lead and mercury, along with other toxic chemicals that leach into the soil, poses a significant threat to agricultural crops in these areas. The accumulation of persistent contaminants in sediment further exacerbates environmental challenges. Sediments, composed of mineral and organic particles found at the bottom of lakes, estuaries, rivers, and oceans, readily trap contaminants and serve as critical indicators of the occurrence, magnitude, and trends of human-induced environmental contamination. [13]

In many aquatic systems, sediments act as sinks for pollutants, which can later be reintroduced into the water column, leading to serious environmental and health consequences. The bottom layers of these water bodies often contain higher concentrations of pollutants compared to the upper layers due to the re-suspension of sediment and the associated contaminants. These sediment-bound pollutants are a major concern for human health and the environment, with combined effects that remain largely unknown. [14]

Additionally, climate change introduces new environmental conditions, creating fresh challenges for pollution and necessitating innovative remediation efforts. One such example is the drying up of salt lakes, where sediments at the bottom of these large watersheds collect pollutants from various human activities and natural sources, including coal burning, mining, agriculture, and urban runoff. As these lakes dry up, the pollutants become airborne in dust particles smaller than 10 microns, which can significantly increase the rates of chronic and acute diseases associated with air pollution. These health impacts include reproductive dysfunction, developmental defects, cognitive impairment, cardiovascular damage, and cancer. [15]
The intricate relationship between industrial activity and sediment contamination highlights the critical need for advanced bioremediation strategies to address the escalating risks to environmental and human health. [13]
As the severity of sediment contamination becomes increasingly apparent, there has been a surge in scientific and public concern globally. Remediation of contaminated sediments now represents a significant challenge, both technically and technologically, as it requires innovative solutions to effectively restore ecosystems and protect public health. The complexity of this task underscores the importance of continued research and development in bioremediation to meet these pressing environmental challenges. [16]

Legislative Drivers of Market Growth

Bioremediation offers a highly promising solution for the clean-up of contaminated sites and provides a sustainable, long-term approach to environmental restoration. The growing demand for biological remediation of industrial pollutants is largely driven by the significant advantages it holds over traditional physical and chemical methods. Conventional approaches, such as the use of oxidizing agents, pollutant adsorption, and electrochemical treatments, often fall short in achieving the desired reduction in contaminant concentrations. These methods are also non-specific, costly, and energy intensive.

In contrast, bioremediation techniques not only address these limitations but also provide a versatile, efficient, and environmentally friendly solution for contaminant removal. With a low-energy footprint and the ability to target a wide range of pollutants, bioremediation is increasingly recognized as a superior alternative that can drive industry growth.

In recent years, there has been a notable increase in the involvement of government agencies and public health organizations in promoting the adoption of bioremediation methods. This growing support underscores the technique's potential to address complex environmental challenges and reflects a broader shift towards more sustainable and effective remediation strategies. [6]

Europe

The European Union (EU) approaches the issue of contaminated sites through a comprehensive and multi-faceted regulatory framework aimed at preventing, managing, and remediating environmental contamination. Unlike the U.S. Superfund program, the EU does not have a single overarching program but instead relies on several directives, regulations, and initiatives that collectively address the problem.

For water bodies and marine spaces, to reduce environmental pollution, several countries have united to decide upon common actions, such as the Oslo Convention to regulate the dumping of dangerous substances from ships and aircraft into the sea in 1972 and the Paris Convention on land-based sources of marine pollution in 1974. Those two conventions merged into the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) in 1992. The Helsinki Commission (HELCOM) was formed in 1974 for the protection of the Baltic marine environment by all the countries bordering the Baltic Sea. The Baltic Sea Action Plan (BSAP) was adopted in 2007 with the goal to restore a good ecological status of the Baltic Sea by 2021. Currently, this goal has been postponed, despite all the efforts and improvements that have been implemented since the beginning of this plan, mainly because the environment needs more time to recover.[10]

Within the European Union, the Water Framework Directive (WFD) adopted in 2000 contains far-reaching goals intended to secure and manage water resources, and by implication, sediments, at the river basin scale. [10] Sediment management is also directly or indirectly included in different European directives, such as the Waste Framework Directive (European Parliament, Council of the European Union 2008) and Habitats Directive (European Parliament, Council of the European Union 1992). Guidelines for management of dredged coastal material have been developed by several international maritime conventions, including the London Convention, OSPAR (signed by all four countries), and the 1992 Helsinki Convention. [11]

The WFD sets "good status" objectives for water bodies throughout the Member States (European Parliament, Council of the European Union 2000). The status is based on chemical and ecological criteria. A classification system has been developed to decide upon chemical status, with threshold values known as "Environmental Quality Standards" (EQS) designated for 33 priority substances and eight other pollutants, including pesticides, and metallic and organic compounds. An additional proposal defined 15 additional priority substances, not mandatory but aiming to improve the definition of "good chemical status." The EQS are defined as annual average concentrations (AA-EQS), as well as maximum allowable concentrations (MAC-EQS), for each single measurement and contaminant. This dual-standard measurement allows long-term and short-term exposure evaluations, respectively. The EQS are mandatory for surface water and groundwater in all signatory nations, whereas EQS for sediment and biota are optional. EQS have not been developed for sediments in Finland, whereas in Norway, Sweden, and Denmark, sediment EQS have been implemented respectively for 28, 6, and 14 contaminants (or contaminant groups).

A specific maritime policy was later established and directed for marine ecosystem protection and conservation by the EU Marine Strategy Framework Directive (MSFD) as well as by a communication from the Commission of the European Communities concerning the EU Strategy for the Baltic Sea Region (Commission of the European

Communities 2009). These regulations highlight the problem of pollution as one of the environmental challenges in European marine waters and the MSFD specifically asks member states to implement monitoring programs for the assessment of the environmental status of marine waters based on the indicative list, including sediment contamination. These monitoring programs need to consider corrective measures to restore the good environmental status. [12]

For soils and terrestrial ecosystems in contrast, there is no specific Soil Directive in the EU yet, but there is a framework called the EU Soil Thematic Strategy. This strategy, established in 2006, outlines measures for protecting and sustainably managing soils across the EU, but it does not have binding legislative power like a directive.

However, there has been ongoing discussion about the need for a Soil Health Law or directive. The EU Soil Strategy for 2030, adopted in 2021, calls for legally binding measures to restore and protect European soils, recognizing soil degradation, contamination, and erosion as major environmental issues. This new legislative framework is expected to form part of the European Green Deal and would address gaps left by existing directives that cover aspects of soil protection indirectly (such as the Water Framework Directive, Groundwater Directive, and various agricultural policies).

In summary, while there isn't a specific binding Soil Directive yet, EU soil protection is guided by various policies, and a new soil law is being considered for future adoption.

Key Components of the EU Approach:

1. **Soil Framework Directive (Proposed):** Although the proposed Soil Framework Directive, which aimed to establish a common framework for soil protection and the identification of contaminated sites, was withdrawn in 2014, soil protection remains a priority within the EU's environmental policy. Member states continue to implement national strategies for soil protection, which include the identification and remediation of contaminated sites. [19]

2. **Environmental Liability Directive (ELD):** The Environmental Liability Directive (2004/35/EC) establishes a framework based on the "polluter pays" principle. It holds operators financially liable for the remediation of environmental damage, including land contamination that poses a significant risk to human health. This directive ensures that those responsible for pollution are accountable for its clean up. [20]
3. **Water Framework Directive (WFD):** The Water Framework Directive (2000/60/EC) plays a crucial role in the protection of water bodies in the EU. It requires member states to prevent and control the pollution of water bodies, including contamination from sediments, and mandates the clean-up of polluted water sources to achieve "good status" for all EU waters. [21]
4. **Industrial Emissions Directive (IED):** The Industrial Emissions Directive (2010/75/EU) regulates the environmental impact of industrial activities, including emissions to air, water, and soil. It sets out requirements for the prevention and remediation of pollution from industrial sites, ensuring that contamination is managed effectively. [22]
5. **Groundwater Directive (GWD):** The Groundwater Directive (2006/118/EC) is designed to protect groundwater resources across the EU by preventing and controlling pollution. It establishes criteria for assessing good groundwater chemical status and includes measures to prevent hazardous substances from contaminating groundwater. Member states must monitor groundwater quality and take steps to restore polluted groundwater to good status. The directive works in conjunction with the Water Framework Directive to ensure comprehensive water protection throughout the EU.
6. **Environmental Quality Standards Directive (EQSD):** The Environmental Quality Standards Directive (2008/105/EC) sets limits for certain pollutants in surface waters across the EU. It aims to protect aquatic ecosystems and human health by establishing concentration thresholds for hazardous substances in water bodies. Member states are required to monitor these

substances and ensure that levels remain within the established limits to prevent further environmental degradation and to support the achievement of "good chemical status" for surface waters.

7. **Marine strategy framework directive: Marine Strategy Framework Directive (MSFD):** The Marine Strategy Framework Directive (2008/56/EC) aims to protect and preserve the marine environment across Europe, promoting sustainable use of seas and ensuring their ecological health. It requires EU member states to achieve "Good Environmental Status" (GES) for marine waters by 2020, using 11 descriptors that assess various aspects of marine ecosystems, including biodiversity, fish populations, and contaminants. One of the key descriptors, Descriptor 6, focuses on sea-floor integrity, including marine sediments. It assesses the physical condition of the seabed and aims to ensure that human activities do not cause long-term degradation of sediment quality or disrupt the structure and function of benthic ecosystems. This descriptor helps ensure that marine sediments maintain their capacity to support ecosystems and services crucial for biodiversity and human use.
8. **Priority substances directive: Priority Substances Directive:** The Priority Substances Directive (2013/39/EU) amends the Water Framework Directive and Environmental Quality Standards Directive to establish a list of priority substances that pose significant risks to or via the aquatic environment. These substances include chemicals, pesticides, heavy metals, and other pollutants that are potentially harmful to aquatic ecosystems and human health. Member states are required to monitor the concentration of these substances in surface waters and ensure that levels remain below the established Environmental Quality Standards (EQS). The directive aims to gradually reduce pollution from priority substances and phase out emissions of particularly hazardous substances (termed "priority hazardous substances") to achieve good chemical status in all EU water bodies.

9. **Waste Framework Directive (WFD):** The Waste Framework Directive (2008/98/EC) sets the basic concepts and definitions related to waste management in the EU, aiming to reduce the environmental and health impacts of waste. It establishes a waste hierarchy prioritizing prevention, reuse, recycling, and recovery before disposal, and requires member states to take appropriate measures to ensure proper waste management practices. Regarding dredged material, the directive clarifies that if dredged material is not discarded and is instead reused or managed in an environmentally sound way, it may not be classified as waste. However, if it is deemed to be waste (for example, if it is contaminated and cannot be reused), it must be handled according to the directive's waste management principles. This ensures that dredging activities, common in maintaining waterways and ports, are conducted in line with environmental protections.
10. **REACH Regulation (Registration, Evaluation, Authorisation, and Restriction of Chemicals):** The REACH Regulation (EC No 1907/2006) is one of the most comprehensive EU laws for chemical safety. It aims to ensure a high level of protection for human health and the environment from risks posed by chemicals. Under REACH, companies that manufacture or import chemicals in quantities of one tonne or more per year must register these substances with the European Chemicals Agency (ECHA), providing detailed information on their properties and safe use. The regulation also includes procedures for the evaluation of substances by ECHA, the authorisation of substances of very high concern, and the restriction of chemicals that pose unacceptable risks. REACH places the burden of proof on companies to demonstrate that their chemicals are safe for use, promoting safer chemical management and encouraging the use of alternative substances where possible.
11. **CLP Regulation (Classification, Labelling, and Packaging of Substances and Mixtures):** The CLP Regulation (EC No 1272/2008) aligns the EU system of classification, labelling, and packaging of chemicals with the globally

harmonized system (GHS). The main goal of the CLP Regulation is to ensure that hazards posed by chemicals are clearly communicated to workers and consumers in the EU through consistent classification and labelling. Under CLP, manufacturers and importers must classify substances and mixtures according to their hazardous properties, such as toxicity, flammability, or environmental impact. Once classified, the chemicals must be labelled with standardized hazard pictograms, signal words, and safety phrases to inform users of the associated risks. Packaging must also be designed to ensure the safe handling of hazardous substances, particularly in consumer products. This regulation plays a critical role in improving chemical safety and transparency across industries in the EU. Both REACH and CLP work in tandem to regulate the safe production, use, and communication of chemical risks within the EU.

12. **European Green Deal and Circular Economy Action Plan:** The European Green Deal and the Circular Economy Action Plan emphasize the need for sustainable management of resources, including the remediation of contaminated sites. These initiatives support the transition to a cleaner economy and encourage the development of innovative bioremediation technologies as part of the broader strategy to address environmental contamination. [23][24]
13. **Nature Restoration Law:** The EU Nature Restoration Law is part of the European Green Deal, aimed at restoring ecosystems and biodiversity across the EU by 2030. The law sets binding targets for restoring degraded ecosystems, including agricultural lands, forests, wetlands, and urban areas, to improve biodiversity and increase resilience to climate change. It also promotes the use of nature-based solutions, such as reforestation and wetland restoration, to address environmental challenges. Regarding brownfields, which are previously developed but now disused or contaminated urban or industrial sites, the Nature Restoration Law could have significant implications for their remediation. Brownfield remediation aligns with the law's

goals by rehabilitating degraded land, reducing contamination, and enhancing biodiversity in urban environments. The law encourages the restoration of these areas through sustainable practices, including the removal or containment of pollutants, replanting native vegetation, and restoring natural hydrology. In the context of brownfield remediation, the Nature Restoration Law supports:

- Ecosystem restoration: Encouraging member states to restore ecological functions on brownfield sites, making them suitable for wildlife, recreation, or other sustainable uses.
- Nature-based remediation: Promoting the use of plants, soils, and natural processes to remediate contaminated sites (phytoremediation) and restore habitats.
- Integration into urban planning: Ensuring that brownfield restoration contributes to healthier urban environments by creating green spaces that enhance biodiversity, reduce pollution, and support climate adaptation efforts.

This law not only addresses biodiversity but also promotes the sustainable regeneration of brownfields, improving land use efficiency and environmental quality in urban settings.

14. **Funding and Research Initiatives:** The EU supports bioremediation and environmental restoration through various funding programs, such as Horizon Europe, which funds research and innovation projects. These initiatives aim to develop and deploy advanced bioremediation technologies and to enhance the understanding of environmental contamination and its remediation.

This broad and detailed legislative framework fuels the growth of bioremediation market by setting binding target for all Member States.

USA

The U.S. Environmental Protection Agency (EPA) oversees the Superfund program, which is dedicated to the clean-up of the nation's most contaminated sites. This program plays a critical role in addressing severe environmental hazards by managing and remediating areas where toxic substances pose significant risks to public health and the environment. In addition to the efforts under the Superfund program, the U.S. government has taken further steps to support the development of innovative remediation technologies. [25]

In February 2022, the America COMPETES Act was enacted, marking a significant legislative milestone. This Act includes provisions for the National Engineering Biology Research & Development Initiative, which aims to advance research and innovation in bioengineering. One of the key focus areas of this initiative is the funding of bioremediation and related bioengineering solutions. By providing financial support for cutting-edge research in these fields, the America COMPETES Act seeks to enhance the effectiveness of environmental clean-up efforts and promote the adoption of sustainable technologies for managing industrial pollution and environmental degradation. This initiative reflects a broader commitment to leveraging scientific advancements to address some of the most pressing environmental challenges facing the country today. [7]

According to the Federal Remediation Technologies Roundtable, the cost of bioremediation can range from $30 to $100 per cubic meter (approximately €28 to €93) or $20 to $80 per cubic yard (approximately €19 to €74), depending on various factors. Soils with high clay content often require additional treatments or a more intensive bioremediation approach, which can significantly increase the overall expense. Optimal conditions for bioremediation include a soil pH of around 7.5, which has been identified as the most conducive for the process. Additionally, the presence of oxygen in the soil can enhance the efficiency of bioremediation, potentially lowering the associated costs by accelerating the degradation of contaminants. [26]

Replication Opportunities

As previously said, in Europe, there are approximately 2.8 million potentially contaminated sites, with only 10% (around 300,000 sites) having been characterized to date. This chapter will focus on identifying some replication opportunities in the 4 member states member of the LIFE SEDREMED partnership and will end with an analysis of a specific opportunity in India. Since the LIFE SEDREMED project focuses on sediment remediation the location described bear specifical problems with inland or coastal sediments.

1. Italy: has identified 42 Sites of National Interest (SIN), covering 170,000 hectares of land and 77,000 hectares of marine area. Key contaminated sites include Priolo, Gela, and Porto Marghera.
2. Belgium: has confirmed contamination at 12,400 sites, with pollution suspected at an additional 83,000 sites. Significant areas of concern include the Port of Antwerp, the Geul River, and the Scheldt River.
3. Germany: reports 221,793 former industrial sites and 19,132 confirmed contaminated sites. Major contaminated areas include the Rhine River, Elbe River, Schweriner See.
4. Finland: sediment contamination is primarily assessed after dredging, with a preliminary survey identifying 28 potentially contaminated sites in inland waters, though a comprehensive nationwide assessment has yet to be conducted.

Italy

Italy presents significant opportunities for the replication and application of bioremediation technologies, particularly within its designated National Interest Sites (SIN). These areas have been identified by the Italian government as requiring urgent environmental remediation due to severe contamination from industrial activities, waste disposal, and other sources of pollution.

Currently, there are 42 National Interest Sites (SIN) across Italy, encompassing a total area of approximately 170,000 hectares. These sites include both terrestrial and marine environments, with the marine areas alone extending over 77,000 hectares. The scale and diversity of these contaminated areas present a unique challenge that bioremediation technologies are well-suited to address.

Bioremediation offers a sustainable and cost-effective solution for the complex contamination issues present in these SINs. The approach can be tailored to the specific contaminants found in different regions, whether they are heavy metals, hydrocarbons, or other toxic substances. By leveraging advanced bioremediation techniques, including the use of genetically optimized microorganisms and enzymes, these areas can be effectively restored, reducing environmental risks and restoring ecological balance.

Furthermore, the successful application of bioremediation in these SINs can serve as a model for similar efforts both within Italy and in other countries facing comparable environmental challenges. The extensive experience gained from these projects can contribute to refining and optimizing bioremediation strategies, making them more effective and scalable for other contaminated sites around the world.

The potential for replication is not only a matter of environmental necessity but also of economic opportunity. Effective remediation of these sites can unlock significant economic benefits, including the rehabilitation of land for new uses, the restoration of ecosystems, and the enhancement of public health and safety. As such, Italy's SINs represent a critical area for the deployment of bioremediation technologies, with the potential for widespread replication and significant positive impact. [31]

Priolo

The Priolo area, located within the territories of Augusta, Priolo, Melilli, and Siracusa in Sicily, represents a critical opportunity for the application of advanced bioremediation technologies. This region spans approximately 5,815 hectares of land and an additional 10,185 hectares of marine area, including the Augusta Bay.[32] The area's environmental challenges are compounded by its history as a large-scale industrial hub, home to major refineries, petrochemical plants, cement factories, and associated infrastructure. The adjacent marine area, which includes the port areas of Siracusa and Augusta, has also been heavily impacted by industrial activities, with significant contamination present in both water and sediment. The presence of waste landfills, former Eternit plants in Siracusa, and sensitive wetland areas like Salina further complicate the environmental landscape, necessitating a comprehensive approach to remediation.

Historically, the predominant activities in Priolo have centered around petroleum refining, processing of its derivatives, and energy production, with industrial settlements dating back to the 1950s. However, since the mid-1980s, there has been a significant decline in industrial activities, leading to economic challenges and a pressing need for land and environmental reclamation. Bioremediation offers a sustainable solution for addressing the extensive contamination in Priolo, particularly in the wake of reduced industrial activity. The application of bioremediation techniques in this region could effectively target pollutants such as hydrocarbons, heavy metals, and other toxic substances, facilitating the restoration of both terrestrial and marine environments.

Moreover, successful remediation of the Priolo area could serve as a valuable model for other regions facing similar industrial legacy issues. The large-scale implementation of bioremediation here could demonstrate the effectiveness of these techniques in revitalizing areas with complex contamination profiles, while also contributing to the local economy through the restoration of land for new, sustainable uses. The extensive industrial history and current environmental degradation in Priolo highlight the urgent need for innovative remediation strategies. Bioremediation not only addresses the existing contamination but also offers a pathway for sustainable development and ecological restoration, making Priolo a prime candidate for the replication of bioremediation technologies on a broader scale.

Gela

The National Interest Site (SIN) "Gela," located entirely within the territory of Gela in the Province of Caltanissetta, Sicily, represents a significant opportunity for the application of bioremediation technologies. Spanning 795 hectares of land, this site is home to a large industrial hub, several oil centers, and multiple landfills. The environmental challenges in Gela are further complicated by the presence of the Gela Biviere Nature Reserve, a coastal lagoon with brackish waters recognized as a wetland of international importance under the Ramsar Convention of 1971. The Nature Reserve covers an area of 331 hectares and serves as a critical habitat for various species.

The Gela area also includes the river basins of the Gela and Acate-Dirillo rivers, as well as the Gattano streams and Valle Priolo canal, all of which are vulnerable to contamination from industrial activities. The region has been identified by the local government as a Site of Community Importance (SCI) and a Special Protection Area (SPA) under the "Habitats" Directive (Directive no. 92/43/EEC) and the "Birds" Directive (Directive no. 79/409/EEC), underscoring its ecological significance and the necessity for targeted environmental protection measures.

Within this SIN, the large-scale industrial hub includes the Multisocietario plant, which houses major companies such as Eni-Raffineria di Gela, Versalis (formerly Polimeri Europa), Eni Rewind (formerly Syndial), ISAF, Enimed, and Ecorigen. The petrochemical plant, constructed in 1960 with the first operations beginning in 1962, has been a central contributor to the region's industrial output. However, the environmental legacy of these activities has left significant contamination that now requires remediation. In recent years, there has been a shift towards converting the Gela Refinery into a biorefinery, reflecting a broader commitment to more sustainable industrial practices. This conversion program presents a unique opportunity to integrate bioremediation efforts with the ongoing transition to greener technologies.

The Gela SIN, with its combination of industrial history, ecological importance, and ongoing industrial transformation, provides a compelling case for the application of bioremediation technologies. The success of bioremediation in this area could not only restore the environment but also serve as a model for similar sites facing the dual challenges of industrial contamination and ecological conservation. By addressing the contamination issues in Gela, bioremediation can facilitate the region's transition to more sustainable practices, while also protecting and enhancing the valuable natural habitats within the area.

Porto Marghera

The National Interest Site (SIN) of Porto Marghera, located within the Municipality of Venice, represents a crucial opportunity for the deployment of advanced bioremediation technologies. The site currently encompasses approximately 1,618 hectares of land, though its original perimeter included a much larger area—spanning 3,221 hectares of land, 350 hectares of port canals, and 2,200 hectares of lagoon territory, covering both public and private lands.

Porto Marghera has historically been a hub of heavy industrial activities, including refinery operations, integrated chemical production at the Macroisole Vecchio and Nuovo Petrolchimico, and steelworks. These activities have left a legacy of significant environmental contamination, making the site one of Italy's most challenging areas for remediation.

The contamination at Porto Marghera is widespread, with numerous families of pollutants detected across different environmental media. In the soil, common contaminants include heavy metals and polycyclic aromatic hydrocarbons (PAHs), while the groundwater is contaminated with metals, PAHs, and organochlorine compounds. These pollutants pose severe risks to both the environment and public health, necessitating a comprehensive and effective remediation strategy.

Additionally, these pollutants severely accumulated in sediments, and Porto Marghera, being a maritime industrial hub still often requires dredging interventions to allow freight transport, bioremediation of contaminated sediments would thus be crucial to increase environmental safety of dredging operations and reduce handling and disposal costs of the dredged material.

Bioremediation presents a promising approach to addressing the contamination at Porto Marghera. By leveraging the natural degradative capabilities of microorganisms and advanced biotechnological tools, bioremediation can target and break down the specific contaminants present in the soil and groundwater. This approach is not only environmentally friendly but also cost-effective, making it well-suited to the complex contamination challenges at this site.

Given the scale and complexity of contamination at Porto Marghera, the successful implementation of bioremediation could serve as a benchmark for similar industrial sites across Europe. The site's strategic location within the Venice municipality, combined with its industrial significance, makes it an ideal candidate for showcasing the effectiveness of bioremediation technologies in restoring heavily contaminated environments. Moreover, the restoration of Porto Marghera could have far-reaching benefits, including the potential for economic revitalization, improved public health outcomes, and the preservation of the surrounding lagoon and canal ecosystems. As such, Porto Marghera stands as a key opportunity for the replication and demonstration of bioremediation technologies, with the potential to influence environmental remediation practices across the region.

Germany

Germany presents a substantial opportunity for the application of bioremediation technologies, given the extensive number of contaminated and potentially contaminated sites across the country. With a history of industrial development and waste disposal practices, Germany faces significant environmental challenges that require innovative and sustainable solutions.

Germany has identified a vast number of sites with potential or confirmed contamination issues:

- Former Waste Disposal Sites: Approximately 95,889 sites across Germany have been identified as former waste disposal areas. These sites often harbor a wide range of contaminants, including heavy metals, organic pollutants, and other hazardous substances, which pose significant risks to soil and groundwater quality.
- Former Industrial Sites: The country is home to 221,793 former industrial sites, many of which are suspected of harboring environmental contaminants due to past industrial activities. These sites include former factories, chemical plants, and other industrial facilities that have left behind pollutants such as polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), and heavy metals.
- Confirmed Contaminated Sites: Germany has confirmed 19,132 sites as contaminated, where the presence of hazardous substances has been verified. These sites require immediate and effective remediation to mitigate the risks to public health and the environment. [33]

The scale of contamination across these sites underscores the urgent need for advanced bioremediation strategies. Bioremediation offers a sustainable and effective solution for treating a wide range of contaminants, making it an ideal approach for the diverse challenges presented by Germany's contaminated sites. The use of microbial degradation, enzymatic breakdown, and other biotechnological methods can effectively target and neutralize pollutants in both soil and groundwater. Furthermore, the successful remediation of these sites would have significant economic and social benefits. Restoring former waste disposal and industrial sites can lead to the revitalization of land for new uses, including residential, commercial, and recreational developments. This, in turn, can stimulate local economies, enhance property values, and improve the quality of life for nearby communities.

Rhine river

The river Rhine originates in the Swiss Alps, reaches the North Sea in the Netherlands and is the most abundant river in terms of river flow to the North Sea. The Rhine catchment area is distributed between nine countries (Switzerland, Austria, Germany, Netherlands, Liechtenstein, France, Belgium, Italy and Luxembourg). More than half of the catchment area belongs to Germany. Switzerland, France and The Netherlands have nearly the same shares in the catchment. At 1,230 km, the Rhine is the sixth largest river in terms of length and as a shipping route it is one of the busiest in the world. More than 58 million people live in the catchment area. The Rhine has been subject to pollution from industrial activities over many decades (e.g. hexachlorobenzene (HCB) discharge with wastewater in 1970-1980). Local contamination also causes problems in the aquatic environment in many tributaries (e.g. the rivers Neckar, Main and Ruhr).

Regulation works were necessary to protect the population from the harmful effects of floods and to realize a water management regime that optimizes water use. Some of the most important measures have been: bed fixation, river-bend cut-offs to increase discharge capacity, dyke building to protect against flooding, and expansion or stabilizing works in shipping channels (groynes, bank and bed fixations, short-cuts, widening and dredging of the channel).

The measures for regulation also had negative effects:

Deterioration of aquatic ecology. These constructions have led to the disappearance of the gradual, shallow water transitions between land and the river, and fish migration has been affected by obstructions which have also led to a decline of habitats for fish, macro fauna and water plants.

Degradation of the river bed. Regulation of the river often implies a narrowing of the channel leading to an increase in flow velocities and rates of bed erosion. A second cause is a shortage of sediment due to: sand extraction in the past from dredging for navigation; and a reduction in inputs of sediment from upstream.

Increase in flood levels. Confinement of the river bed by the construction of dikes leads to higher flood levels.

In order to be prepared for more extreme river discharges in the future due to climate change, programmes to reinforce dikes are continuing, but there are limits in heightening river dikes. Examples of measures are deepening or widening of riverbeds, construction of secondary channels, relocation of dikes inland and lowering of groynes. Dredging and dredged material management is a crucial aspect for realisation of the programme.

Dredging and disposal activities are problematic because in places the sediments are contaminated by HCB. The development of strategies (to remove contaminated sediments, to reduce dredging of sediments and to dispose them in an ecologically friendly and economically acceptable manner) is an important sediment management task for the Rhine waterway.

The Rhine catchment area is heavily influenced by communal and industrial sources of pollution. These include discharges from wastewater treatment plants and runoff from industrial zones, which have introduced a range of contaminants into the river system. The river's proximity to dense industrial regions and urban centers has exacerbated the pollution, making the Rhine a critical focus for environmental remediation efforts.

The Ruhr area, one of Germany's most industrialized regions, has a particularly high concentration of large wastewater treatment plants, as well as significant chemical and mining industries located near the Rhine. The heavy industrial activity in this area has contributed to the accumulation of pollutants in both the river and its tributaries. The Lippe River, a major tributary of the Rhine, is similarly affected by industrial activities, adding to the overall contamination burden.

Further downstream, the Rotterdam harbour area in the Netherlands, although having a relatively lower number of wastewater treatment plants, is dominated by extensive industrial activity, particularly in the chemical sector. The industrial output in this area has led to the discharge of various hazardous substances into the Rhine, affecting both the water quality and sediment health as the river approaches the North Sea.

Given the scale and diversity of contamination sources along the Rhine, bioremediation presents a significant opportunity for environmental restoration. The application of bioremediation technologies can target specific pollutants introduced by industrial activities and wastewater discharges, helping to restore the ecological balance of the river.

For example, in the Ruhr area, bioremediation could be applied to treat the sediments and waters contaminated by heavy metals, PAHs, and other industrial pollutants. Microbial degradation and phytoremediation techniques could be used to detoxify and remove contaminants, reducing the environmental and health risks associated with these polluted sites.

Similarly, in the Rotterdam harbour area, bioremediation could focus on breaking down complex organic chemicals and hydrocarbons released by the chemical industries. The use of advanced microbial consortia and engineered enzymes could enhance the degradation of persistent pollutants, leading to cleaner sediments and improved water quality.

The successful implementation of bioremediation along the Rhine could serve as a blueprint for similar efforts across other European rivers and industrial regions. The Rhine's diverse contamination profile, coupled with its ecological and economic importance, makes it an ideal candidate for demonstrating the effectiveness of bioremediation on a large scale. The lessons learned from remediation projects along the Rhine could inform strategies for other major rivers facing similar challenges, fostering broader adoption of sustainable environmental practices across Europe.

Elbe river

The Elbe River, the third-largest river in Central Europe, stretches 1,091 kilometers and covers a catchment area of 148,268 square kilometers. Originating in the Giant Mountains (Krkonoše) in the Czech Republic, the Elbe flows through major European cities such as Berlin, Hamburg, Prague, Leipzig, and Dresden before emptying into the North Sea. The river's basin is predominantly within Germany, encompassing around two-thirds of the entire area, with the remaining portion in the Czech Republic and minor parts in Austria and Poland. With a long-run discharge mean of 877 cubic meters per second at its mouth, the Elbe plays a vital role in the region's ecology and economy.

- Contamination Sources and Environmental Challenges

The Elbe River basin is home to more than 25 million people and is characterized by a long history of industrial and mining activities, particularly in the German and Czech regions. Additionally, around 56% of the entire catchment area is intensively used for agriculture, contributing to the river's complex contamination profile. Despite dynamic developments and improvements in water quality since the political changes of the late 1980s, the Elbe remains one of the most heavily polluted rivers in Central Europe.

The river's natural resources, including wetland and floodplain forest habitats, are under continuous threat from industrial and agricultural pollutants. Persistent organic pollutants (POPs) such as pp-DDT and hexachlorobenzene (HCB) are present at concentrations that pose significant risks to the marine environment, particularly in the tidal areas near the Port of Hamburg. Maintenance dredging is essential to keep navigation channels open, requiring the removal of 15-20 million cubic meters of sediment annually. However, up to one million cubic meters of this dredged material is so heavily contaminated that it cannot be safely relocated within the estuary and must be disposed of on land, leading to additional costs of nearly 50 million Euros per year.

Furthermore, the lower Elbe's grasslands, traditionally used for grazing cattle and sheep, have been contaminated by dioxins from river sediments due to regular flooding. This contamination has led to restrictions on agricultural use, necessitating the introduction of specific management regimes to ensure that dioxin levels in foodstuffs, milk, and meat do not exceed allowable limits.

The Elbe River represents a critical opportunity for the application of bioremediation technologies. Given the complex and extensive contamination challenges in the river basin, bioremediation offers a sustainable and cost-effective approach to restoring the river's ecosystems and reducing the health risks associated with its pollution.

Bioremediation could be applied to address the contamination in both sediments and water, particularly targeting POPs like pp-DDT, HCB, and dioxins. The use of microbial consortia and engineered enzymes could enhance the degradation of these persistent pollutants, reducing their concentrations in the river system and minimizing their impact on the environment and human health.

In the tidal areas near Hamburg, bioremediation could complement existing dredging efforts by treating contaminated sediments on land, potentially reducing the costs and environmental risks associated with their disposal. Additionally, bioremediation techniques could be employed to restore contaminated floodplain areas, allowing for the safe resumption of agricultural activities and reducing the need for restrictive management regimes.

The successful implementation of bioremediation along the Elbe River could serve as a model for other transboundary river systems in Europe and beyond. The Elbe's diverse contamination challenges, coupled with its ecological and economic significance, make it an ideal candidate for demonstrating the effectiveness of bioremediation on a large scale. The lessons learned from bioremediation projects along the Elbe could inform strategies for other rivers facing similar issues, promoting the broader adoption of sustainable environmental practices across the continent.

By addressing the contamination in the Elbe River through bioremediation, there is potential not only to restore this crucial waterway but also to enhance its natural resources and improve the livelihoods of the millions of people who depend on it. The Elbe’s restoration could set a precedent for the management of industrial and agricultural pollution in other major river systems, contributing to the global effort to protect and restore vital freshwater ecosystems.

Schweriner see (lake)

Schweriner See, a hard-water lake located approximately 20 kilometers south of the Baltic Sea in the westernmost part of the Mecklenburg Lake District in northeastern Germany, represents a significant opportunity for the application of bioremediation technologies. The lake has a long history of anthropogenic contamination, with increasing levels of pollutants recorded in its sediments since the early- to mid-19th century, coinciding with the Industrial Revolution. This period marked the introduction of heavy metals and other contaminants into surface waters, with evidence suggesting that pollution in the lake may have begun over 200 years ago.
The eutrophication of Schweriner See is well documented, with historical records dating back to around 1820 CE indicating a decline in water quality in the city's well. In response to these early signs of water quality deterioration, sewage was discharged directly into Schweriner See and its tributaries. This practice exacerbated the lake's eutrophication, a problem that became increasingly severe through the late 20th century. By the 1950s, eutrophication was recognized as a major environmental issue for Schweriner See, prompting the implementation of measures aimed at improving water quality.
The contamination of Schweriner See is primarily driven by the historical discharge of sewage and industrial pollutants into the lake and its tributaries. The introduction of heavy metals, nutrients, and other contaminants over the centuries has led to significant water quality issues, particularly eutrophication, characterized by excessive nutrient loading and the subsequent overgrowth of algae and aquatic plants.
Eutrophication has had profound effects on the lake's ecosystem, including oxygen depletion, loss of biodiversity, and the disruption of aquatic food webs. Despite efforts to address these issues since the mid-20th century, the legacy of pollution

continues to impact Schweriner See, necessitating further intervention to restore the lake's ecological balance and water quality.

Bioremediation offers a promising solution for the restoration of Schweriner See by targeting both the historical and ongoing sources of contamination. The application of bioremediation techniques can help to degrade and remove heavy metals, nutrients, and other pollutants from the lake's sediments and water, thereby reducing the impacts of eutrophication and improving overall water quality.

Microbial bioremediation could be employed to break down organic pollutants and enhance nutrient cycling within the lake, helping to mitigate the effects of eutrophication. Additionally, phytoremediation techniques, such as the use of aquatic plants to absorb and accumulate heavy metals and other contaminants, could be implemented to further reduce pollutant levels in the lake.

The successful application of bioremediation in Schweriner See could serve as a model for the restoration of other lakes and water bodies in the region that face similar challenges. The integration of bioremediation with other lake management strategies, such as reducing nutrient inputs and enhancing natural filtration processes, could lead to significant improvements in water quality and the overall health of the lake's ecosystem.

Schweriner See's history of contamination and ongoing water quality challenges provide a compelling case for the replication of bioremediation technologies across similar aquatic environments in Europe and beyond. The lessons learned from bioremediation efforts in Schweriner See could inform broader strategies for managing eutrophication and pollution in other hard-water lakes and freshwater ecosystems.

By restoring Schweriner See through bioremediation, there is potential not only to improve the ecological health of the lake but also to enhance its value as a natural resource for the surrounding communities. The success of such efforts could inspire further applications of bioremediation in other contaminated water bodies, contributing to the global effort to protect and restore vital freshwater ecosystems.

Finland

Finland presents a unique landscape for the application of bioremediation technologies, particularly in the context of sediment contamination. Unlike other European countries with extensive records and systematic approaches to identifying and remediating contaminated sites, Finland's efforts have been more localized, primarily focused on assessing sediment contamination in relation to dredging activities. This approach reflects the country's emphasis on maintaining navigable waterways while ensuring environmental safety, but it also highlights the gaps in systematic and nationwide surveys of contaminated sediments.

In Finland, the status of sediment contamination is generally assessed only for relocation purposes following dredging operations. This practice ensures that contaminated sediments are not inadvertently spread to uncontaminated areas during dredging. However, there has not been a comprehensive, nationwide survey specifically aimed at identifying all contaminated sediments within the country.

A preliminary national survey of contaminated sediments in inland waters has identified 28 possible or known sites across Finland. These sites, while providing some insight into the extent of contamination, likely represent only a fraction of the potentially contaminated areas in the country. The limited scope of these assessments suggests that many contaminated sites remain undocumented and untreated, posing ongoing risks to water quality, aquatic ecosystems, and public health.

All marine waters in Finland are brackish waters, along the coastline of the Baltic Sea. The shores are typically rocky and fragmented into numerous islands. The archipelago is a product of glacial erosion during the Ice Age and has resulted in uplifting of the land. The uplifting is especially strong in the Gulf of Bothnia, rating for up to 9 mm year−1. The coastline in the island zone is shallow; therefore, sedimentation is restricted to wind-protected deeps. Erosion of sediment is common. The rivers bring sediments in addition to associated anthropogenic substances from the catchments. Estuaries reflect the catchment properties and human actions therein. For example, dioxins enter the seabed from the River Kymijoki and heavy metals from the acid sulfate soils of the rivers at the western coast. The Baltic Sea is the most important transport route for trade and there are several active harbors where sedimentation and dredging are common issues.

The leading environmental administrative body in Finland responsible for setting guidelines and policy for the implementation of European directives and national legislation is the Ministry of Environment (Ympäristöministeriö). The Finnish Environmental Institute (SYKE) is a national expert body responsible for advising and guiding monitoring, survey, and research programs. The practical work is done by the Regional Centers for Economic Development, Transport and the Environment (ELY) or even at city or municipality level. ELY centers follow and classify the chemical status of water bodies according to the WFD and amendment directives. The Finnish Water Way is an International Water Strategy which boldly announces the goals and means for protecting the waters. This follows the examples of United Nations SDG 6: "Ensure availability and sustainable management of water and sanitation for all." However, the practical actions protecting environment mainly stem from the EU legislation.

There is no national systematic survey plan in Finland regarding contaminated sediments. Some areas have been identified and monitored but not many have been remediated, especially concerning marine sediments. Jaakkonen (2011) presented a preliminary national survey of contaminated sediments in inland waters. It identified 28 known and suspected sites, mainly located south of the country. Typical contaminants were metals, PAHs, PCBs, oil, and organic tin and chlorinated compounds. In the worst cases, PCB concentrations were at parts per million levels. Since then, some other sites have been identified and related to mining activity and heavy metals. Because no EQS have been set for sediment values within the WFD in Finland, the focus is mainly on water and biota thresholds. The trends in sediment concentrations are sometimes surveyed but they are not necessarily leading to remediation actions. It is frequent to perform dredging, even though the main motivation is usually not the environmental remediation itself, but the use of waterways for navigation or construction purposes. To our knowledge, capping has only been performed in one site, and it was not a marine site. A guide was published in 2015 to support decision for handling and relocating dredged sediments as a function of their contamination levels (Ympäristöministeriö 2015). The guide includes concentration levels for the most common contaminants (PAHs, sum PCBs and dioxins, metals, TBT). [34]

Neva Bay

Neva Bay is the shallowest and easternmost part of the Gulf of Finland (Baltic Sea). St. Petersburg, Russia's second largest city, occupies the coastal area where the Neva River debouches into Neva Bay. St. Petersburg has a protracted history of industrial, transportation and urban related activity that have affected Neva Bay. By the sealing off the bay from the eastern Gulf of Finland, the St. Petersburg Flood Protective Facility, which was constructed from the 1970's to 2011, transformed Neva Bay into a "technogenic" lagoon. Neva Bay sediments record a unique history of pollution near the metropolis. Heavy metal concentrations of most elements studied varied consistently throughout sediment cores. Temporal trends indicate that metals started to accumulate abruptly in the first half of the 20th century. Zinc, lead and copper were the first metals to reach contaminant thresholds implicating the regional base metal industry as a source. Significant increase in cadmium levels a decade or two later suggests pollution from the regional chemical industry. Comparison of geochemical data collected from sediment cores and recent annual sediment surveys highlighted the temporal history and potential sources of pollution in Neva Bay. Intensive dredging in 2007-2008 resuspended and redistributed contaminated sediment around Neva Bay causing a dramatic increase in benthic sediment heavy metal concentrations.

Concentrations of all measured metals subsequently declined from 2009-2014 relative to the elevated values observed for 2007-2008. Pollution history of Neva Bay bottom sediments is closely linked with changing of sedimentation conditions. Analyses of sedimentological data collected by 20th and 21st century scientific surveys reveal dramatic shifts in Neva Bay sedimentation processes over the last three centuries. The western part of Neva Bay has transitioned from a sand-dominated system to one of mud accumulation with the aerial extent of mud deposition expanding significantly during the 20th century. This inventory coupled with an understanding of primary natural and anthropogenic processes can help inform decision makers to support the overall ecological health of the bay.

The sediments in Neva Bay have been increasingly impacted by a variety of pollutants due to the bay's proximity to dense urban areas and major industrial zones. The influx of contaminants from wastewater discharges, industrial runoff, and maritime activities has led to the accumulation of heavy metals, hydrocarbons, and other persistent organic pollutants in the bay's sediments.

The ongoing sediment contamination poses risks not only to the local aquatic ecosystems but also to the broader Gulf of Finland, affecting water quality, marine life, and the health of communities that rely on these waters for food, recreation, and transportation.

Given the scale and complexity of contamination in Neva Bay, bioremediation offers a promising approach to mitigating the environmental impact. The application of bioremediation technologies could target the degradation of hydrocarbons, the detoxification of heavy metals, and the breakdown of other organic pollutants present in the sediments.

Bioremediation in Neva Bay could involve the use of microbial consortia that are specifically adapted to cold-water environments, enhancing the natural degradation processes in this northern region. Additionally, phytoremediation—using aquatic plants to absorb and concentrate pollutants—could be applied in the shallow areas of the bay, providing a cost-effective and environmentally friendly solution.

The successful implementation of bioremediation strategies in Neva Bay could significantly improve sediment quality, reduce the risks to marine ecosystems, and enhance the overall health of the Gulf of Finland. This would also contribute to the long-term sustainability of St. Petersburg's waterways, which are vital to the city's economy and cultural heritage.

Neva Bay presents a unique opportunity to develop and refine bioremediation techniques that can be applied in similar coastal and estuarine environments. The lessons learned from bioremediation efforts in this bay could inform broader strategies for managing contaminated sediments in other parts of the Gulf of Finland and beyond.

Given the shared environmental challenges faced by countries around the Baltic Sea, there is significant potential for collaboration on bioremediation projects, allowing for the exchange of knowledge, technologies, and best practices. The success of such initiatives in Neva Bay could serve as a model for international efforts to protect and restore other heavily impacted coastal regions.

Kokemäki river

The Kokemäki River near Pori, Finland, has experienced significant contamination primarily due to industrial discharges, including heavy metals like mercury, cadmium, nickel and other pollutants from local industries. Over decades, these contaminants have accumulated in the river's sediments, leading to long-term environmental and health risks. A major incident involved the accidental release of 1,200 kilograms of nickel into the river from the Harjavalta nickel refinery, which is operated by Norilsk Nickel. The spill caused significant environmental damage, contaminating the water and sediments of the river. The high concentration of nickel posed serious threats to aquatic ecosystems, and authorities had to take immediate measures to contain the spread and assess the impact on the environment.

The contamination led to a temporary ban on fishing and water usage in the affected areas, and extensive monitoring of water quality and aquatic life was initiated. The

event highlighted the vulnerability of the Kokemäki River to industrial accidents and the need for effective long-term remediation strategies, including the potential use of bioremediation to address contaminated sediments. [40]
Bioremediation offers a promising solution for cleaning up these contaminated sediments. For the Kokemäki River, microbial bioremediation and phytoremediation (using plants that can absorb or transform heavy metals) could be applied. These approaches would leverage naturally occurring organisms to either break down the pollutants or immobilize them, reducing their bioavailability and toxicity in the ecosystem. Bioremediation in this case could focus on the use of microbes that can tolerate heavy metals like nickel, potentially reducing their bioavailability and mitigating long-term ecological damage.

Belgium

Belgium, with its rich industrial history, faces significant challenges in managing contaminated sites, which have only gained prominence since the early 1990s. The complex federal structure of Belgium, comprising the regions of Wallonia, Flanders, and Brussels, means that legislation and management of contaminated sites are handled regionally, with varying levels of advancement. Among these, Flanders has the most developed system for managing contaminated sites, with a significant number of sites requiring remediation.

Port of Antwerp

The Port of Antwerp, one of Europe's largest and most important ports, plays a central role in Belgium's economy but also presents substantial environmental challenges. The extensive industrial activities in and around the port have led to significant contamination of the surrounding sediments and water bodies. Heavy metals, hydrocarbons, and other industrial pollutants have accumulated over decades, posing risks to both the aquatic environment and public health.

The contaminated sediments in the Port of Antwerp could be effectively managed through bioremediation technologies. Microbial bioremediation, which uses bacteria and other microorganisms to degrade organic pollutants, could be employed to break down hydrocarbons and other contaminants in the port's sediments. Phytoremediation, involving plants that can absorb and stabilize heavy metals, could also be implemented along the port's shoreline and surrounding areas. These bioremediation strategies would not only reduce pollutant levels but also help restore ecological balance in one of Europe's most vital industrial hubs.

Scheldt River

The Scheldt River, which flows through Belgium, the Netherlands, and France, is another critical waterway affected by industrial pollution. The river has been subjected to significant environmental pressures, particularly from agricultural runoff, industrial discharges, and urban wastewater, leading to contamination of its waters and sediments. The river's role as a major transportation route further complicates its environmental management.

For several decades, periodical dredging of river sediments has been necessary to allow for shipping traffic on the river Scheldt. Sediments were disposed along the shores in the alluvial plain without concern for the potential presence of contaminants. Up to 82% of the areas that were affected by dredged sediment disposal was found to be polluted by at least one of the metals Cd, Cr, Zn or Pb. Concentrations of Cd, Cr and Zn were, in 10% of the cases, higher than 26, 1900 and 2800 mg/kg, respectively. Cu and Ni concentrations were of no environmental concern on any site. The pollution levels encountered warrant for caution as most of the soils affected by historical dredged sediment disposal are currently in use for agriculture, nature development or forestry. Several studies revealed that the quality of sediments in the upstream part of the Scheldt in Flanders was very bad based on biological, ecotoxicological and physicochemical criteria (Ministerie van de Vlaamse Gemeenschap, 1995; De Cooman et al., 1998, De Deckere et al., 2000).

To estimate the geographical extent and the environmental consequences of historical sediment disposal on land along inland water rivers in Flanders, a detailed survey was initiated in 1997 on behalf of the Flemish Authorities. [35]

Bioremediation offers a sustainable solution for managing the contamination in the Scheldt River. Techniques such as microbial degradation could be used to target organic pollutants in the river's sediments, while phytoremediation could help manage nutrient runoff and heavy metal contamination in both the water and surrounding floodplains. Implementing these techniques could improve water quality, reduce the ecological impacts of pollution, and enhance the river's overall health.

Geul River

The Geul River in East Belgium is a notable example of severe heavy metal contamination, primarily resulting from historical lead (Pb) and zinc (Zn) mining activities within its drainage basin. The overbank sediments of the river are highly contaminated with lead, zinc, and cadmium (Cd), with pollution levels traceable back several centuries. Geochemical analyses of vertical overbank sediment profiles, sampled 1 km north of the Plombieres mine tailings, have enabled the reconstruction of metal fluxes dating as far back as the 17th century.

These vertical profiles are divided into three major units, each corresponding to different industrial periods. The sedimentological criteria and the distribution of contaminants within these profiles reveal the historical intensity of mining activities. The alluvial sediments containing the highest concentrations of heavy metals are linked to the peak mining period of the 19th century. Notably, zinc mining at the La Calamine open mine began before the large-scale exploitation of subsurface PbS-ZnS deposits. This sequence is clearly reflected in the vertical profiles by an initial rise in zinc content, followed by a marked increase in lead and copper concentrations.

The extent of contamination in the alluvial deposits has been further assessed through geochemical analysis of sediment samples taken from two depth ranges: 0-20 cm and 80-100 cm. Most of the upper samples are found to be extremely contaminated, indicating recent and severe pollution. However, significant local variations in heavy metal concentrations in the lower samples suggest that the degree of contamination varies depending on the specific overbank sediment horizon sampled at a depth of 80-100 cm. This variability highlights the challenges of accurately characterizing the contamination through "blind" sampling in shallow boreholes, as such methods can yield erratic and unreliable results, this issue is clearly present also in the Bagnoli site.

The historical and ongoing contamination of the Geul River's sediments underscores the need for targeted and effective remediation strategies. Addressing this issue through bioremediation could offer a sustainable solution, reducing the environmental and health risks associated with these legacy pollutants and contributing to the restoration of the river's ecosystem.

The Geul River presents a unique opportunity for the application of bioremediation technologies to address heavy metal contamination. Phytoremediation, using plants that can hyperaccumulate heavy metals, could be applied to stabilize and remove these contaminants from the overbank sediments. Additionally, microbial bioremediation could be explored to enhance the natural degradation and immobilization of heavy metals in the soil and sediment layers.

The challenges of accurately characterizing contamination due to geochemical variations in sediment profiles highlight the need for careful monitoring and targeted remediation efforts. Implementing bioremediation in the Geul River basin could significantly reduce the environmental and health risks associated with heavy metal contamination, while also providing a model for similar efforts in other regions affected by mining activities.

Extra EU case study: India

India has explored the field of sediment bioremediation, particularly in areas related to water pollution, heavy metal contamination, and restoration of river ecosystems. While sediment bioremediation is not as prominently developed in India as in some other countries, several research initiatives and projects have been undertaken to address environmental challenges involving contaminated sediments.

Key areas where India has worked on sediment bioremediation include:

- Ganga River Restoration Projects: As part of the Namami Gange Program, efforts have been made to clean the Ganga River by addressing sediment contamination due to industrial pollutants, agricultural runoff, and municipal waste. Bioremediation techniques, including microbial and plant-based approaches, have been considered for restoring the health of the river's sediment. [37]
- Research on Heavy Metal Bioremediation: Several Indian research institutions have studied the use of microorganisms and plants to remediate sediments contaminated with heavy metals like arsenic, mercury, cadmium, and lead. This research primarily focuses on industrial zones and mining areas where sediment pollution is a major concern. For instance, Indian Institute of Technology (IIT) researchers have studied how indigenous bacteria can degrade or immobilize toxic contaminants in sediments.
- Wetland Conservation and Sediment Management: Wetlands in India, such as the East Kolkata Wetlands, have been used as natural systems for sediment bioremediation through the use of aquatic plants and microbial communities. These wetlands help in the breakdown of organic pollutants and the mitigation of sediment contamination from sewage and industrial effluents. [38]
- Coal Mining and Industrial Areas: Studies have been conducted to evaluate the effectiveness of bioremediation in coal mining areas, especially in regions like

Jharkhand and Chhattisgarh, where sediment contamination from mining operations is a concern.

- Lake and Urban Waterbody Restoration: Projects in cities like Bangalore have focused on bioremediation of sediments in lakes to address eutrophication and pollution from urban wastewater. Microbial treatments and phytoremediation methods have been tested to improve sediment quality and water clarity. [39]

MEDREHUB – Building on the Legacy of SEDREMED

In order to facilitate replication and transfer across the sites described in the previous chapter the project foresees the establishment of The Mediterranean Remediation and Innovation Hub (MEDREHUB) in Bagnoli with the ambitious goal of becoming a central hub for the development of cutting-edge remediation and environmental monitoring technologies. This hub aims to bring together key players from European academia and industry to collaborate on innovative approaches to environmental restoration and sustainable development. MEDREHUB will not only focus on advancing technical solutions but also serve as a magnet for attracting additional EU and national funding. By positioning Bagnoli as a center of excellence, the hub is expected to generate significant economic and social value for the region, revitalizing the local economy and contributing to broader European environmental goals.

The hub will concentrate its efforts on three critical sectors:

1. Remediation Technologies and Monitoring: Developing and refining advanced technologies for the clean-up and continuous monitoring of contaminated sites.
2. Nature Restoration: Promoting the restoration of natural ecosystems that have been degraded by industrial activities, focusing on biodiversity conservation and habitat regeneration.
3. Water Treatment Technologies: Innovating solutions for the treatment of polluted water, ensuring the protection of aquatic environments and safe water resources.

In addition to its technical work, MEDREHUB will play a key role in public engagement and education. It will host workshops, training sessions, and other outreach activities designed to involve citizens in environmental issues, raise awareness, and promote community participation in sustainable development initiatives. Through these efforts, MEDREHUB aims to foster a culture of environmental stewardship and innovation in Bagnoli and beyond. MEDREHUB will be a key part of the replication and transfer strategy and will be further detailed in deliverable B5.1.

Stakeholder Mapping

Overview

Nisida Environment has developed a table that contains an overview of the stakeholders identified as part of the LIFE SEDREMED Stakeholder and Market Analysis. The analysis aims to identify and engage key actors who can support the transferability and replicability of project results. The table includes stakeholders from various geographical regions, sectors, and scientific fields relevant to the project. The aim is to map out individuals and organizations whose expertise and involvement can contribute to sustaining and expanding the project's impact beyond its initial scope.

The mapping has been structured around the 3 divulgation events organized by LIFE SEDREMED (Brussels 02/2023, Rome 03/2024, Helsinki 06/2024) and the database from SEDNET conferences in 2021 and 2023, finally the mapping was finalized by desk research. Below the categories that can be found in the mapping:

- Geography (sea-basin): Mediterranean, North Sea, Baltic Sea, Atlantic Ocean.
- Countries: The project engages stakeholders from a wide variety of countries, with a notable focus on European nations, reflecting the EU-funded nature of the project, and with higher numbers for the 3 countries in which the divulgation events have taken place.
- Sectors / Scientific Fields: Stakeholders cover a broad range of topics related to sediment management and environmental sustainability. These include highly specialized fields like port authority, sediment management & monitoring, sediment remediation, dredging, policy makers and consultancies.
- Categories: The stakeholders come from diverse backgrounds, including academic institutions, experts and consultants, NGOs, governmental bodies, private sector companies, international agencies, reflecting a multi-disciplinary approach.

Total Stakeholders: 313

Sea-basins represented: 5 distinct regions (Mediterranean, Baltic Sea, North Sea, Atlantic Ocean and Black Sea) with also stakeholders indicated as EU-wide or others.

Countries Represented: 23 countries, including Italy, Croatia, France, the USA, Netherlands, Germany, Spain, and others.

Sectors / Scientific Fields: Several fields such as Sediment Remediation, Sediment management, dredging, policy etc.

Categories of Stakeholders: 9 categories including Academic Institutions, Expert/Consultants, Government Agencies, Private Companies, Public Companies, Municipalities & local authorities, and Civil Society/NGO/Local Organizations, International organization & agencies.

Table1

Geography	Country	Sector / Scientific Field	Category	Organization name	Name, Surname
Mediterranean	Italy	Association of Port Authorities	Public company	Assoporti	Oliviero Giannotti
North Sea	Belgium	Bioengineering	Academic Institution	UCL	Patrick Gerin
Mediterranean	Italy	Coastal and sediment management	Ministry/Gov. Agency	ISPRA - Superior Institute for Environmental Protec	Fabio Pascarella
Mediterranean	Italy	Coastal management	Academic Institution	National Research Council (CNR)	Mario Sprovieri
Mediterranean	Italy	Conservation	UN / international agency	World Water Assessment Programme	Michela Miletto
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	INVITALIA	Davide Del Cogliano
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	INVITALIA	Edoardo Robortella
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	INVITALIA	Lorenzo Morra
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	Struttura Commissariale Bagnoli	Attilio Auricchio
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	Struttura Commissariale Bagnoli	Filippo De Rossi
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	Struttura Commissariale Bagnoli and Municipality c	Gaetano Manfredi
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	Ministry of Environment	Giuseppe Lo Presti
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	Struttura Commissariale Bagnoli	Giuseppe Napolitano
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	Ministry of Environment	Anna Perinelli
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	Ministry of Environment	Daniela Fiore
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	Ministry of Environment	Luciana Distaso
Mediterranean	Italy	Contaminated site management	Ministry/Gov. Agency	Struttura Commissariale Taranto	Vito Felice Urricchio
Mediterranean	Italy	Contaminated site monitoring	Ministry/Gov. Agency	ISPRA - Superior Institute for Environmental Protec	Antonella Vecchio
Mediterranean	Italy	Contaminated site monitoring	Ministry/Gov. Agency	ISPRA - Superior Institute for Environmental Protec	Michele Fratini
Mediterranean	Italy	Contaminated site remediation	Private company	SIMAM - Acea	Alessandro Carfi

Figure 1: Screenshot of the mapping that has been made available to project partners

Case study: Italy

Several organizations in Italy are involved in sediment management and bioremediation, each contributing to different aspects of this critical work. **MASE** (Ministry of Environment and Energy Security) plays a leading role by setting national guidelines and overseeing remediation efforts, ensuring that sediment bioremediation projects align with Italy's environmental regulations and sustainability goals. MASE facilitates coordination among various regional and local agencies to implement bioremediation techniques, including the use of microorganisms and plants to neutralize or remove contaminants from soil and water. Through MASE's coordination, Italy has been able to promote more sustainable and eco-friendly remediation practices, addressing widespread contamination from industrial activities and hazardous waste sites.

SOGESID and **ISPRA** are two other key players in Italy's bioremediation efforts. SOGESID, as a state-owned company, manages the technical aspects of large-scale remediation projects, offering solutions that often integrate bioremediation as a cost-effective and environmentally friendly option for cleaning contaminated land and water bodies. **ISPRA** (Italian Institute for Environmental Protection and Research) conducts extensive research on environmental contamination, particularly in relation to bioremediation techniques. Their scientific work supports the development of new, efficient methods for addressing pollution, including studying the impact of contaminants on ecosystems and testing biological agents for remediation. ISPRA's findings are crucial for advancing bioremediation science and its application in Italy.

ISS (Istituto Superiore di Sanità), **ARPA** (Regional Environmental Protection Agencies), and **INVITALIA** also contribute significantly to bioremediation efforts. ISS, Italy's leading public health institute, studies the human health impacts of environmental contamination and evaluates the safety of bioremediation methods. **ARPA** operates on a regional level, providing technical expertise, monitoring, and regulatory enforcement for bioremediation projects, ensuring that local initiatives meet environmental standards. **INVITALIA**, the national agency for inward investment and economic development, manages the remediation projects of industrial sites by setting and overseeing the tenders, often preffering bioremediation projects that promote economic redevelopment while addressing environmental damage in a sustainable manner. Additionally, the Italian mapping is completed by several port authorities which manage contaminated sediments, private companies which run large remediation projects, environmental and engineering consultancies that work on permitting and project preparation of remediation works and NGOs that divulgate environmental issues and put pressure on the public and private sector to achieve good environmental status.

Bibliography

[1] MarkWide Research. (2021). Global bioremediation market. [https://www.grandviewresearch.com/industry-analysis/bioremediation-market-report/methodology]

[2] U.S. Environmental Protection Agency. (2001). Use of bioremediation at Superfund sites. EPA 542-R-01-019. Washington, DC: U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. Retrieved from http://www.epa.gov/tio/

[3] Khan, M. (2021). Increased pollution due to COVID-19 pandemic and bioremediation: A dire need of management. *Abasyn Journal of Life Sciences, 4*(1), 61-64. https://www.ajlifesciences.com

[4] Jiang, Y., Zhang, H., Deng, W., Zhang, H., & Wang, L. (2021). Catalytic degradation of volatile organic compounds using novel catalysts: A review. *Chemical Engineering Journal*, 421, 129587. https://doi.org/10.1016/j.cej.2021.129587

[5] Dang, T. A., Kamali-Bernard, S., & Agbodjan Prince, W. (2013). Design of new blended cement based on marine dredged sediment. *Construction and Building Materials*, 41, 602-611. https://doi.org/10.1016/j.conbuildmat.2012.11.088

[6] Pasetto, R., Martin-Olmedo, P., Martuzzi, M., & Iavarone, I. (2016). Exploring available options in characterizing the health impact of industrially contaminated sites. *Ann Ist Super Sanità*, 52(4), 476-482. https://doi.org/10.4415/ANN_16_04_03

[7] U.S. Congress. (2022). H.R. 4521, The America COMPETES Act of 2022. Rules Committee Print 117-31. U.S. House of Representatives.

[8] Prokop, G., Schamann, M., & Edelgaard, I. (2000). Management of contaminated sites in Western Europe (Topic report No. 13/1999). European Environment Agency.

[9] European Commission: Directorate-General for Research and Innovation, EU missions – Soil deal for Europe – What is the EU mission – A soil deal for Europe, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2777/171313

[10] European Commission. (2000). Water Framework Directive. Retrieved from https://environment.ec.europa.eu/topics/water/water-framework-directive_en
[11] HELCOM. (2012). Helsinki Convention: Protecting the Marine Environment of the Baltic Sea Area. Retrieved from https://helcom.fi/about-us/convention/#:~:text=The%20Helsinki%20Convention%20includes%20the,sustainable%20use%20of%20marine%20resources.
[12] Lehoux, A.P., Petersen, K., Leppänen, M.T. et al. Status of contaminated marine sediments in four Nordic countries: assessments, regulations, and remediation approaches. *J Soils Sediments* 20, 2619–2629 (2020). https://doi.org/10.1007/s11368-020-02594-3
[13] Ferrario, F., De Angelis, A., Di Franco, D., Scopelliti, G., Castriota, L., Consoli, P., ... & Ceccherelli, G. (2020). Challenges for restoration of coastal marine ecosystems in the Anthropocene. *Frontiers in Marine Science*, 7, 544105. https://doi.org/10.3389/fmars.2020.544105
[14] Boskalis Westminster. (2009). Finland-Hamina Port Project. Terramare Oy. Retrieved from [https://boskalis.com/media/eodfnyg1/finland-hamina_port_project.pdf]
[15] Cobo, M., Goldhammer, T., & Brothers, S. (2024). A desiccating saline lake bed is a significant source of anthropogenic greenhouse gas emissions. *One Earth, 7*(8), 1414-1423. https://doi.org/10.1016/j.oneear.2024.07.001
[16] Sinnett, D., Bray, I., Baranyi, G., Braubach, M., & Netanyahu, S. (2022). Systematic review of the health and equity impacts of remediation and redevelopment of contaminated sites. *International Journal of Environmental Research and Public Health*, 19(9), 5278. https://doi.org/10.3390/ijerph19095278
[17] Troquet, J., & Troquet, M. (2002). Economic aspects of polluted soil bioremediation. In C. A. Brebbia, D. Almorza, & H. Klapperich (Eds.), Brownfield Sites: Assessment, Rehabilitation and Development (pp. 268-276). *Southampton: WIT Press*. ISBN 1-85312-918-6.

[18] Lofrano, G., Libralato, G., Minetto, D., De Gisi, S., Todaro, F., Conte, B., Calabrò, D., Quatraro, L., & Notarnicola, M. (2016). In situ remediation of contaminated marine sediment: an overview. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-016-8281-x

[19] European Commission. (2024). A European Green Deal: EU Soil Strategy for 2030. European Parliament.

[20] European Parliament, & Council of the European Union. (2004). Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage. Official Journal of the European Union, L143, 56-75.

[21] European Parliament, & Council of the European Union. (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Union, L327, 1-73.

[22] European Parliament, & Council of the European Union. (2010). Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast). Official Journal of the European Union, L334, 17-119.

[23] European Commission. (2019). The European Green Deal. COM(2019) 640 final. Brussels: European Commission.

[24] European Commission. (2020). A New Circular Economy Action Plan for a Cleaner and More Competitive Europe. COM(2020) 98 final. Brussels: European Commission.

[25] U.S. Environmental Protection Agency. (n.d.). The Superfund Cleanup Program. Retrieved from http://www.epa.gov/superfund/index.htm

[26] Magar, V. S., Alleman, B., Leeson, A., Abbott, J., & Lynch, R. (2002). Application, performance, and costs of biotreatment technologies for contaminated soils. *U.S. Environmental Protection Agency*, EPA/600/R-03/037.

[27] Kensa, V. M. (2011). Bioremediation: An overview. *Journal of Industrial Pollution Control*, 27(2), 161-168.
[28] Ayilara, M. S., & Babalola, O. O. (2023). Bioremediation of environmental wastes: The role of microorganisms. *Frontiers in Agronomy*, 5, Article 1183691. https://doi.org/10.3389/fagro.2023.1183691
[29] Dell'Anno, A., Beolchini, F., Rocchetti, L., Luna, G. M., & Danovaro, R. (2012). High bacterial biodiversity increases degradation performance of hydrocarbons during bioremediation of contaminated harbor marine sediments. *Environmental Pollution*, 167, 85-92. https://doi.org/10.1016/j.envpol.2012.03.043
[30] Dell'Anno, F., Rastelli, E., Tangherlini, M., Corinaldesi, C., Sansone, C., Brunet, C., Balzano, S., Ianora, A., Musco, L., Montereali, M. R., & Dell'Anno, A. (2021). Highly contaminated marine sediments can host rare bacterial taxa potentially useful for bioremediation. *Frontiers in Microbiology*, 12, 584850. https://doi.org/10.3389/fmicb.2021.584850
[31] Araneo, F., Bartolucci, E., Congi, M. P., & Vecchio, A. (2023). Lo stato delle bonifiche dei siti contaminati in Italia: secondo rapporto sui dati regionali. ISPRA, Rapporti 387/23. ISBN 978-88-448-1166-2.]
[32] Di Leonardo, R., Mazzola, A., Tramati, C. D., Vaccaro, A., & Vizzini, S. (2014). Highly contaminated areas as sources of pollution for adjoining ecosystems: The case of Augusta Bay (Central Mediterranean). Marine Pollution Bulletin, 89(3), 417-426. https://doi.org/10.1016/j.marpolbul.2014.10.023
[33] Kallert, U. (2018). Contaminated sites. In ARL – Akademie für Raumforschung und Landesplanung, Handwörterbuch der Stadt- und Raumentwicklung (pp. 77-82). Hannover: Leibniz Institute. https://nbn-resolving.org/urn:nbn:de:0156-55990855
[34] Manzetti, S. (2020). Heavy Metal Pollution in the Baltic Sea, from the North European Coast to the Baltic States, Finland and the Swedish Coastline to Norway. Fjordforsk AS, Technical Reports, 6:8, 1-90.
[35] Vandecasteele, B., De Vos, B., & Tack, F. M. G. (2003). Temporal-spatial trends in heavy metal contents in sediment-derived soils along the Sea Scheldt river

(Belgium). *Environmental Pollution, 122*(1), 7-18. https://doi.org/10.1016/S0269-7491(02)00282-8

[36] European Commission: Joint Research Centre, Payá Pérez, A. and Rodríguez Eugenio, N., Status of local soil contamination in Europe – Revision of the indicator 'Progress in the management contaminated sites in Europe', Publications Office, 2018, https://data.europa.eu/doi/10.2760/093804

[37] Namami Gange Programme: Sahu, J., & Sai Ram, C. V. (2017). *Namami Gange Programme*. Members' Reference Service, Lok Sabha Secretariat. Retrieved from https://www.loksabha.nic.in/Reference_Note/Namami_Gange

[38] East Kolkata Wetlands Case Study: Under2 Coalition. (2024). East Kolkata Wetlands: A Community-Led Nature-Based Solution to Combat Climate Change. Department of Environment, Government of West Bengal. Retrieved from https://www.ekwma.in

[39] Lake Conference Paper on Bioremediation: Bhat, S. P., Mahesh, M. K., Asulabha, K. S., Sincy, V., Vinay, S., & Ramachandra, T. V. (2016). Bioremediation Potential of Macrophytes in Varthur and Bellandur Lakes, Bangalore. In R. T. V., Subash Chandran, M. D., & M. Alva (Eds.), Proceedings of the 10th Biennial Lake Conference: Conservation and Sustainable Management of Ecologically Sensitive Regions in Western Ghats (pp. 118-126). Sahyadri Conservation Series, Environmental Information System, Indian Institute of Science, Bangalore.

[40] IMPEL – French Ministry of Sustainable Development / DGPR / SRT / BARPI – Center for Economic Development, Transport and the Environment in Southwest Finland. (2017). Nickel sulphate discharge into a river: Harjavalta, Finland, July 2014. IMPEL.