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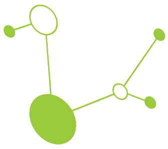
PoLaRecCE

Summary presenting the results of the development strategies implemented on the demonstration sites

WP2 - Best available practices and on-site techniques for environmental site assessment and soil recovery



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1. Castenaso demonstration site (Italy)

1.1. Initial problem of land degradation

The demonstrative site in Castenaso is located in an urban area close to the Idice river, in Emilia Romagna, Italy (Figure 1). The site is on an alluvial terrace, with flat morphology, an average altitude of 53 m a.s.l. and a continental climate (annual average temperature 13.3 °C; annual average rainfall 709 mm). The site is represented by an old kiln measuring 24,000 m^2 and with an almost rectangular shape. In 1979, it was filled with partially vitrified fly ash and glass-ceramic waste (VFA), which was then covered with an earthly material. This material is considered a human-transported material (HTM 20 cm thick, with a volume of about 3500 m^3) [1] (Figure 2). In 2006, the layer of waste was 20/130 cm thick, with a volume of about 17,000 m^3. The Italian law threshold was exceeded for the following toxic elements: lead (Pb), copper (Cu), cadmium (Cd) and zinc (Zn). The contamination was limited to the waste and possibly to the surface of the soil where the waste meets the soil [2, 3].

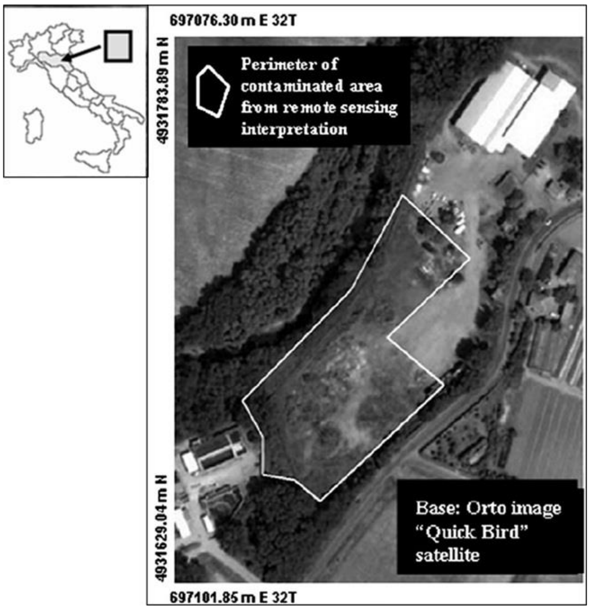

Figure 1. Localisation of the Castenaso reclaimed site (modified from [1])

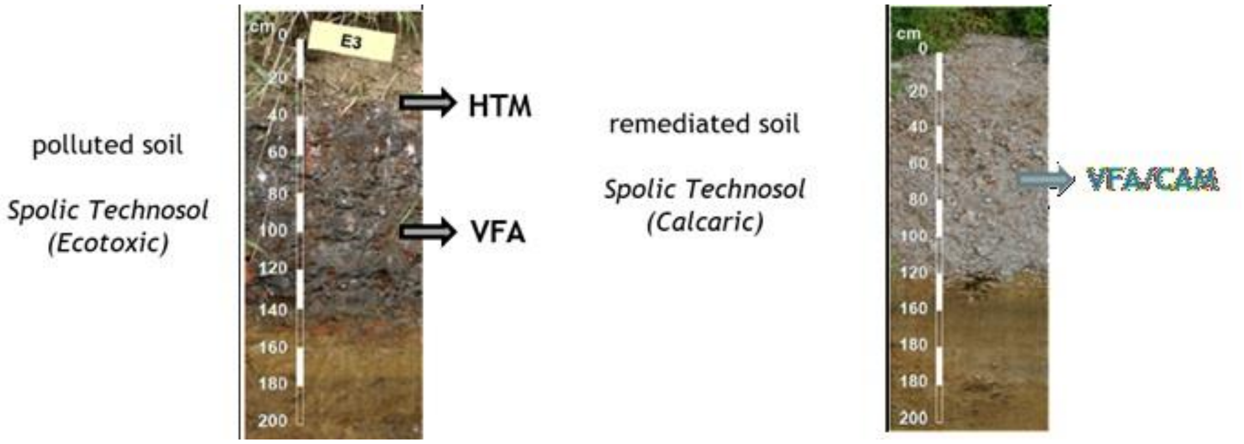

Figure 2. Representation of soil profile polluted and after remediation (modified from [1])

1.2. The strategy and solutions applied on the demonstration site

In 2009-2010, the in situ remediation treatment was carried out by mixing VFA with mixed with $Ca(OH)_2$ and smectitic marlstone at a w/w ratio of 20% and 5% respectively (VFA/CAM) [1] (Figure 2). The in situ remediation essentially consisted of interventions aimed at blocking the PTEs in the affected matrix and inhibiting their leaching [2]. The main steps of the final reclamation project were [2]:

- Removal of wastes
- Screening and disposal of coarse material, consisting mainly of urban solid wastes
- Mixing of screened materials with mixed with $Ca(OH)_2$ and smectitic marlstone
- Placement of a waterproof layer (Figure 3)
- In-situ relocation of the inert material and profiling of the layer
- Placement of the drainage system
- Covering with geotextile net and soil (about 30 cm) (Figure 4)
- Monitoring plan

Figure 3. Placement of a waterproof layer and profiling of the layer in 2009-2010. Source [2]

Figure 4. Covering with geotextile and soil (about 30 cm) in 2009-2010. Source [2]

1.3. The determination of the potential of ecosystem services results from the implementation of the developed strategy

Reclamation efforts in 2009-2010 have satisfactory immobilized potentially toxic elements (PTEs) within the contaminated soil and prevented their leaching [1].

In January 2025, DISTAL-UNIBO, in collaboration with Castenaso Municipality, conducted a site sampling to propose indicators that could serve as robust parameters for evaluating the status of soil and its recovered capacity to store carbon in long term, while maintaining its functionality related to the physical, chemical and biochemical properties of soil organic matter. This approach gave detailed information on the organic matter quality stored in reclaimed soils and the effects on soil C sequestration over a long period.

Figure 5. Soil investigations in 2025: a) soil cover; b) pits location (red squares); c) investigated pits

Five soil pits (CST1–CST5) were excavated to depths of 18–24 cm in the Castenaso reclaimed site (Figure 5) to assess soil chemical, physical, and biological properties. The soils were slightly to moderately alkaline (pH 7.7–8.2) and contained variable amounts of carbonates (10–344 g kg^{-1}). The highest carbonate contents were found in pit CST2, located closest to the Idice River, reflecting the influence of flooding and alluvial sediment deposition.

Soil organic carbon (SOC) and total nitrogen (N) contents were generally low throughout the site. SOC ranged from 5.21 to 16.56 g kg^{-1} and N from 0.25 to 1.60 g kg^{-1}, with the lowest values recorded in the surface layer of CST2. Notably, none of the samples reached the 2% SOC threshold commonly considered necessary to maintain key soil functions and ecosystem services [4-8], indicating poor organic matter accumulation despite the site being unmanaged since 2010.

Bulk density increased with depth, ranging from 1.11 to 1.76 g cm^{-3}. Several subsoil layers exceeded 1.6 g cm^{-3}, indicating compaction that may limit root growth, water infiltration, and soil aeration [9]. Soil carbon stocks ranged from 24.52 to 31.88 Mg ha^{-1} (mean 28.94 ± 3.05 Mg ha^{-1}), while nitrogen stocks ranged from 2.43 to 3.46 Mg ha^{-1} (mean 3.00 ± 0.41 Mg ha^{-1}). These values are considerably lower than those typically reported for agricultural and grassland soils in the Emilia-Romagna plain [10].

Visual Soil Assessment (VSA), as index evaluating the overall quality of soil based on visual indicators of the main physical, biological and chemical soil properties [11], highlighted several limitations, including poor earthworm abundance, shallow rooting depth, weak soil structure, and low organic matter content. However, erosion, crusting, and ponding were generally absent. Overall VSA scores ranged from 27.0 to 28.5 (mean 27.6 ± 0.8), indicating a moderate level of soil quality [11].

Overall, since its reclamation in 2009–2010, the site has effectively immobilized potentially toxic elements (PTEs) and prevented their leaching [1]. However, long term soil development remains constrained by low organic matter content, subsoil compaction, and recurrent flood-related disturbances.

Table 1. Assessment of soil ecosystem services for Castenaso demonstration site

Service	***Service Importance Level***				
	Pivotal	***Important***	***Necessary***	***Not necessary***	***Irrelevant***
Soil forming	*X*				
Water retention			*X*		
Mitigating the effects of climate change			*X*		
Immobilization/filtering of pollutants	*X*				
Nutrient cycling	*X*				
Biomass production for energy purposes					*X*
Food production					*X*

CO_2 sequestration			X		
Aesthetic, cultural and landscape functions		X			

1.4. Conclusions

Reclamation efforts have allowed immobilization of potentially toxic elements (PTEs) within the contaminated soil and prevented their leaching [1], however restoration of soil functionality in long term is limited, as indicated by both C and N storage and VSA. After 15 years since its reclamation, the soil has limitations due to low C and N stocks, high density below soil depth of 10-15 cm, low potential roots depth due to the presence of geotextile net covering inert treated materials, poor structure probably due to the low amount of organic matter. In addition, in the area there is a power line pylon and the site is prone to flooding. Nevertheless, alternative non-food production usage appears as promising approach to exploit soil ecosystem services related to support for instance biodiversity conservation. This can be achieved even when taking into account the risk of flooding and the presence of power lines.

2. Arnoldstein demonstration site (Austria)

2.1. Initial problem of land degradation

The municipality of Arnoldstein is located in Carinthia (Kärnten), southern Austria, in the valley of the “Gail” river. The region has a centuries-old history of mining and ore processing. Mining in the surrounding area (Bleiberg, Raibl) dates back to pre-Christian times, while ore smelting activities were relocated to Arnoldstein from the 15th century onwards. During the 20th century, industrial operations intensified substantially, with extensive production of lead, zinc, cadmium, germanium, and fertiliser products.

The period from the 1950s to the 1970s was characterised by particularly high emissions of heavy metals and other pollutants, causing widespread damage to the local vegetation and the surrounding environment. Although industrial emissions ceased in 1992, the legacy contamination remains measurable in soils throughout the area. Today, soils in Arnoldstein and its surroundings are affected by elevated concentrations of Pb, Zn, and Cd. These soils are used for agriculture, gardening, and residential purposes – uses that carry inherent risks given the potential for plant uptake and entry into the food chain.

Until recently, remediation efforts have been limited largely to private gardens, where soil replacement has been the primary intervention. Agricultural and public-use areas remain largely unaddressed.

The experimental field site is a part of an agricultural area affected by historical heavy metal deposition from decades of local smelting and industrial activity. Soils at the site are used, or were formerly used, for agricultural purposes, yet soil metal concentrations significantly exceed Austrian national threshold values (ÖNORM L 1075:2017) for safe agricultural use.

The total metal concentrations were measured in the soil, alongside the applicable Austrian threshold values (ÖNORM L 1075:2017). The metal concentrations as well as the thresholds are shown in Table 2.

Table 2. Total metal concentrations of the soil in Arnoldstein at the experiment initiation in 2013

Metal	Measured total concentration (mg kg^{-1})	ÖNORM L 1075 threshold (mg kg^{-1})	Exceedance factor
Cadmium (Cd)	7.6	<1	~7.6×
Zinc (Zn)	1,533	<300	~5.1×
Lead (Pb)	1,252	<100	~12.5×

These values confirm that the site is substantially contaminated with all three metals, with lead exceedance being particularly pronounced. The soil's moderate pH and high organic carbon content are relevant to metal speciation and bioavailability.

2.2. The strategy and solutions applied on the demonstration site

As an alternative to conventional soil excavation and replacement, in situ immobilization represents a promising approach for managing large-scale metal-contaminated sites. This strategy involves the application of soil amendments that reduce the bioavailability and mobility of contaminants within the soil matrix, thereby limiting their transfer into the food chain, reducing leaching risks, and enabling the safe, non-food use of contaminated land.

Commonly used amendments include biochar (a carbonaceous material produced by pyrolysis of organic matter), mineral additives such as iron oxides and calcium-rich materials, and combinations thereof. These materials can adsorb metals, raise soil pH, or precipitate metals as insoluble compounds.

The field experiment was established in spring 2013. The experimental design was a randomised block design comprising four treatments replicated four times, arranged across a field of 43 × 13 m (Fig. 6A). The field was divided into four blocks (sections), each containing four plots measuring 6 × 4.5 m. This resulted in a total of 16 experimental plots (4 treatments × 4 replicates, n = 4). Four treatments were applied to the topsoil (0–10 cm depth) at an application rate of 3% (by weight):

Control: Untreated soil; no amendments applied.

P-BCN: Nitrogen-enriched poplar biochar. Biochar was produced by pyrolysis and enriched with nitrogen to improve soil fertility alongside its immobilization function.

GSFe: A mixture of gravel sludge and iron oxide. Iron oxides are well-established sorbents for heavy metals, particularly lead and cadmium, under neutral to slightly acidic conditions.

P-BCN + GSFe (combined treatment): Application of both amendments simultaneously.

All amendments were incorporated mechanically into the topsoil layer (0–10 cm) at the time of application (Fig. 6B).

Figure 6. Initial setup of the experiment with the plot arrangement (A) and a photograph of the site with the incorporation of the soil amendments

Miscanthus × giganteus (giant miscanthus, commonly known as elephant grass) was selected as the test plant. This perennial energy grass is well-suited for phyto-management strategies on contaminated soils due to its high biomass yield, low maintenance requirements, and suitability as a feedstock for bioenergy production. Its use enables the productive, non-food exploitation of contaminated land while the remediation process is ongoing.

2.3. The determination of the potential of ecosystem services results from the implementation of the developed strategy

The application of gravel sludge with iron oxides (GSFe) and nitrogen-enriched poplar biochar (P-BCN) in spring 2013 resulted in a significant reduction in the bioavailability of Cd, Zn, and Pb in the topsoil (0–10 cm) immediately following amendment incorporation. Notably, the immobilization effect has remained largely stable over the subsequent ten-plus years of unmanaged field conditions.

This finding is highly significant from a practical remediation perspective. Despite the absence of any maintenance, reapplication, or active management of the site since 2014, the amendments continue to exert a measurable and statistically significant reduction in metal bioavailability in the treated plots compared to the untreated control.

A slight remobilization was observed over time, particularly for lead (Pb). This is consistent with findings from other long-term amendment studies, where the sorption capacity of iron oxides for

Pb may diminish under fluctuating redox and pH conditions. The ammonium nitrate (NH_4NO_3) extractable fraction of cadmium (Cd), zinc (Zn) and lead (Pb) are shown in Figure 7 for 0-10 cm soil depth.

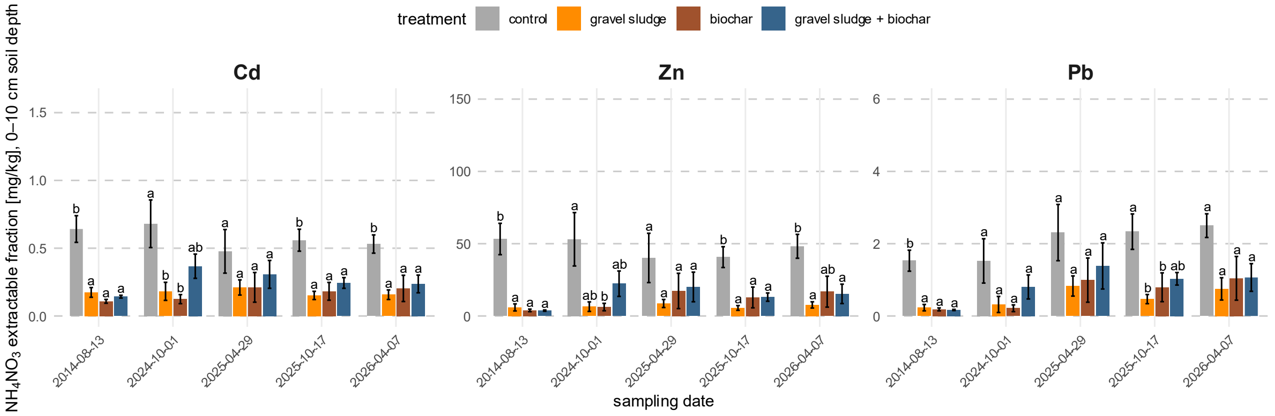

Figure 7. Ammonium-Nitrate-extractable heavy metal contents for the soil layer 0 - 10 cm. Data is presented as means ± standard deviation (SD). Differences among treatments were assessed using one-way analysis of variance (ANOVA). Statistically significant differences between individual treatment groups are indicated by different letters ($p < 0.05$).

No statistically significant reduction in metal concentrations was observed in leaf biomass across most individual treatments. Only the combined treatment (P-BCN + GSFe) showed a reduction in metal contents in leaves, suggesting that the synergistic application of both amendment types may be required to achieve a detectable effect in aboveground plant tissue.

In stem biomass a statistically significant reduction in cadmium (Cd) concentrations was found in plots treated with biochar (P-BCN). This is a relevant finding for the non-food use of Miscanthus biomass (e.g. for energy or fiber production), as lower Cd concentrations in harvested stems reduce concerns associated with the combustion or processing of this material.

For Zn and Pb, moderate but statistically non-significant reductions in stem concentrations were observed. The lack of statistical significance may reflect variability between plots or the inherent complexity of metal partitioning within the plant.

Figure 8. Miscanthus demonstration site at Arnoldstein in 2025

Table 3. Assessment of soil ecosystem services for Arnoldstein demonstration site

Service	***Service Importance Level***				
	Pivotal	***Important***	***Necessary***	***Not necessary***	***Irrelevant***
Soil forming	*X*				
Water retention			*X*		

Mitigating the effects of climate change			X		
Immobilization/filtering of pollutants	X				
Nutrient cycling	X				
Biomass production for energy purposes			X		
Food production					X
CO_2 sequestration			X		
Aesthetic, cultural and landscape functions			X		

2.4. Conclusion

The results of the Arnoldstein field experiment, encompassing more than ten years of real-world field conditions, lead to the following key conclusions:

- Long-term stability of immobilization: The application of biochar (P-BCN) and mineral amendments (GSFe) effectively and durably reduced the bioavailability of Cd, Zn, and Pb in the contaminated topsoil (0–10 cm). This effect persisted for over ten years under unmanaged field conditions, providing rare empirical evidence for the long-term stability of in situ immobilization.

- Moderate remobilization of lead: A slight but measurable remobilization was observed, particularly for Pb. This warrants continued monitoring and highlights the importance of long-term follow-up studies for contaminated land management.

- Element-specific plant uptake effects: Reductions in plant uptake were limited and element-specific. The most consistent effect was observed for Cd in Miscanthus stems in biochar-treated plots, which is of direct practical relevance for the safe non-food use of the harvested biomass.

- Site usability maintained: The results demonstrate that gentle in situ remediation enables the continuing use of contaminated land for the production of non-food biomass (e.g. energy crops such as Miscanthus), contributing to sustainable land management without the need for costly soil removal.

Overall, this approach represents a promising and transferable strategy for the safe, productive use of historically polluted soils, with relevance for numerous contaminated sites across Central Europe.

3. Bytom demonstration site (Poland)

3.1. Initial problem of land degradation

Soil contamination remains one of the major environmental challenges in Europe. Across 38 European countries, more than 2.5 million sites are considered potentially contaminated, while approximately 342,000 sites have already been confirmed as contaminated. The main sources of contamination include municipal and industrial waste, which accounts for about 38% of contaminated sites, as well as activities related to the extraction, production, processing, and distribution of raw materials in the industrial and commercial sectors, responsible for approximately 34% of contaminated areas. Among the most widespread soil contaminants in Europe are mineral oils and trace metals, including lead, arsenic, cadmium, and mercury. Together, these pollutants account for around 60% of all soil contamination.

In Poland, this issue is particularly relevant in regions historically shaped by intensive industrial activity. The unsustainable development of heavy industries, including metal ore processing, mining, and the overexploitation of natural resources during the second half of the twentieth century, has transformed a significant proportion of arable land into marginal or degraded areas. It is estimated that approximately 0.9 million hectares of agricultural land in Poland are affected by contamination-related constraints, particularly heavy metal pollution, rendering these areas unsuitable for food and feed production. In regions such as Upper Silesia, Lower Silesia, and Lesser Poland, soil quality standards for metal concentrations are exceeded at certain locations.

Upper Silesia, located in southern Poland, provides a particularly important example of this problem. Once the industrial heartland of the country, the region was strongly associated with hard coal mining, metallurgy, and other heavy industries. As a result, its landscape consists of a mosaic of industrial and post-industrial sites, waste deposits, dense transport infrastructure, urban areas, and agricultural land. Farming has a long tradition in Upper Silesia; however, decades of industrial emissions have significantly degraded soil quality. Many agricultural soils in the region are either heavily contaminated or contain elevated concentrations of potentially toxic elements, such as cadmium, lead, arsenic, and zinc. In some locations, zinc concentrations reach phytotoxic levels. Consequently, food and feed production on such soils should be avoided.

Despite these risks, contaminated land in the region continues to be used for crop cultivation and hobby gardening. This is partly due to limited public awareness of the health risks associated with heavy metal contamination, as well as local customs and long-standing agricultural practices. Heavy metals can enter the food chain through crops grown on contaminated soils, posing a potential threat to both human and animal health. Therefore, there is an urgent need to identify alternative, safe, and economically viable land-use options for contaminated agricultural soils.

One promising solution is the cultivation of energy crops, particularly Miscanthus. Miscanthus is a perennial C4 grass characterized by high biomass productivity, efficient resource use, and relatively low input requirements. Its cultivation on contaminated land may provide a safe alternative to conventional food and feed production while generating biomass for renewable energy. In this context, Miscanthus can contribute both to the productive use of otherwise underutilized land and to the environmental stabilization of contaminated soils.

Soil contamination in this area resulted from the historical deposition of metal-bearing dust and oxides emitted by a nearby zinc and lead smelter. The permissible limits for agricultural soils in Poland are 100 mg kg^{-1} for Pb, 300 mg kg^{-1} for Zn, and 4 mg kg^{-1} for Cd. The concentrations of these metals exceed these thresholds severalfold (Tab.4). Consequently, the site provides a highly relevant case study for assessing the feasibility of Miscanthus cultivation on contaminated farmland and evaluating whether the biomass produced under such conditions can be safely utilized for energy purposes.

Table 4. Total content of Pb, Cd, Zn and their bioavailable fraction in soil from Bytom demonstration site (data provided by IEIA)

Total metal content	
Pb (mg kg^{-1})	527 ±21.0
Cd (mg kg^{-1})	19.9 ±1.0
Zn (mg kg^{-1})	1900 ±170
Bioavailable fraction ($CaCl_2$)	
Pb (mg kg^{-1})	0.03 ±0.01
Cd (mg kg^{-1})	1.35 ±0.05
Zn (mg kg^{-1})	84.0 ±5.6

3.2. The strategy and solutions applied on the demonstration site

This solution has been tested since 2015 at an experimental plot established in Bytom, Upper Silesia, Poland (Fig. 9), on agricultural soil heavily contaminated with cadmium, lead and zinc. It is maintained by the Institute for Ecology of Industrial Areas (IEIA). The plot has been investigated within the framework of the MISCOMAR and MISCOMAR+ projects. These projects aimed to develop model concepts for energy crop production that maximize environmental and economic benefits at both the farm and landscape scales. The proposed concepts are intended to inform policy makers, farmers, environmental institutions, and the wider public about the potential of Miscanthus for the sustainable utilization and restoration of contaminated land. They may also support the broader acceptance of Miscanthus cultivation in sensitive or multifunctional landscapes, including water protection zones and intensively farmed areas.

Figure 9. Location of the Bytom demonstration site

Four seed-based Miscanthus genotypes – GNT1, GNT3, GNT34, and GNT41 – as well as a rhizome-based genotype, TV1, similar to *Miscanthus* × *giganteus*, were initially planted. Due to severe frost and a snowless winter, GNT1 and GNT3 did not regrow after the first winter and were replaced in 2016 by GNT5 and GNT14. The replacement genotypes, together with GNT34, GNT41, and TV1, showed high adaptation to both heavy metal contaminated soils and the climatic conditions of Poland. More than 80% of these genotypes survived into the second growing season.

In subsequent growing seasons, the plantation was monitored through photosynthetic and phenotypic assessments, while biomass was harvested in autumn as a green harvest and in spring as a brown harvest. The field trials demonstrated that the yield potential of seed-based Miscanthus genotypes can be comparable to, and in some cases even exceed, that of the rhizome-propagated Miscanthus × giganteus-like hybrid TV1. This finding is particularly important because seed-based genotypes may offer advantages for large-scale cultivation, including lower propagation costs and greater genetic diversity.

The research also showed that Miscanthus plants grown on heavy metal contaminated soils accumulated only very low concentrations of lead, cadmium, and zinc in aboveground biomass. Higher concentrations of these metals were found in the roots. This suggests that Miscanthus is suitable not primarily for phytoextraction, but rather for phytostabilization. By retaining metals mainly in the belowground parts of the plant and developing a dense system of roots and rhizomes, Miscanthus can help stabilize contaminated soils and reduce the risk of metal dispersal through wind and water erosion.

Another important observation was that, at the contamination levels present at the experimental site, heavy metals did not significantly affect plant growth, physiological parameters, or biomass yield. Moreover, seed-based genotypes generally showed lower metal uptake than the rhizome-based TV1 genotype. This indicates that carefully selected Miscanthus genotypes may be particularly well suited for biomass production on contaminated agricultural soils, while minimizing the transfer of heavy metals into harvestable plant material.

3.3. The determination of the potential of ecosystem services results from the implementation of the developed strategy

The energy potential of Miscanthus biomass produced on contaminated land was also assessed. Gasification tests conducted within the project showed that the biomass can serve as a valuable energy source. Importantly, the tests indicated that heavy metals do not re-enter the environment when the gas produced from biomass gasification is combusted in a gas engine. This supports the view that Miscanthus biomass from contaminated soils can be used safely in appropriate energy conversion systems, provided that the quality and chemical composition of the feedstock are properly monitored.

The cultivation of Miscanthus on heavy metal contaminated farmland may therefore offer multiple benefits. It provides farmers with an alternative source of income from land that is unsuitable for food or feed production. It supports the production of renewable biomass and contributes to the diversification of rural economies. At the same time, it may deliver environmental benefits by stabilizing contaminated soils, limiting erosion, reducing the risk of pollutant transfer into the food chain, and improving land management in post-industrial regions.

However, the long-term environmental and commercial viability of this solution depends on continued monitoring and research. It is necessary to assess not only biomass yield and energy quality, but also changes in soil properties over time. Future analyses should include heavy metal concentrations, organic matter content, soil organic carbon, and soil fertility. Such data will be essential for determining whether long-term Miscanthus cultivation can contribute to gradual improvement of soil quality while maintaining safe and profitable biomass production.

Overall, the experience from Upper Silesia indicates that Miscanthus is a highly promising crop for the sustainable management of heavy metal contaminated arable land. In regions where conventional agriculture poses risks to food safety, Miscanthus cultivation can provide a practical alternative that combines biomass production, environmental protection, and economic value. The results obtained so far suggest that, with appropriate genotype selection and feedstock monitoring, Miscanthus may become an important component of land-use strategies for contaminated and marginal soils in Poland and other industrial regions of Europe.

Figure 10. PoLaRecCE partners visiting the demonstration site in Bytom.

Figure 11. Miscanthus growing on the Bytom demonstration site (end of May 2026)

Table 5. Assessment of soil ecosystem services for Bytom demonstration site

Service	***Service Importance Level***				
	Pivotal	***Important***	***Necessary***	***Not necessary***	***Irrelevant***
Soil forming		*X*			
Water retention		*X*			
Mitigating the effects of climate change			*X*		
Immobilization/filtering of pollutants	*X*				
Nutrient cycling				*X*	
Biomass production for energy purposes	*X*				
Food production					*X*
CO_2 sequestration		*X*			
Aesthetic, cultural and landscape functions				*X*	

3.4. Conclusion

Research conducted by the Institute for Ecology of Industrial Areas on an experimental plot in Bytom demonstrated the following benefits of Miscanthus cultivation on marginal and contaminated land:

- **High Yield:** Biomass production reaches 25 to 30 tonnes of dry matter per hectare annually.
- **Long Lifespan:** The plantation remains highly productive for 10 to 15 years, with annual harvesting starting from the second year.
- **Heavy Metal Tolerance:** Miscanthus thrives on contaminated soils without accumulating heavy metals in its above-ground parts, making the biomass safe for energy production.

- **Carbon Sequestration:** The crop absorbs large amounts of carbon dioxide, capturing up to 30 tones of CO_2 per hectare every year.
- **Low Maintenance:** The plants require minimal fertilization and tolerate poor soil conditions exceptionally well.
- **Food vs. Fuel Solution:** Cultivation utilizes degraded industrial lands, meaning it does not compete with food crops for fertile agricultural soil.

4. Trzebinia demonstration site (Poland)

4.1. Initial problem of land degradation

The Górka Quarry in Trzebinia is the result of former limestone and marl mining operations that lasted from the early 1920s to the mid-1970s. The site covers an area of 10.5 hectares and is located directly adjacent to the Górka Refractory Materials Plant in Trzebinia (Lesser Poland province) (Fig. 12). Starting in 1954, the Górka Cement Plant was adapted to change its production profile, which consisted in starting the production of refractory materials, especially high-alumina materials (their production started in 1966). In the Górka quarry, approximately 1M Mg of waste from alumina production (red mud) was collected. Highly alkaline leachates (Fig. 13) (pH close to 13.5) threatened the natural environment [12].

Figure 12. Location *of Górka Quarry.*

Figure 13. View *of the quarry filled with waste and alkaline liquid in 2009*

4.2. The strategy and solutions applied on the demonstration site

The main goal of the reclamation of quarry was to:

- create opportunities for plant growth that will provide basic protection for the reclaimed facility,
- stabilize the soil cover of the embankment mass and protect it against wind and water erosion,
- prevent the erosion of the embankment mass by absorbing rainwater through the plant root zone,
- limit surface runoff from the embankment slopes

The waste filling the dump was insulated with a layer of bentomat to limit rainwater infiltration and the washing of pollutants into the dump (Fig. 14). A 50 cm layer of native ground (mixture clay and limestone rubble) overlies on the bentomat, upon which a turf layer was initiated by selecting appropriate species of grass and herbaceous plant mixtures. The vegetation on the internal dump (top and slopes) is intended to serve as an anti-erosion barrier (water and wind erosion) and a stabilizing barrier (Fig. 15), reducing the risk of landslides at the bentomat-native ground interface [13]. An important element of the quarry's reclamation is its renaturalization towards xerothermic communities.

Figure 14. Bentomat *insulation of the slopes of the internal dump*

Figure 15. The effect *of sodding the surface of the dump on a 10-year scale*

4.3. The determination of the potential of ecosystem services results from the implementation of the developed strategy

The main task of reclamation was to protect the stored waste from infiltration of rainwater and the formation of alkaline leachates. The complete coverage of the dump with vegetation allowed for the implementation of the second stage consisting in renaturalization of quarry. This process involves restoring specific xerothermic plant communities and their accompanying fauna to the quarry area and initiating soil-forming processes. Over 130 species of herbaceous plants have been inventoried in the quarry and its immediate vicinity. The dense layer of vegetation promotes water retention thanks to high interception. The undoubted advantage of the quarry's renaturalization is the improvement of its aesthetic and landscape functions (Fig. 16).

Figure 16. Xerothermic *vegetation communities on the quarry surface.*

Table 6. Assessment of soil ecosystem services for Trzebinia demonstration site

Service	***Service Importance Level***				
	Pivotal	***Important***	***Necessary***	***Not necessary***	***Irrelevant***
Soil forming	*X*				
Water retention			*X*		
Mitigating the effects of climate change			*X*		
Immobilization/filtering of pollutants				*X*	
Nutrient cycling				*X*	
Biomass production for energy purposes					*X*
Food production					*X*
CO_2 sequestration			*X*		
Aesthetic, cultural and landscape functions	*X*				

4.4. Conclusion

The final effect of reclamation, consisting in isolating the waste inside the dump, was achieved thanks to the use of bentomat and the formation of a dense vegetation cover on the surface of the dump. Renaturalization efforts, conducted over 10 years, have yielded the desired results. Vegetation coverage of the internal waste heap and slopes has reached nearly 100%, creating a positive visual impact and reducing wind and water erosion. Initiating the soil-forming process gradually increases sequestration of CO_2 and biodiversity.

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