BIOSYSMO

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Executive Summary

Environmental pollution is a critical challenge within the European Union (EU), impacting human health and ecosystems. Despite the urgency of the situation, only a small fraction of contaminated sites is undergoing remediation. The BIOSYSMO project, under the Horizon Europe program, presents bioremediation as a sustainable and cost-effective solution. Bioremediation leverages the natural processes of microorganisms and plants to degrade or immobilize pollutants, aligning with the EU's Zero Pollution ambition. The project aims to enhance the efficiency and scalability of bioremediation across EU sites through targeted case studies and the development of synergistic biosystems.

However, the widespread adoption of bioremediation faces significant political, institutional, regulatory and financial barriers. There is a lack of consistent long-term policies, an absence of private sector advocacy and a fragmented decision-making process across governance levels. The lack of technical expertise within institutions further complicates the promotion and approval of bioremediation projects. Regulatory challenges include the absence of EU-wide soil pollution limits, making it difficult to standardize soil quality practices. While water regulations are being revised to introduce stricter standards, this does not always correspond with investment in the necessary technology. Additionally, regulations surrounding the introduction of microbes into the environment, as well as the use of genetically modified organisms (GMOs) for bioremediation, are either unclear or overly restrictive.

To overcome these barriers, the policy brief recommends strengthening political support, addressing institutional fragmentation, standardizing regulatory frameworks, clarifying regulations on microbial interventions, re-evaluating GMO legislation and providing financial incentives and support.

Summary of identified political, institutional, regulatory and financial barriers, impact of those barriers and recommended actions to overcome those barriers.

Barrier	Impact	Recommended Action
Lack of political will and consistent policies	Inadequate support for bioremediation technologies, deterring investor confidence.	Implement EU-wide bioremediation support mechanisms.
Lack of private implication	Slow progress in the adoption of bioremediation due to minimal external pressure for change.	Encourage formation of private-sector coalitions and public-private partnerships; Support the ALL4BIOREM cluster.
Institutional fragmentation	Bureaucratic delays and confusion in the decision-making process for bioremediation projects.	Simplify decision-making processes; Expand technical training programs.
Lack of technical expertise within institutions	Hindered promotion and approval of bioremediation projects due to insufficient knowledge.	Offer specialized training for local and regional authorities on bioremediation technologies.
Lack of EU-wide soil pollution limits	Difficulty in standardizing best practices and assessing soil health across Member States.	Adopt EU-wide soil pollution limits.
Stricter water regulations	High investment needed to meet new standards without corresponding technological upgrades.	Align water regulations with technological investments.
Unclear regulations on microbial interventions	Inefficient approval processes for using microbes in bioremediation.	Establish clear guidelines for microbial use in bioremediation.
Lack of mechanisms for GMO use in bioremediation	Slowed research and environmental application of genetically modified organisms.	Review and update GMO legislation; Leverage NGT regulation.
Financial barriers	Limited resources for municipalities to undertake soil remediation projects.	Establish EU urban soil remediation funds; Integrate soil health into EU funding criteria; Develop national soil registries.

By implementing these recommendations, the transition to bioremediation can be accelerated, contributing to the restoration of contaminated lands and the protection of EU citizens and natural habitats.

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1 Introduction

Environmental pollution is a critical issue in the European Union (EU), with widespread soil, sediment and water contamination posing significant risks to human health, agriculture and ecosystems. Environmental pollution, as a result of industrialization and modern human activity, has severely impacted on the quality of life, ecosystem functionality and economic stability across Member States. It is estimated that there are approximately 694,000 registered polluted soil sites across the EU-28, with the potential for this number to escalate to 2.8 million (*1*). Frequently, associated water bodies are also affected by soil contamination. In addition, diffuse source pollution affects 38% of surface water bodies and point source pollution affects 18% (*2*). Only a fraction of these sites, about 11%, are currently undergoing remediation efforts (*1*). The causes for non-remediation are various and range from lack of appropriate legal instruments, difficulties to identify the liability for the remedial action or lack of funds for “orphan sites” (i.e., those sites where the polluter-pays principle cannot be applied).

Pollutants such as heavy metals, mineral oils, polycyclic aromatic hydrocarbons (PAHs) and chlorinated hydrocarbons present in soil and groundwater are not only detrimental to ecosystems but also to human health and agriculture. Reports indicate that 21% of agricultural soils have cadmium (Cd) concentrations above the limit for drinking water; 83% of EU soils have residual pesticides; and 51% of land is affected by mercury (Hg) atmospheric deposition which put soil and aquatic ecosystems at risk (*3*). Additionally, emerging contaminants like endocrine-disrupting chemicals (EDCs) and pharmaceuticals pose new threats, as they frequently evade conventional wastewater treatment and contaminate receiving water bodies (*4*).

Soil and water pollution have vast implications, ranging from the degradation of agricultural lands, which threatens food security, to the contamination of drinking water sources, which endangers public health. The public and private financial burden of remediation is substantial, with estimates reaching up to €119 billion per year (*5*). Traditional remediation methods, such as excavation and chemical treatments, not only come with high costs but also often disrupt soil ecosystems and result in resource wastage.

The EU regulatory landscape is adapting to the pressing need for better pollution management and soil protection. Current directives that form the foundation for national policies include:

- The Water Framework Directive (2000/60/EC) is the main law for water protection in the EU, aiming to achieve “good status” for all EU water bodies (inland, transitional, coastal and groundwater) through integrated river basin management and regular monitoring. It is supported by “daughter” directives such as the Environmental Quality Standards Directive (2008/105/EC, amended by 2013/39/EU) and the Groundwater Directive (2006/118/EC, amended by 2014/80/EU). These are currently under revision.
- The Waste Framework Directive (2008/98/EC) sets the basic concepts and definitions related to waste management, including the “waste hierarchy” (prevention, reuse, recycling, recovery, disposal) and introduces the “polluter pays principle” and “extended producer responsibility”.
- The Revised Industrial and Livestock Rearing Emissions Directive (IED 2.0) (2010/75/EU, amended by 2024/1785) is the main EU instrument regulating pollutant emissions from industrial installations, including large-scale livestock rearing. The revision aims to strengthen emission limits, broaden the scope and improve environmental and health protections.

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- The Environmental Liability Directive (2004/35/EC) establishes the “polluter pays principle” for environmental damage, making operators financially liable for prevention and remediation of damage to water, land, and biodiversity.

Understanding the severity of the pollution problem and the regulatory context in which bioremediation will be deployed is crucial for policymakers. It is imperative to recognize the potential of innovative solutions like BIOSYSMO to significantly reduce the number of polluted sites, mitigate health and environmental risks, and advance the EU's environmental objectives. This policy brief aims to present how the BIOSYSMO project may contribute to restoration of contaminated lands and protection of the well-being of its citizens and natural habitats, while providing insight into the identified barriers to implementation.

2 Project context and research

Spanning from September 2022 to August 2026, the Horizon Europe BIOSYSMO project presents bioremediation as a sustainable, cost-effective and environmentally friendly alternative to conventional physicochemical methods. Bioremediation harnesses the natural capacity of microorganisms and plants to degrade, transform or immobilize pollutants, contributing to the EU's Zero Pollution ambition for a toxic-free environment. BIOSYSMO aims to refine this approach, enhancing its efficiency and scalability to address the extensive problem of pollution across various EU sites.

The BIOSYSMO project has defined several case studies focused on both heavily polluted sites and areas affected by diffuse pollution across Europe (Figure 1), ensuring impact-driven results. The project harnesses the capabilities of microorganisms and plants adapted to contaminated environments to metabolize and withstand target pollutants. These organisms are combined to form synergistic biosystems, integrating bacteria, fungi and plants with complementary traits and metabolic pathways, to optimize the degradation and sequestration of complex pollutant mixtures. A computationally assisted framework supports the design and optimization of these systems, leveraging computational biology approaches for greater efficiency. Briefly, BIOSYSMO’s case studies are progressing as follows:

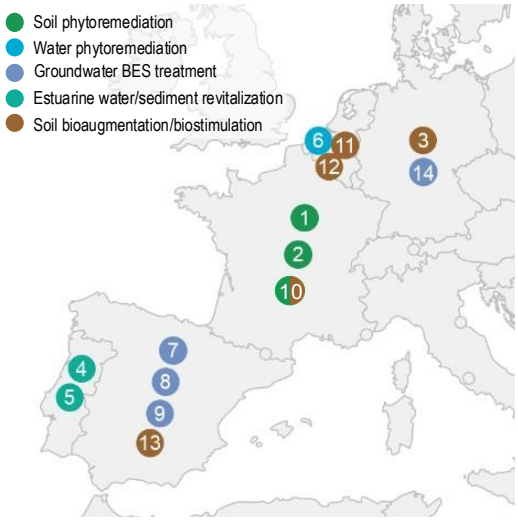

Figure 1. BIOSYSMO’s sites across Europe

Soil phytoremediation using poplar/microbe biosystems. Poplar is an industrial crop with high potential for cultivation in polluted and degraded lands. BIOSYSMO’s research has shown that it is possible to increase resistance and accumulation capacities of poplar to heavy metals by genetic engineering. Moreover, inoculation of poplar, both wild and modified varieties, with fungal strains isolated and enriched from a metal-polluted site resulted in a reduction of plant biomass, but an increased capacity for zinc accumulation in the stem. Given the good results, field studies are being performed with the poplar wild variety inoculated with fungal strains.

Groundwater treatment with bioelectrochemical systems (BES). BES are innovative technologies that combine microbiology and electrochemistry to treat polluted environments using microorganisms that interact with electrodes. BIOSYSMO is exploring BES technologies for targeting metals, hydrocarbons and chlorinated compounds. For the BES targeting hydrocarbons, a flat-plate system

with liquid cathode has shown promising results and will be scaled up. Importantly, the liquid cathode configuration potentially enables the *in situ* treatment of groundwater. Moreover, the systems will be tested with artificially structured biofilms, which potentially enable rational design of the microbial consortia responsible for pollutant degradation. On the other hand, the BES targeting metals will be integrated with a phytoremediation system based aquatic plants.

Water phytoremediation with plant/microbe biosystems. Plant-growth promoting rhizobacteria (PGPR) are being tested to enhance the metal resistance of aquatic plants. Plants such as *Phragmites australis* (common reed) exposed to metal-laden water have shown capable of stabilizing metals around their root system, effectively reducing metal concentrations in the water. Additionally, the growth of *P. australis* does not seem to be adversely affected by the presence of metals, suggesting its potential as a robust candidate for the phytostabilization of metal-contaminated wastewaters. When *P. australis* is inoculated with specific PGPR developed within the BIOSYSMO project, we observe enhanced plant growth and biomass production. The next phase of the project will involve scaling up the water phytoremediation process as well as its integration with a BES bioreactor to further improve metal removal from wastewater.

Estuarine water and sediment revitalization with plant/microbe biosystems. Estuarine ecosystems are fragile and often subject to pollution from upstream diffuse sources, including heavy metals and pharmaceuticals. Within the BIOSYSMO project, bacteria isolated from estuarine environments are combined into microbial consortia and inoculated to aquatic plants like *Juncus maritimus* (sea rush), with the goal of detoxifying estuarine waters of heavy metals and pharmaceutical contaminants. Our research has identified particularly effective bacterial strains that, when combined into a consortium, can significantly degrade the pharmaceutical ketoprofen. Moreover, conventional microbial isolation methods are being compared with innovative microfluidic methodologies. In the next phase of the project, scaled-up experiments will simulate estuarine flooding events, like daily tides, to assess the efficacy of our bioremediation techniques in waters contaminated with pharmaceuticals.

Bioaugmentation and biostimulation for soil depollution. Different strategies are being developed to enhance the breakdown of polyaromatic hydrocarbons (PAHs) and pesticides in contaminated soils. One approach focuses on isolating and enriching bacteria capable of degrading these pollutants, using both traditional methods and cutting-edge microfluidic techniques. In parallel, genetic engineering is being employed to introduce lindane and atrazine degradation pathways into selected bacterial hosts, aiming to reinforce and complement native microbial communities. In the next phase, the most effective microorganisms will be evaluated in scaled-up experimental settings.

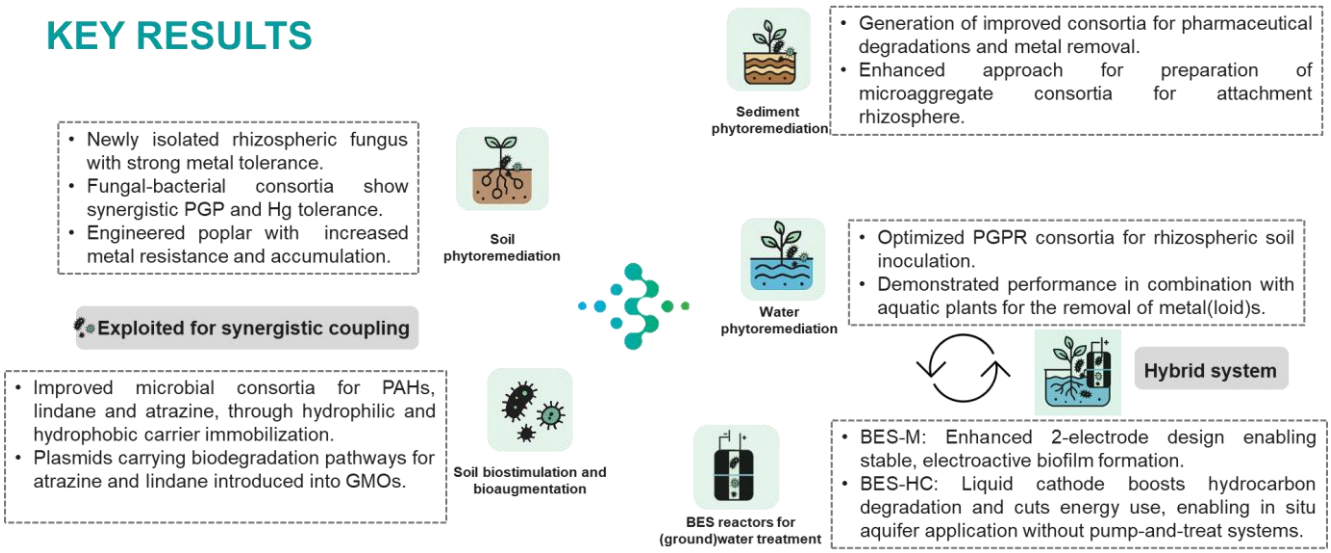

Figure 2. Summary of the key BIOSYSMO's results to date.

Currently, the project's efforts are focused on scaling the solutions and testing them in environmentally relevant conditions. With this effort we aim to bring bioremediation solutions closer to real-life application.

3 Barriers to implementation

The BIOSYSMO project has identified effective bioremediation measures to address soil, water and sediment contamination by various pollutants. Nevertheless, large scale implementation of bioremediation technologies in the EU faces significant barriers.

Political Barriers

Lack of political will and consistent long-term policies at the national level. While bioremediation offers considerable medium- and long-term benefits, short-term political objectives often take precedence, leading to insufficient backing for these technologies. The initial investments required for bioremediation may be substantial and the uncertainty of policy continuity across political cycles, particularly at national level, can deter investors.

Lack of private implication. The absence of private lobbying groups advocating for bioremediation slows progress. Although the public sector may support these technologies, the general public's limited awareness results in minimal external pressure for change. Engaging the private sector through lobbying could expedite the adoption of bioremediation, which tends to be slow within public administration.

Institutional Barriers

Institutional fragmentation of the decision-making process. The decision-making process is fragmented across European, national, regional and local levels, leading to confusion about which authority is responsible for promoting and approving bioremediation projects. This fragmentation results in bureaucratic delays. For instance, securing permits for in-situ bioremediation is often a lengthy process.

Lack of technical expertise within the institutions. The institutions responsible for promotion of environmental protection projects, particularly at the local and regional level, often lack technically

specialized staff with knowledge of bioremediation technologies, which hinders both the promotion of these technologies and a clear understanding of their benefits and implementation processes.

Regulatory Barriers

Lack of EU-wide soil pollution limits. The absence of EU-wide soil pollution limits complicates the standardization and scalability of the best practices for maintaining soil quality. Presently, there are no coherent regulations that define indicators for monitoring and evaluating essential soil remediation actions. Although the *Proposal for a Directive on Soil Monitoring and Resilience* (COM/2023/416) establishes a framework for observation, it falls short of setting enforceable targets for remediation efforts.

Stricter water regulations. Most of the EU-level water regulations are being thoroughly revisited in the frame of the Green Deal strategy and the Zero Pollution Action Plan. The proposed *Directive amending the Water Framework Directive, the Groundwater Directive and the Environmental Quality Standards Directive* (2022/0344/COD) as well as the *revised Urban Wastewater Treatment Directive* (COM/2022/541), are expected to introduce more rigorous water quality standards. However, the implementation of these stricter standards often proceeds without corresponding investments in technological upgrades necessary to achieve them. Complying with these standards necessitates significant investment, with an estimated €255 billion needed to meet existing water legislation (*6*).

Unclear regulations regarding addition of microorganisms to the environment. In situ bioremediation is hindered by unclear regulations concerning the introduction of microbes into the environment. Regulations exist mainly for microbial products with biostimulant effects, and a specific list of microorganisms is subject to these rules. However, bioremediation often involves not just adding external microbes but also using those isolated from the contaminated site itself to boost the degradation of pollutants. The rules for these techniques are either poorly defined or completely lacking.

Lack of mechanisms for using genetically modified organisms (GMOs). New genomic techniques (NGT) have a large potential to accelerate the development of novel plants and microorganisms with pollutant resistance traits and improved pollutant removal efficiency. However, the use of GMOs in bioremediation is severely restricted by current legislation, which imposes a lengthy approval process that hinders the environmental application of modified plants and microbes. This strict regulation also slows down research in this field. Nevertheless, the *Proposal for a new Regulation on plants produced by certain new genomic techniques* (COM/2023/226) is acknowledged. This proposal recommends that NGT plants that could also occur naturally or by conventional breeding ('category 1 NGT plants') would be subject to a verification procedure, based on criteria set in the proposal. NGT plants that meet these criteria would be treated like conventional plants and exempted from the requirements of the GMO legislation. This proposal could potentially streamline the use of innovative plant-based bioremediation solutions in the future.

Addressing these barriers can unlock significant environmental and economic benefits for the EU. By establishing clear policies, investing in technical expertise and updating regulatory frameworks to support bioremediation, the EU can improve environmental health, protect public well-being and stimulate green innovation. BIOSYSMO's results highlight the potential for bioremediation to contribute to a cleaner and more prosperous future for all.

4 Recommendations

This section reflects on recommended actions that can contribute to overcoming the identified barriers. The BIOSYSMO project can contribute to the implementation of these actions by generating robust data and demonstrating the effectiveness of innovative bioremediation methods through pilot studies. Thereby, the project provides evidence-based support to policy development and the implementation of EU-wide strategies. Additionally, BIOSYSMO engages key stakeholders and participates in dissemination actions along with EU projects through the ALL4BIOREM cluster, increasing the impact of our activities. Overall, initiatives like BIOSYSMO are essential in driving policy reforms supporting the Zero Pollution Action Plan, EU Soil Strategy and Green Deal.

1. Strengthen Political Support and Engagement:

→ **Implement EU-wide bioremediation support mechanisms**: Develop mechanisms to coordinate bioremediation efforts across Member States, ensuring continuity in long-term policies and facilitating investor confidence.

→ **Advocate for bioremediation through EU lobbying platforms**: Encourage the formation of private-sector coalitions or public-private partnerships to raise awareness and support for bioremediation, leveraging existing EU lobbying structures. Support the ALL4BIOREM cluster.

2. Address Institutional Fragmentation:

→ **Simplify decision-making processes**: Develop mechanisms to streamline decision-making processes across governance levels, minimizing bureaucratic delays and clarifying responsibilities.

→ **Expand technical training programs**: Offer specialized training for local and regional authorities on bioremediation technologies to enhance institutional expertise and capability for project promotion and approval.

3. Standardize Regulatory Frameworks:

→ **Adopt EU-wide soil pollution limits**: Introduce uniform soil quality standards to facilitate the standardization of remediation practices and the assessment of soil health across Member States.

→ **Align water regulations with technological investments**: Ensure that revised water quality standards under new EU directives are coupled with financial support for necessary technological advancements, thereby balancing regulatory demands with implementation capabilities.

4. Clarify Regulations on Microbial Interventions:

→ **Establish clear guidelines for microbial use in bioremediation**: Define and communicate specific regulations for the introduction of native and externally sourced microorganisms in environmental applications, creating a transparent and efficient approval process.

5. Re-evaluate the Regulatory Mechanisms for GMOs:

→ **Review and update GMO legislation**: Re-evaluate existing regulations on microbial GMOs considering recent advances in NGTs and improved safety features. Promote policy mechanisms that streamline the approval process for field research involving environmentally focused genetic modifications and their safety systems.

→ **Leverage NGT regulation**: Utilize the proposed NGT regulation to expedite the development and deployment of plant-based bioremediation techniques.

6. Financial Incentives and Support:

→ **Establish EU urban soil remediation funds**: Create dedicated funds accessible to municipalities for soil remediation projects, financed through EU cohesion instruments.

→ **Integrate soil health into EU funding criteria**: Include soil remediation and bioremediation initiatives as key components of funding programs such as LIFE+ and the Common Agricultural Policy (CAP).

→ **Develop national soil registries**: Encourage Member States to create comprehensive soil registries that include historical pollution data, aiding in the prioritization and monitoring of remediation efforts.

By implementing these recommendations, policymakers can effectively address the various barriers to the deployment of bioremediation technologies, fostering a cleaner and healthier environment across the EU.

5 Conclusions

The BIOSYSMO project proposes bioremediation as an essential tool for addressing the problem of soil, water and sediment pollution within the EU. Despite its potential, full-scale implementation is hindered by certain challenges. Regulatory gaps, such as the lack of EU-wide soil pollution limits and unclear guidelines for microbial use, impede the standardization of bioremediation practices. Furthermore, the financial burden to meet stricter water quality standards is not always accompanied by parallel investments in technology.

A strategic policy response is needed to overcome these challenges. This includes fostering political commitment, harmonizing regulatory frameworks and ensuring financial mechanisms aligned with the technological needs of revised environmental standards.

The brief advocates for policy reforms that can facilitate the transition towards widespread adoption of bioremediation, highlighting the need for cohesive and supportive governance. By addressing the outlined barriers, policymakers can unlock the transformative impact of bioremediation, leading to a greener, more sustainable future for the EU.

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